Effects of Space Weathering on the Reflectance Spectra of Silicate Asteroids (Postprint)

Authors:

Date: 2024-12-03T00:00:00+00:00

Abstract

Space weathering research is of great significance for remote sensing inversion of asteroid surface environment and composition. Currently, research results on spectral changes in asteroids induced by space weathering are not consistent, and there is a lack of unified understanding regarding weathering patterns on silicate asteroids. Based on a large-sample research approach, we compiled laser irradiation experiments on four ordinary chondrites (H, L, and LL types), seven silicate single minerals, and six groups of olivine-pyroxene mixtures with varying proportions, analyzed changes in the visible-near-infrared reflectance spectra (0.45–2.5 μm) of samples before and after irradiation, and investigated the influence of space weathering on silicate asteroid spectra by integrating asteroid spectral data. The results demonstrate that space weathering does not induce significant shifts in the 1 μm absorption center, but causes an increase in the absorption area ratio (2 μm band area / 1 μm band area). Therefore, the use of "1 μm absorption center – absorption area ratio" plots for distinguishing meteorite types remains valid, indicating that space weathering has minimal impact on mineralogical classification. In principal component analysis diagrams, A-type asteroids exhibit a weathering trend nearly parallel to the α line, while other silicate asteroids display a "Q-Sq-S" weathering trend. The asteroid classification system based on Sloan Digital Sky Survey data (SDSS dataset) confuses the classification of olivine-rich asteroids and may underestimate the population of A-type asteroids. This systematic analysis of space weathering patterns and spectral variation laws for silicate asteroids provides practical value for advancing understanding of space weathering effects on asteroid spectra and for quantitative mineral remote sensing inversion.

Full Text

Preamble

Vol. 65 No. 6

Nov., 2024

ACTA ASTRONOMICA SINICA Vol. 65 No. 6 Nov., 2024 doi: 10.15940/j.cnki.0001-5245.2024.06.011 The Influence of Space Weathering on the Reflectance Spectra of Silicate Asteroids∗ ZHANG Qin-wei1;2 ZHANG Peng-fei3 WANG Peng-yue4 JIANG Te5 LU Yu1 HAN Hui-jie4 PANG Rong-hua3 LI Yang3 ZHANG Hao5 JIN Yan6 WU Yun-zhao1;4† (1 Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023) (2 School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026) (3 Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081) (4 State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Macau 999078) (5 Planetary Science Institute, China University of Geosciences, Wuhan 430074) (6 Earth Observation System and Data Center, China National Space Administration, Beijing 100101)

Abstract

Research on space weathering is of great significance for remote sensing inversion of asteroid surface environments and compositions. Currently, research results on spectral changes in asteroids caused by space weathering are not unified, and there is a lack of systematic understanding of weathering patterns for silicate asteroids. Based on a large-sample research approach, we compiled laser irradiation experiments on four ordinary chondrites (H, L, and LL types), seven silicate single minerals, and six groups of olivine-pyroxene mixtures with different proportions. We analyzed changes in the visible-near-infrared reflectance spectra (0.45–2.5 (cid:22)m) of samples before and after irradiation, and investigated the influence of space weathering on silicate asteroid spectra by combining them with asteroid spectral data. The results show that space weathering does not cause significant shifts in the 1 (cid:22)m absorption center, but leads to an increase in the band area ratio (2 (cid:22)m band area/1 (cid:22)m band area). Therefore, using the “1 (cid:22)m absorption center–band area ratio” diagram to distinguish meteorite types remains effective, indicating that space weathering has minimal impact on mineralogical classification. In principal component analysis plots, A-type asteroids exhibit a weathering trend nearly parallel to the (cid:11) line, while other silicate asteroids show a “Q-Sq-S” weathering trend. The asteroid classification system based on Sloan Digital Sky Survey (SDSS) data may confuse the classification of olivine-rich asteroids and may underestimate the number of A-type asteroids. This study systematically analyzes the space weathering patterns and spectral variation laws of silicate asteroids, providing practical value for deepening understanding of space weathering effects on asteroid spectra and for quantitative mineral remote sensing inversion.

Key words planets and satellites: surfaces, moon, asteroids: general

As remnants of planetary accretion, asteroids preserve rich information about the early solar system environment. Investigating the distribution of asteroids with different compositions throughout the solar system is crucial for understanding the distribution, evolution, and migration of solar system materials \cite{1–3}. Since solar energy is concentrated primarily in the visible-near-infrared wavelength range, and the silicate minerals that constitute asteroids mostly exhibit absorption features in this range, visible-near-infrared reflectance spectroscopy has become an important means of characterizing asteroid material composition. Currently, multiple asteroid spectral survey missions have been conducted internationally \cite{3–8}, accumulating massive amounts of visible-near-infrared reflectance spectral data for asteroids.

