frontiers | Frontiers in Astronomy and Space Sciences

TYPE Brief Research Report
PUBLISHED 03 March 2025
DOI 10.3389/fspas.2025.1427387



OPEN ACCESS

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RECEIVED 03 May 2024
ACCEPTED 23 January 2025
PUBLISHED 03 March 2025

CITATION
Kereszturi A, Gyollai I, Biri S, Juhász Z, Király C, Pál BD, Rácz R, Rezes D, Sulik B, Szabó M, Szalai Z and Szávai P (2025) Evaluation of simulated space weathering-based meteorite alteration and potential influence on mechanical deformation of rubble pile asteroids.
*Front. Astron. Space Sci.* 12:1427387.
doi: 10.3389/fspas.2025.1427387



# Evaluation of simulated space weathering-based meteorite alteration and potential influence on mechanical deformation of rubble pile asteroids

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Asteroids with the potential to impact Earth have become a significant focus of scientific research and applied space technology. These bodies are expected to be key targets for mitigation actions and space mining activities in the coming decades. Understanding their material characteristics is challenging due to the effects of space weathering, which alters the mineral composition and structure of their surfaces, resulting in featureless infrared spectra. This study details laboratory tests of artificial solar wind effects on meteorites, revealing key changes including decreasing magnesium content in olivine, water loss-induced mineral changes, and general amorphization of the crystalline lattice. Although these alterations affect only a thin surface layer (and not the bulk regolith volume) of grains exposed on asteroid surfaces, they can influence the mechanical properties of most small (100 m-class) asteroids through physical surface contacts as most small asteroids are rubble piles with rotation, shape-altering grain migration, and surface mixing. The mechanical properties of only a very thin surface layer of specific grains are influenced; however, the behavior of granular aggregates with such influenced surfaces could be mixed by the YORP effect. This study reviews established findings, explores potential implications for asteroid behavior, and identifies future research directions.

KEYWORDS

**meteorites, asteroids, space weathering, mineral changes, laboratory analysis**

## 1 Introduction

Space weathering significantly affects asteroid surfaces, but its influence on the internal properties and joint behavior of grain within rubble pile asteroids, particularly on the mixing processes under unique microgravity conditions, remains poorly understood

(Kereszturi A. 2014). Asteroids occasionally impact Earth, with large-scale collisions causing rare, catastrophic extinctions over geological timescales. Smaller, more frequent impacts, however, can still have devastating consequences for humanity (De and Rene, 2023; Lubin and Cohen, 2023). As a result, near-Earth asteroids (NEAs) have become a key focus of recent research, particularly regarding their orbital dynamics, physical characteristics, and mineralogical properties, to prepare effective mitigation strategies. Beyond optical camera-based detections, infrasound detectors (Ott et al., 2021) and space-based observations have confirmed the current rate of fireballs and bolide explosions (Peña-Asensio et al., 2022), highlighting the persistent danger these bodies represent. Understanding NEA composition and mechanical properties is crucial, with studies analyzing meteorites on Earth and meteorite analogs (Amiko et al., 2020) to investigate their mineralogy and the effects of space weathering on airless bodies (Chapman, 2004). Space weathering processes universally affect the surfaces of solar system bodies that lack atmospheres or magnetic fields, contributing to the spectral discrepancies between meteorites and asteroids. Meteorites typically represent the intact or less-weathered interiors of asteroids, while asteroid spectra reflect heavily weathered surfaces. Artificial space weathering tests were conducted to better understand the spectral differences between meteorites and their weathered surface host asteroids in order to properly correlate their spectra.