Based on analysis of reflectance, slope, absorption position, and other parameters from these spectral curves, researchers have established asteroid spectral classification systems \cite{9–14}. Furthermore, comparative studies between meteorites and asteroid reflectance spectra have facilitated the establishment of "Meteorite-Asteroid Links" \cite{15–16}, enabling laboratory meteorite research to be applied to observed asteroids and thus improving our understanding of material distribution in the solar system. For example, S-complex (including Q, S, Sa, Sq, Sr, Sv types) and V-type asteroids have silicate compositions (such as olivine and pyroxene), corresponding to ordinary chondrites and HED meteorites, respectively [**?**].

Asteroids exposed to space for long periods experience micrometeorite impacts, cosmic and solar high-energy radiation, and other processes that cause physical processes such as fragmentation, cementation, sputtering, and deposition on their surfaces. Their chemical composition, physical characteristics, and spectral features change accordingly; these processes are collectively termed "space weathering" \cite{17–18}. Space weathering is considered the main cause of differences between asteroid spectra and laboratory meteorite spectra, hindering our understanding of asteroid material composition and evolutionary history. Early lunar-based research showed that space weathering causes decreased reflectance (darkening), weakened absorption, and increased visible-near-infrared spectral slope (reddening), known as the "lunar model" \cite{17, 19–20}. Subsequent exploration of the S-type asteroid Itokawa further supported the "lunar model" \cite{21–23}. However, recent explorations of asteroids (4) Vesta, (162173) Ryugu, and (101955) Bennu \cite{24–26} and laboratory simulation studies of carbonaceous meteorites \cite{27–31} have shown that asteroid space weathering patterns are not uniform and are closely related to the initial material and weathering degree of asteroids [**?**]. Zhou et al. [**?**] summarized the spectral effects of space weathering on C-type asteroids and found that the alteration mechanism of space weathering on C-type asteroid materials is unclear, leading to debates about spectral effects. Furthermore, in-situ spectral data from Chang'e-3 showed that space weathering effects on spectra are wavelength-dependent: the visible-near-infrared continuum slope (VNCS) increased, while the visible band (extending to the ultraviolet band) spectral slope decreased (i.e., "bluing") [**?**]. Subsequently, based on meteorite simulation experiments and asteroid spectral data analysis, the idea that space weathering changes asteroid spectral types has been proposed. Numerous studies have revealed a trend from Q-type asteroids representing fresh material to S-type asteroids representing mature material [?, ?]. This helps identify ordinary chondrite parent bodies with different space weathering ages on their surfaces and provides clues for understanding their evolutionary history. Lantz et al. [?] systematically discussed the spectral evolution trends of carbonaceous asteroids and proposed that the surface of (101955) Bennu may have experienced a transition from C-type to B-type asteroids. Hasegawa et al. [?] compared pre- and post-impact spectra of (596) Scheila through telescope observations, confirming the evolution trend from D-type to T-type asteroids. Future research is expected to discover more possible spectral type evolutions caused by space weathering through deeper investigations.

Currently, space weathering simulation experiments mainly include two types: ion implantation to simulate solar wind high-energy particle radiation and laser irradiation to simulate micrometeorite impacts. Comparison of these two simulation experiments shows that the timescale for solar wind irradiation to cause significant spectral changes is about $10^{4–10}6$ years, while the timescale for micrometeorite impact effects is about $10^{8–10}9$ years \cite{35–36}. Meanwhile, solar wind particle radiation mainly affects the uppermost surface layer (< 1 (cid:22)m) [?], with very shallow penetration depth, whereas micrometeorite impacts affect deeper material components. Therefore, solar wind radiation may dominate in the inner solar system, while micrometeorite impacts may be the main contributor in main-belt asteroids [?]. The space weathering process studied in this paper is primarily based on pulsed laser simulation of micrometeorite impact processes to understand the long-term spectral effects of space weathering on asteroid surfaces.

The main types of near-Earth and inner main-belt asteroids are silicate asteroids (such as S-type and Q-type) [?]. Although research on space weathering is already extensive, two key scientific questions regarding the spectroscopy of silicate asteroid space weathering remain unresolved. First, does space weathering change the absorption position of silicate asteroids in the visible-near-infrared band, and how? Second, how does space weathering change the spectral types of asteroids? These two questions are crucial for inferring asteroid material composition and evolution. Therefore, based on extensive pulsed laser irradiation experimental data from meteorites, single minerals, and mineral mixtures, this paper analyzes the effects of space weathering on various sample spectral parameters. On this basis, we further compare sample spectra with asteroid spectral types to understand the influence of space weathering on silicate asteroid reflectance spectra and provide fundamental support for interpreting and quantitatively inverting asteroid spectral data.