Space weathering processes are driven by various factors, including irradiation, implantation, sputtering from galactic and solar ions, UV irradiation, impacts, and daily temperature fluctuations. At the mineral scale, artificial space weathering experiments have revealed several key effects. Ion irradiation causes silica amorphization, as recorded via IR spectroscopy (Demyk et al., 2004), which is often accompanied by an increase in the Fe/Si ratio (Dukes et al., 2015), as observed in the Tagish Lake sample. Lantz et al. (2015) identified shifts in the infrared bands of phyllosilicate and olivine within 2.7–10 μm toward the Fe-rich range, indicating Mg loss and an increased Fe ratio. The process of sputtering is preferential because Mg is lost more easily than the heavier Fe (Hapke et al., 1975), resulting in amorphization and band broadening, as confirmed via Raman spectroscopy (Brucato et al., 2004; Demyk et al., 2004). Irradiation causes amorphization and chemical changes, attenuating absorption bands (Hapke, 2001; Clark et al., 2002; Chapman, 2004) in general, along with erosion, transport, and redeposition of elements through ion sputtering. These processes form chemically distinct, surface-deposited rims (Noguchi et al., 2014). Micrometeorite impacts can induce melting, vaporization, and recondensation, leading to the formation of reduced iron nanoparticles on the grain rims, which contribute to optical changes (Noble et al., 2007) by reddening and darkening the surfaces. Band position shifts of olivine toward longer wavelengths in the Murchison meteorite were observed after irradiation (Brunetto et al., 2014), as well as the formation of Fe nanoparticles (Thompson et al., 2019). Similarly, npFe0 and nanophase iron–nickel particles were also detected in irradiated CV and CO chondrites (Zhang et al., 2022).

This study investigates the primary effects of simulated space weathering on grain surfaces and the potential secondary consequences for grain–grain interactions within rubble pile asteroids. The findings may have implications for mitigation strategies targeting NEAs. Space weathering alters the thin surface layers of grains, potentially affecting mineral strength and grain–grain interactions at points of physical contact. These changes could theoretically influence the mechanical behavior of rubble pile asteroids, which are composed of loosely bound grains that are mixed and redistributed during shape-altering processes. Improved understanding of grain-scale behavior, as well as the previously mentioned specific effects, is essential for developing effective mitigation strategies against asteroids, such as artificial impact-induced consequences. This work aims to outline the background, raise key questions, and guide future research in this underexplored area. It is important to note that laboratory irradiation tests do not fully replicate regolith weathering as they exclude factors such as temperature cycling and impact effects.

An important milestone in the defense against NEAs was NASA's Double Asteroid Redirection Test (DART), which demonstrated the kinetic impact method by targeting Dimorphos, the secondary of the S-type binary NEA (65,803) Didymos (Daly et al., 2023). The action produced a well-observable impact plume and altered the orbital period of Dimorphos by approximately 33 s (Thomas et al., 2023), indicating that the ejecta (Li et al., 2023) of a diminishing tail feature (Kareta et al., 2023) significantly contributed to the momentum transfer. High-resolution images of the surface, down to approximately 5 cm in spatial resolution, were captured during the mission. Observations of moderately small NEAs, such as Dimorphos, suggest rubble pile structures based on their boulder field observations and porosity volumes. For instance, Dimorphos exhibits a porosity of approximately 30%, contrasting with the lower porosities of compositionally similar L and LL meteorite analogs (8.0% and 9.5%, respectively). This elevated porosity might indicate a rubble-pile interior, which may also be influenced by the shapes of granular materials.

Recent asteroid sample return missions have provided new insights into the role of space weathering on various asteroids. Evidence of space weathering has been observed on Bennu, where young craters are darker and redder than their surroundings (exhibiting a positive spectral slope) due to smaller particle sizes and/or fresh exposure of organics from impacts (Clark et al., 2023). The equator, the oldest surface on Bennu, has similar darker and redder characteristics, possibly due to the development of nano- and microphase opaques. Samples from the carbonaceous asteroid Bennu (Lauretta et a. 2024) revealed dark grains with hummocky and irregular shapes, which were composed of hydrated phyllosilicates, magnetite, organics, carbonates, sulfides, presolar grains, and phosphates, all indicating past aqueous alteration. The sampled mid-latitude location experienced moderate peak temperatures, suggesting that the regolith collected by OSIRIS-REx is not heavily space-weathered. However, the presence of particle surfaces with vesiculated melt droplets and weathered or etched magnetite grains is indicative of space weathering.

Samples from Ryugu, acquired by the Hayabusa2 mission, revealed grains with diverse silicate mineralogies, indicating heterogeneous and incomplete aqueous alteration enriched with many organics (Yesiltas et al., 2024). Near-infrared band changes observed on the surface of Ryugu suggest a global space weathering (Hiroi et al., 2023). Matsouka et al. (2023) demonstrated that micrometeoroid bombardment, which promotes dehydration, is a more effective weathering mechanism on Ryugu than solar wind implantation. This process has resulted in more homogeneous space-weathered grain surfaces compared to those observed on Itokawa. Additionally, possible analogies have been identified between the scoriaceous fusion crust of the Tagish Lake meteorite and the space-weathered "frothy layer" on Ryugu's grain surfaces, particularly in terms of vesicularity (Shehaj et al., 2024). The origin of these vesicles remains uncertain, but recent analyses suggest that they may result from space weathering. This hypothesis is being further investigated through simulations using 400 keV $Ar^+$ ion bombardment, which aims to replicate space weathering processes and support the interpretation of features observed on Ryugu's grains (Palomba et al., 2024).

Samples from the S-type asteroid 25,143 Itokawa exhibited evidence of space weathering, with sulfur-bearing Fe-rich nanoparticles identified in a 5–15-nm surface layer of olivine, pyroxene, and plagioclase. These nanoparticles were likely formed by vapor deposition. Sulfur-free Fe-rich nanoparticles were also observed deeper within ferromagnesian silicates, potentially resulting from metamictization and reduction of $Fe^{2+}$ (Noguchi et al., 2011). A black zone on Itokawa was found to be more space-weathered than a surrounding bright region, with spectra similar to those of LL5-6 chondrites. The dark region exhibited a shorter mean optical path length and a higher concentration of nanophase iron, suggesting that small asteroids like Itokawa could serve as parent bodies for LL chondrites (Hiroi et al., 2006).

## 2 Methods

This section outlines the general methodological framework relevant to simulated space weathering and its consequences, providing context for the mineral-scale effects of artificial particle irradiation. Specific examples are provided, presenting laboratory measurements and numerical data to illustrate observable changes.

Over the past decades, numerous artificial space weathering experiments have been conducted on various meteorites and reference minerals, using protons and heavier nuclei. Although interactions with protons represent the most common type of event, heavier nuclei, including those of galactic cosmic ray origin, may exert stronger but less frequent effects. The cumulative impact and relative roles of solar wind ions and cosmic ray-originated ions, however, remain poorly understood.

Changes induced by artificial irradiation have been analyzed primarily via Fourier transform infrared (FTIR) spectroscopy, typically on bulk samples (Lantz et al., 2017; Brunetto et al., 2014; 2020). Raman spectroscopy-based measurements have also been employed, for example, in studies of olivine (Lantz et al., 2015). Additionally, measurements in the near-ultraviolet (NUV) and visible-near-infrared (VNIR) ranges have been conducted on silicates and meteorites (Kanuchova et al., 2015), as well as on materials such as polystyrene (Kanuchova et al., 2010; Kanuchova et al., 2017).

Example numerical values from the authors' own work are provided below to illustrate the scale of changes caused by simulated space weathering. These results were obtained from the irradiation of the NWA 10,580 $CO_3$-type meteorite, a poorly altered primitive meteorite containing unweathered material. The meteorite was irradiated with 1 keV $H^+$ protons produced by an ECR ion source (for technical details, see Biri et al., 2021) at the ATOMKI institute under vacuum conditions. Three irradiation sessions were conducted as follows: 15 s ($10^{11}$ ion/cm$^2$) for the first irradiation, 1 h ($10^{14}$ ion/cm$^2$) for the second, and 1 day ($10^{17}$ ion/cm$^2$) for the third. All ion fluences were cumulative. As each irradiation reinforced the effects of previous sessions, the cumulative consequences must be considered. The strongest effects were expected after the third irradiation.

The observed changes were analyzed via infrared spectroscopy using a VERTEX 70 FTIR spectrometer. Measurements were conducted with 32 scans over the 400–4,000 cm$^{-1}$ range and performed for 30 s at a spectral resolution of 4 cm$^{-1}$. Spectral data were processed using Bruker Optics' Opus 5.5 software. The field of view using the IR × 15 objective was 200 μm in diameter, making this method suitable for moderately smooth rock sample surfaces, while the DRIFTS Praying Mantis accessory was also used and showed characteristics of bulk samples. Two key parameters were determined, namely, peak position and full width at half maximum (FWHM). FWHM values were calculated manually by measuring the width of spectral bands at their half height. The accuracy of peak position measurements was ±0.5 cm$^{-1}$, as determined by the OPUS software manual. Peak shifts were quantified by comparing band appearance and maximal positions before and after irradiation and correlated with databases like those by Lafuente et al. (2016).