2.1 Irradiation Experiment Data Collection

Given that studying the spectral effects of space weathering through single or few samples lacks representativeness, this study analyzes spectral data from numerous experimental samples to obtain universal conclusions. We collected reflectance spectral data from 17 laser irradiation experiments, including samples of 4 ordinary chondrites (H, L, and LL types), 7 silicate single minerals, and 6 groups of olivine-pyroxene mixtures with different proportions. Some spectral data were obtained from the Reflectance Experiment Laboratory (RELAB) spectral database, while others came from published literature. The laser irradiation experimental parameters, sample information, and data sources for all collected samples are listed in Table 1 .

Since some experiments used different samples from the same source, we labeled samples from the same source for distinction (e.g., San Carlos olivine 1# and 2#). All reflectance spectral data before and after irradiation were collected in the 0.45–2.5 (cid:22)m range. The reflectance spectra of samples before and after irradiation are shown in Figure 1 [Figure 1: see original paper].

2.2 Spectral Parameter Analysis

Since reflectance is an important indicator for measuring space weathering effects, this study first compiled the absolute reflectance at 0.55 (cid:22)m (R0:55, sample reflected light intensity/standard whiteboard reflected light intensity) for all samples before and after irradiation. Due to historical reasons, asteroid observation data are normalized at 0.55 (cid:22)m. To better compare sample data with asteroid data, we also normalized all collected sample spectral data at 0.55 (cid:22)m, i.e., dividing the reflectance values at all wavelengths by the reflectance value at 0.55 (cid:22)m to obtain normalized reflectance. Subsequently, we calculated the visible-near-infrared continuum slope (Slope) at 1 (cid:22)m from the spectral data before and after irradiation. We also analyzed the 1 (cid:22)m absorption center (Band 1 Center, BC1) and 2 (cid:22)m absorption center (Band 2 Center, BC2), 1 (cid:22)m band area (Band 1 Area, BA1) and 2 (cid:22)m band area (Band 2 Area, BA2), and the band area ratio (Band Area Ratio, BAR, defined as BA2/BA1). Specific calculation methods are described in Wu et al. [**?**] and Lindsay et al. [**?**].

Furthermore, we analyzed the spectral data before and after irradiation using two asteroid classification methods. (1) We used the asteroid spectral classification tool developed by the Massachusetts Institute of Technology to calculate the first principal component (PC1) and second principal component (PC2) of the spectral data. This tool is based on the Bus-Demeo classification method; details can be found in DeMeo et al. [**?**]. (2) We used the asteroid classification system employed by the Sloan Digital Sky Survey (SDSS) dataset to calculate the spectral data before and after irradiation. This method uses the slope of the g (0.4686 (cid:22)m), r (0.6166 (cid:22)m), and i (0.7480 (cid:22)m) bands (gri-slope) and the color index of the i (0.7480 (cid:22)m) and z (0.8932 (cid:22)m) bands (z -i color) to classify asteroids. Specific calculation methods can be found in DeMeo et al. [**?**] and Nesvorny et al. [**?**].

3.1 Changes in Sample Spectral Parameters

Table 2 lists the spectral parameters of samples before and after laser irradiation, and Table 3 lists the changes in spectral parameters before and after irradiation. As shown in Table 3, all samples have negative ΔR0:55 and positive ΔSlope values, indicating that laser irradiation experiments reduce reflectance while increasing the visible-near-infrared continuum slope at 1 (cid:22)m, i.e., "darkening" and "reddening." The spectral plots of multiple irradiations of the same sample (Figure 1), ΔR0:55, and ΔSlope (Table 3) show that both "darkening" and "reddening" increase with space weathering degree. Under the same laser energy, the darkening degree of the "olivine-pyroxene mixing system" increases with increasing olivine proportion, while the reddening degree does not show an obvious pattern.

After laser irradiation, the 1 (cid:22)m and 2 (cid:22)m absorption centers do not show systematic changes (i.e., uniform shifts toward shorter or longer wavelengths), but the BAR of almost all samples increases after irradiation.

Figure 2 [Figure 2: see original paper] shows the variation of the 1 (cid:22)m band center with band area ratio before and after irradiation. The "1 (cid:22)m absorption center–band area ratio" diagram can effectively separate different types of silicate meteorites [?]. After irradiation, two LL chondrite samples move closer to L chondrites, while L chondrites move closer to LL chondrites, gradually approaching but not completely crossing the boundary between the two types (Figure 2). Therefore, based on our samples, space weathering has minimal impact on mineralogical classification, and using the "1 (cid:22)m absorption center–band area ratio" diagram to distinguish different meteorite types remains effective. Future experimental data with larger sample sizes can verify this conclusion.

Figure 3 [Figure 3: see original paper] shows the variation of the visible-near-infrared continuum slope at the 1 (cid:22)m absorption position with band area ratio before and after irradiation. Except for pure pyroxene samples, the arrow directions of simulated weathering for all other samples point from the ordinary chondrite region to the asteroid region, indicating that silicate asteroids generally exhibit space weathering spectral reddening effects.

3.2 Comparison of Space Weathering Between Meteorites and Asteroids

The space weathering trend results obtained from spectral data processing based on the Bus-DeMeo classification method are shown in Figure 4 [Figure 4: see original paper]. The (cid:11) line distinguishes spectra with and without 2 (cid:22)m absorption; the left side of the (cid:11) line represents lack of 2 (cid:22)m absorption, while the right side represents presence of 2 (cid:22)m absorption [?]. Data points for pure olivine samples before and after irradiation are located on the left side of the (cid:11) line. When pyroxene is added, the

PC2 value increases, moving data points to the right side of the (cid:11) line. Fresh olivine data points concentrate in the A-type asteroid region, with space weathering trend arrows parallel to the (cid:11) line and pointing in the direction of increasing PC1 and decreasing PC2 . Pre-irradiation data points for the "olivine-pyroxene mixing system" mainly concentrate in the Q-type asteroid region. The black dashed arrow in the figure indicates the distribution trend of fresh mixed mineral samples. The mineral content of olivine and pyroxene has a clear controlling effect on their positions in the principal component analysis plot. As pyroxene content increases, both PC1 and PC2 values increase, while the angle between the space weathering trend arrow and the (cid:11) line gradually increases. LL chondrites (typically more olivine-rich) and H chondrites (typically more pyroxene-rich) data also show similar trends. The space weathering trend arrows for both mixed minerals and meteorites show a "Q-Sq-S" weathering trend. Notably, the space weathering trend arrow for the OL4EN1 sample crosses the (cid:11) line. Orthopyroxene data points are closer to the V-type asteroid region because V-type asteroid surfaces are richer in pyroxene [**?**]. However, the space weathering directions of the four pyroxene samples also show some differences: after irradiation, the Clinopyroxene and EN samples show increased PC1 and significantly decreased PC2 , while the Bamble orthopyroxene 1# and Bamble orthopyroxene 2# samples show increased PC1 but unclear PC2 changes.

Figure 5 [Figure 5: see original paper] shows the space weathering trend results obtained from spectral data processing based on the SDSS asteroid classification system [**?**]. After irradiation, all samples show increased gri-slope (reddening) and increased z -i (shallower 1 (cid:22)m absorption). The space weathering trends of mixed minerals and meteorites both show a "Q-S" pattern. Pyroxene data are closer to the V-type asteroid region. However, it is noteworthy that the spectral data of olivine samples cannot correspond to the A-type asteroid region: both have z -i values concentrated around -0.2, but their gri-slope values are clearly not unified, with a large number of irradiated olivine samples falling in the distribution region of Q-type asteroids.

4.1 Impact of Space Weathering on Asteroid Spectra

Compared with previous simulation experiments, the data collected in this study include more sample types and different irradiation conditions. All samples show decreased reflectance, reddened visible-near-infrared continuum slope at 1 (cid:22)m, and weakened absorption features after irradiation. With increasing laser energy, the same sample becomes "darker" and "redder." For the L6 chondrite Chateau Renard and the San Carlos olivine 2# samples with multiple irradiations, as the total irradiation amount increases, their ΔR0:55 changes gradually decrease (reflectance reduction slows), indicating that space weathering tends toward saturation.