## 3 Summary of mineral changes

The results of the authors' tests are presented below, along with related findings from other studies for review and context. According to the increasing impact, the following types of alterations are expected to occur as the crystalline lattice is progressively disrupted during irradiation:

1. Emergence of metastable phases: Metastable phases may form ephemerally under conditions differing from those of stability. Although these aspects have primarily been studied under Earth-related conditions, such as in sediments and thermal alterations (Milliken, 2014), previous research by Lindsley et al. (1972) evaluated the metastable properties of pyroxferroite related to smectites in cosmic materials. Radiation-induced metastable structures have also been observed in specific mineral-like alloys as well (Lilienfeld et al., 1987), where irradiation can modify grain boundaries and dislocations (Chesser et al., 2024). However, these effects have rarely been explored in irradiated meteorites.
2. Defect production in the crystalline lattice: The next stage involves the formation of defects, where the long-term behavior, such as vacancy migration, is influenced by temperature (Campbell et al., 2002, Closel et al., 1994). These defects might reduce the band strength and increase FWHM values in general.
3. Element migration, replacement, and ion integration: Irradiation can lead to changes in the crystalline lattice. For example, olivine composition changed from Fo-50–60 (Hamilton 2010) to Fo-30–35 after irradiation in Frontier Mountain 95,002 and Lancé meteorites (Brunetto et al., 2020). Similarly, an increase in the Fe/Si ratio was observed in the Tagish Lake sample after ion irradiation (Dukes et al., 2015).

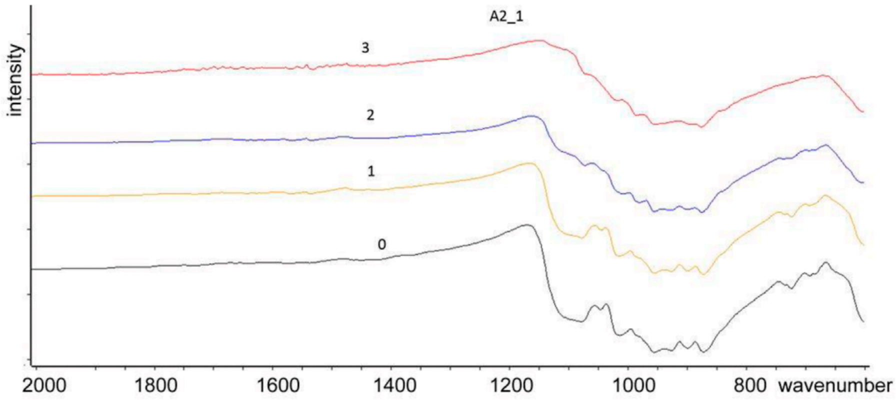


FIGURE 1
Example DRIFT detector-based infrared reflection spectral curves for the NWA 10580 sample before irradiation (0) and after gradually increasing irradiation actions by Gyollai et al., 2024. Please note the vertical offset of the curves for better visualization, the horizontal axis shows the $cm^{-1}$ values.

4. Amorphization and mineral decomposition: At higher levels of irradiation, excessive defects and element loss or implantation result in amorphization and decomposition. For silicates, this occurs through the depolymerization of $SiO_4$ tetrahedra and the decomposition of the related part of the lattice, which is observable as weakened or missing spectral bands. It is important to note that these four stages progressively lead to mechanical changes in the affected minerals. Although the early stages are challenging to identify spectroscopically, the later stages may produce significant macroscopic consequences, as possibility partly explored in this work.

Specific results from our laboratory tests demonstrated changes induced by artificial solar wind simulations that are generally consistent with the weakening of spectral bands reported in the literature. Characteristic examples include irradiation-driven changes observed in the NWA 10580 meteorite, as described in the Methods section. The primary types of changes identified were peak shifts. For the prominent meteorite components pyroxene and feldspar, negative shifts were observed after the first and second irradiation sessions, ranging from −4 to −41 $cm^{-1}$, likely due to Mg loss (Lantz et al., 2017). Conversely, a positive shift occurred after the third strongest irradiation action, with values between +7 and +30 $cm^{-1}$, indicating general distortion of the $SiO_4$ tetrahedra (Sharp and De Carli, 2006; Johnson et al., 2003; 2007). Minor peaks corresponding to certain minerals were generally weakened or disappeared, following irradiation. Additionally, the olivine doublet at 849 $cm^{-1}$ and 880 $cm^{-1}$ merged into a single peak at 887 $cm^{-1}$, further supporting the conclusion of $SiO_4$ disordering. A representative spectral curve series is presented in Figure 1, recorded by Gyollai et al. (2024). Below, only the results related to amorphization and Mg/Fe changes are highlighted as the most prominent effects contextualized with the behavior of the weathered surface layer on grain interactions. Further specific details regarding mineral alterations can be found in the cited works.

Numerical band positions are provided in Table 1 to quantify the spectral changes observed in typical meteorite minerals from the analyzed sample. Although data for comparing band position changes are limited, especially in the IR range, few standards and FWHM measurements are available from irradiation studies in the existing literature. Earlier research predominantly focused on Raman spectroscopy rather than IR measurements. In this study, example values for peak positions and FWHM changes are listed in Table 1, 2.

The last column of Table 1 provides guidance for researchers conducting future laboratory tests, offering insights into the scale of band shifts to aid in estimating observability. The first, and to some extent, the second irradiation induced metastable states in the crystal structures of Mg-bearing minerals. Increasing fluences of irradiation led to amorphization of the crystal structure, primarily through Mg loss from $MgO_6$ octahedra (Lantz et al., 2015; Lantz et al., 2017). Feldspar, which was already in a less-crystallized state prior to irradiation, exhibited further distortion of $SiO_4$ tetrahedra during irradiation. This amorphization trend in feldspar, reflected in positive peak shifts, is consistent with the observations reported by Johnson et al. (2003) and Gyollai et al. (2024), which primarily occurred following the second irradiation. It is possible that the weakly crystallized feldspar required stronger irradiation to produce further observable distortions. FWHM changes for the major bands of feldspar exhibited an increasing trend, while olivine and pyroxene showed a decreasing trend after weaker irradiations, followed by an increasing trend after stronger irradiation sessions. The effects of irradiation-induced changes in infrared peaks partially resemble those caused by shock deformation, presenting opportunities for future synergistic studies.

Although space weathering processes primarily alter the microscopic characteristics of minerals and most ions and microscopic impact events do not penetrate deeply into the minerals, it is worth exploring whether these effects could influence larger spatial scales, for example, the mechanical behavior of grains within rubble pile asteroids (Bierhaus et al., 2023). The mechanical properties, global shape, and internal stability of such asteroids depend on the size, shape, and surface adhesion of individual grains. As asteroids undergo spin-state modifications, their global shapes may adapt to new equilibrium states through grain flow or

TABLE 1 Average peak position shift after irradiations in the reflection mode in $cm^{-1}$. Average original peak positions are indicated at "band" column in $cm^{-1}$ for minerals which were observable after all of the irradiation actions.

| Mineral | Band | First irr. ($cm^{-1}$) | Deviation | Second irr. ($cm^{-1}$) | Deviation ($cm^{-1}$) | Third irr. ($cm^{-1}$) | Deviation ($cm^{-1}$) | Avg. Dev. irr. ($cm^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Olivine | 849.2 | −11.33 | 6.5 | 2 | 12.8 | 1.8 | 5.7 | 8.3 |
| Feldspar | 1152.1 | −1.58 | 20.4 | 2.16 | 19.9 | −1.4 | 15.7 | 18.7 |
| Pyroxene | 1047.2 | −7.8 | 14.9 | 7 | 19.6 | 1.4 | 5.6 | 13.4 |
| Spinel | 666.1 | −3.22 | 5.9 | 0.11 | 1.9 | 3.4 | 2.9 | 3.6 |

TABLE 2 Average FWHM values of major mineral bands with standard deviations. At the end of the table, the average deviation after the irradiations was calculated. These data of the table contain such measurements, where the given bands appeared before and after all irradiation tests.

| Mineral | Band | Before irradiation | Deviation | First irradiation | Deviation | Second irradiation | Deviation | Third irradiation | Deviation |
|---|---|---|---|---|---|---|---|---|---|
| Olivine | 849.3 | 9.8 | 4.4 | 17.5 | 4.5 | 6.8 | 1 | 4.3 | 1.03 |
| Olivine | 887.6 | 12 | 3.1 | 8.4 | 2.2 | 6.5 | 2.5 | 12.0 | 13.9 |
| Feldspar | 1149.8 | 76.4 | 31.4 | 86.3 | 25.2 | 84.8 | 30.4 | 99.8 | 19.8 |
| Pyroxene | 1048.4 | 29.2 | 14 | 22.1 | 11.2 | 22.3 | 20.5 | 21.3 | 9.03 |
| Spinel | 668.5 | 65.8 | 40.7 | 51.4 | 46.3 | 65.6 | 41.9 | 76.6 | 33.09 |

rolling interactions (Banik et al., 2022). Since space weathering can affect the surface hardness of the grains, which is linked to mineral structure and amorphous states, the potential implications of these modifications are considered below.

## 3.1 Aspects of mechanical grain behavior

Ion migration and crystalline lattice destruction, as described in datasets such as those by Railsback (2006), result in decreased rigidity and mechanical properties within a very thin surface layer during various irradiation tests (Chaves et al., 2023 Harries and Langenhorst, 2014; Yang et al., 2017). A key challenge is to evaluate whether mechanical changes in this thin surface layer could influence the collective behavior of asteroid regolith grains. Alterations to amorphous structures and other mineralogical changes may reduce mechanical hardness (Zaccone, 2023) as amorphization is known to decrease the hardness of minerals (Leggett, 1991; Thorpe and Tichy, 2001). For example, the Mohs hardness of Mg-rich olivine (forsterite) decreases as its composition shifts toward Mg-poor fayalite.

In this context, hardness is considered a basic mechanical property, although it is important to note that mechanical behavior is also influenced by factors such as porosity and grain size of the crystals. For simplicity, this discussion focuses solely on mechanical hardness. The aim of this work is to explore the potential effects of irradiation-induced grain surface modifications and their implications for the temporal aspects of shape changes. However, detailed numerical calculations of the possible consequences are beyond the scope of this paper.

In rubble pile asteroids, individual grains occasionally move relative to each other during deformation caused by changes in rotational speed, such as those driven by the YORP effect. This movement allows the asteroid to achieve an equilibrium shape (Sanchez and Scheeres, 2018; Walsh et al., 2017). The timescale for YORP effect-induced shape changes ranges from 1 to 100 million years (Botke et al., 2006), depending on the size, mass, and other characteristics of the given asteroid. This range is roughly comparable to the timescale for space weathering-induced changes relevant to the main asteroid belt solar distance, estimated at 1–100 million years (Hasegawa et al., 2022; Sunho and Masateru, 2022). These estimations are based on observable amorphization using average solar wind exposure, although they are rough approximations on the exposure duration of the same surface of asteroids that do not account for mixing or fragmentation caused by impacts.

As rotational speed increases, the oblateness of the body increases (e.g., the body becomes more flattened), causing boulders and grains to roll toward lower latitudes, potentially burying previously surface-exposed weathered grains. Small, low-mass objects among asteroids strongly influenced by the YORP effect (Holsapple, 2009), such as those in the potentially hazardous asteroid (PHA) group, are particularly susceptible to these shape changes due to their low gravity (Pleasko et al., 2024; Regály et al., 2023). These objects often have diameters of a few hundred meters. During changes in oblateness, mechanical attrition and friction occur as grains interact. Grain movement and critical slope angles depend on their shape (Jacobson and Scheeres, 2010; Kereszturi, 2023), according to the stability and spatial density of their mechanical contacts (Ferrari and Alessi, 2023; Hirabayashi, 2023).

For example, given the current obliquity of Ryugu, the asteroid is expected to be spinning down at a rate of $-1.71 \times 10^{-6}$ deg/day$^2$, corresponding to a change in the rotation period from 3.5 h to 7.6 h over approximately 2.15 million years (Kanamaru et al., 2021). In cases where hardness decreases, any grain movement, such as creeping or rolling, is facilitated by the softening of minerals. Softer minerals deform more quickly under attrition, smoothing and destroying protrusions and enabling easier movement. However, hardness changes are not well understood for all minerals under irradiation. For example, phyllosilicates may transform into oxides through OH loss, but this transformation does not necessarily result in mechanical softening.

The role of cohesion, determined by the number and characteristics of grain–grain contacts, has been studied in the context of momentum transfer-related grain movement in asteroids (Raducan et al., 2019). As cohesion decreases, the ratio of ejected momentum to impactor momentum increases. This ratio also increases, as the initial porosity and internal friction coefficient decrease. This later may be associated with reduced hardness, which allows for rounding of grains. However, this modeled aspect focuses on sudden changes affecting a relatively small volume of grains, whereas YORP-driven shape changes act over longer timescales and influence larger numbers of grains, permitting more gradual, friction-driven shape modifications. The friction coefficient between grains has been identified as an important parameter (Brisset et al., 2020), particularly under low gravity conditions (Brisset et al., 2018). Despite its importance, available data and modeling methods remain insufficient to fully evaluate the potential consequences of the processes outlined in this work.

Although the thickness of the affected grain surface layer is small, its macroscopic effects on grain behavior and regolith dynamics should not be overlooked (Kobayashi et al., 2020; Kobayashi et al., 2023; Takano et al., 2020). Grains interact primarily through this thin surface layer, and even minor changes could influence the mechanical stability of grain groups by altering their threshold angles. Surface roughness plays a key role as protrusion helps grains interlock, while smoother grains are more prone to rolling and sliding, potentially affecting the global shape of an asteroid and the manner in which it achieves equilibrium.

Global shape changes have significant implications for asteroid surfaces. Using the model proposed by Banik et al. (2022), top-shaped asteroids are made up of loose regolith lying atop a solid core (potential-related consequences are detailed below). For example, in the case of Bennu, a previously faster spin state may have been slowed by impact-induced global landslides, leading to its current spin rate. As the spin rate dropped below a critical threshold, regolith flow from higher latitudes accumulated at the equator.

Both observational data and theoretical modeling of the interior structure changes driven by the YORP effect remain poorly explored. Substantial differences are anticipated between the two theoretical end cases mentioned above: one where the entire asteroid is composed solely of grains (including the center) and another where a solid core is covered by debris. In the latter case, grains in the shallow subsurface layer are expected to exhibit greater mobility, potentially resulting in stronger mixing and more observable effects. The irradiated and slightly decreased hardness of the top surface layer of grains may further influence granular behavior in the latter scenario involving transport over a solid core.

Given the differences in the mechanical stability of grain groups within rubble pile asteroids, the considerations outlined in this work are important as they could affect the planning and implementation of mitigation strategies for hazardous NEAs. Additionally, amorphization reduces heat conduction, which could further impact asteroid regolith and grain behavior. Changes in porosity may have an even greater influence, altering mechanical contacts where heat conduction occurs.

## 3.2 Mechanical properties of meteorites

Several research studies have been conducted to explore the mechanical properties of meteorites and, by inference, asteroids. Moyano-Cambero et al., 2017 analyzed the highly shocked, low-porosity Chelyabinsk ordinary chondrite meteorite, which is likely similar in composition to S- or Q-type asteroids. Nanoindentation experiments revealed mechanical property variations across different regions of the meteorite that were unrelated to compositional differences. The differences were attributed to grain size as smaller mean particle sizes—produced by repetitive shocks—can increase hardness. Additionally, low-porosity sections promote higher momentum multiplication, which is defined as the ratio of the impact-induced momentum change in the target and the momentum of the projectile. Light lithology materials were found to facilitate greater momentum multiplication, while the low fracture toughness of shock veins promotes material ejection by impact and further increases momentum multiplication, potentially resembling observations from the DART impact event.

A laboratory comparison of grain physical properties between the Itokawa asteroid and the Chelyabinsk meteorite using nanoindentation (Tanbakouei et al., 2019) showed that Young's modulus for Itokawa samples was slightly higher than that for the Chelyabinsk chondrite. This difference is very small and may result from the increased compaction of Itokawa grains, suggesting that Itokawa particles are better able to absorb elastic energy during an impact than Chelyabinsk chondrite.

To date, no results in the literature have confirmed the mechanical grain surface property-related aspects hypothesized in this work. Although the mechanical effects of space-weathered grain surfaces are expected to be minor, they remain poorly understood. It may be worthwhile to explore whether space weathering-induced fragmentation and microscopic void formation could be linked to irradiation-driven alteration as these processes occur concurrently. This potential connection could offer a novel perspective for future research.

The potential effects of mechanical changes in the grain surface layer require further investigation, although this lies beyond the scope of the present work. Future studies could benefit from highly sophisticated grain surface mechanical analyses, including attrition tests, which would necessitate well-designed instruments and controlled conditions. Additionally, transmission electron microscopy (TEM) could be used to assess amorphization levels and compare grain surface modifications across analog materials with varying hardness. Such independent inputs would enhance our understanding of the granular behavior of rubble pile asteroids and facilitate the implementation of these findings into models of small asteroids' mechanical strength and deformation.

Based on the aspects presented above, the following main research questions are proposed to evaluate the potential consequences of irradiation-induced grain-scale changes for asteroids in the near future:

1. Asteroid modeling: Improved models are needed to better understand the speed and scale of YORP effect-driven rotational modifications and their associated shape changes, with a focus on the populated and hazardous near-Earth object category of asteroids under 1 km in diameter.
2. Grain rearrangement studies: Future asteroid missions should investigate the typical movement of grains on and within rubble-pile asteroids. For example, the HERA mission for Dimorphos could provide valuable insights through surface observations and radar-based internal analyses (Michel et al., 2024).
3. Grain-size estimation: High-resolution asteroid imagery combined with Earth-based thermal inertia measurements should be jointly analyzed to estimate the typical grain sizes on small near-Earth asteroids.
4. Laboratory simulations: Artificial space weathering experiments using higher ion bombardment fluences and energies, paired with mechanical analyses of irradiated grain behavior, should be conducted in laboratories to expand the understanding of grain surface changes.

## 4 Conclusion

Using artificial irradiation experiments on meteorites in laboratory settings, various mineral lattice changes were observed, leading to hardness decreases through amorphization and the introduction of lattice deflects in a very thin surface layer of the target meteorites. These changes were tracked through shifts in infrared peak positions and FWHM values for minerals such as olivines, pyroxenes, and feldspars. At high fluences, these processes resulted in significant mineral lattice changes and amorphization, which corresponded to 10–100 million years of space weathering exposure, albeit confined to an extremely thin surface layer.

Despite extensive and growing mineral-based research linking meteorites and their parent asteroids through infrared spectral characteristics (Moyano-Cambero et al., 2016; Tanbakouei et al., 2019; Trigo-Rodríguez et al., 2011; 2014), including spectra recorded during meteor ablation in Earth's atmosphere (Madiedo et al., 2014), further investigations are necessary to fully understand the effects of space weathering on spectral bands. This review highlights specific infrared bands where certain minerals retain their diagnostic features despite weakening spectral signatures. Improved mineral identification, particularly for components like phyllosilicates observed on Ryugu and in meteorites (Storz et al., 2024), is critical, especially considering their metal cation-dependent band shifts and volatile content as potential sources of primordial water delivery to Earth (Trigo-Rodríguez et al., 2009).

Infrared spectral analysis also supports primordial condensation studies, which aim to reconstruct processes in the solar nebula (Trigo-Rodríguez et al., 2009). This work is particularly relevant for refractory condensates such as forsteritic olivine (Weinbruchi et al., 2000) and various isotopic and elemental analyses (Kobayashi et al., 2020). Predicting spectral alterations caused by space weathering influences the design and channel arrangement of future infrared detectors, as well as data processing schemes for upcoming missions. Such missions should prioritize identifying primordial condensates and assessing water content. Further efforts are required to clarify the changes in typical meteorite-forming minerals and their source asteroids, emphasizing the need for targeted spectral band or filter arrangements over equidistant, uniformly distributed bands.

Finally, the mechanical implications of the thin, irradiation-modified surface layer warrant consideration. Grain surface characteristics may influence joint grain group-scale mechanical processes, potentially affecting global deformation-driven shape changes in rubble-pile asteroids by facilitating the smoothing process of grain surface undulations. Although this effect is expected to be minor and likely overshadowed by other unique microgravity-driven phenomena present on small asteroids, it is nonetheless worth evaluating for its potential consequences.

## Author contributions

AK: writing–original draft and writing–review and editing. IG: investigation and writing–original draft. SB: formal analysis and writing–original draft. ZJ: validation and writing–review and editing. CK: investigation and writing–original draft. BP: investigation and writing–review and editing. RR: formal analysis and writing–original draft. DR: methodology and writing–original draft. BS: conceptualization and writing–review and editing. MS: formal analysis and writing–original draft. ZS: validation and writing–review and editing. PS: formal analysis and writing–original draft.

## Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This project was supported by the K_138594 Project of NKFIH. The authors acknowledge the Europlanet 2024 RI, which has been funded by the European Union's Horizon 2020 Research Innovation Program under grant agreement No. 871149. ZJ is grateful for the support of the Hungarian Academy of Sciences through the János Bolyai Research Scholarship.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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