The ΔBC1 values for most samples are very small ($<$ 10 nm), indicating that space weathering does not cause significant shifts in the 1 (cid:22)m absorption center. It is also worth noting that different samples do not show a consistent pattern in the shift direction of the 1 (cid:22)m absorption center, which may explain why the 1 (cid:22)m absorption centers of different maturity lunar soils and silicate asteroid regoliths are not uniform \cite{46–47}. The 1 (cid:22)m absorption center of some samples (e.g., Chateau Renard) shifts toward longer wavelengths by 10–15 nm, possibly due to the addition of glass (a space weathering product), because iron-bearing glass exhibits broad absorption features at longer wavelengths (1.07–1.20 (cid:22)m) \cite{48–50}. The 1 (cid:22)m absorption center of a few samples (e.g., Kheneg Ljouad) shifts toward shorter wavelengths by 10–15 nm, possibly due to nanophase metallic iron particles (np-Fe0, another space weathering product) [**?**]. This provides possible explanations for absorption center shifts but does not affect the understanding that space weathering has minimal impact on absorption centers. The shifts in 1 (cid:22)m absorption centers for the vast majority of samples are within $±$10 nm, which can serve as a reference value for future studies on space weathering-induced shifts in the 1 (cid:22)m absorption centers of silicate asteroids.

After undergoing the same laser energy irradiation, the "olivine-pyroxene mixing system" shows that pure olivine samples have their 1 (cid:22)m absorption area reduced by 87.1%, while pure pyroxene samples have their 1 (cid:22)m absorption area reduced by 32.1%. Under the same energy, the darkening degree of the "olivine-pyroxene mixing system" increases with increasing olivine proportion, supporting the conclusion that pyroxene is more resistant to weathering than olivine \cite{52–53}. Because olivine responds to space weathering faster than pyroxene, samples with higher olivine proportions darken faster, and the 1 (cid:22)m band area decays faster than the 2 (cid:22)m band area, which is why the BAR of samples increases after irradiation.

4.2 Impact of Space Weathering on Asteroid Spectral Classification

Q-type, Sq-type, and S-type asteroids are all parent bodies of ordinary chondrites, but Q-type represents less-weathered ordinary chondrite material, Sq-type represents moderately weathered ordinary chondrite material, and S-type represents highly weathered ordinary chondrite material [**?**]. Q-type asteroids have higher albedo, lower spectral slope, and deeper absorption than Sq and S-type asteroids [**?**]. For small near-Earth asteroids, surface renewal processes opposite to space weathering (such as tidal drag, spin-up, periodic thermal cycling, meteorite/micrometeorite collisions) are more intense, causing S-type to revert to Q-type, which is consistent with observations that Q-types are smaller in size and mostly exist in near-Earth regions [**?**]. The space weathering trends of mixed minerals and meteorites in Figures 4 and 5 both indicate that silicate asteroids have a "Q-Sq-S" weathering trend, supporting the view that differences in spectral characteristics between S-type and Q-type asteroids are mainly related to space weathering degree [**?**].

The direction parallel to the boundary between Q-type and Sq-type asteroids in Figure 4 can reflect material composition. Spectra in the lower left region have deeper and broader 1 (cid:22)m absorption bands (more olivine-rich). As PC2 increases toward the upper right region, the 1 (cid:22)m absorption band becomes narrower with deeper and broader 2 (cid:22)m absorption bands (more pyroxene-rich), meaning this direction can also reflect changes in band area. This provides some possible explanations for the inconsistent space weathering trends of pyroxene samples: affected by irradiation energy and sample composition differences, the BA2 values of Bamble orthopyroxene 1# and Bamble orthopyroxene 2# samples remain basically unchanged before and after irradiation, while the BA2 values of Clinopyroxene and EN samples significantly decrease after irradiation (Table 2), resulting in inconsistent horizontal components of space weathering trend arrows.

The space weathering trend arrow for the OL4EN1 sample approaches and slightly crosses the (cid:11) line (Figure 4), possibly because the BA2 value after irradiation is too small (Table 2). Previous studies on shock darkening of the Chelyabinsk meteorite also showed crossing of the (cid:11) line [?]. Our results indicate that asteroids dominated by olivine content may experience effects similar to shock darkening after sufficiently long space weathering.

The distribution region of A-type asteroids in the SDSS asteroid classification diagram does not match the distribution region of irradiated olivine (Figure 5), which may be related to the SDSS data itself. SDSS data include large amounts of asteroid data but have low spectral resolution and narrow wavelength range (only 0.354–0.913 (cid:22)m). For many asteroid types (especially L, S, Q, A types), their band data can only indicate the presence of 1 (cid:22)m absorption features but cannot accurately calculate absorption depth and shape [?], so this classification has considerable uncertainty. It has previously been found that the A-type asteroid (11616) 1996 BQ2 in the Cybele region cannot be accurately classified into the A-type asteroid region due to its low slope (gri-slope value of 1.98, z -i value of -0.15) [?], similar to our sample irradiation results. Therefore, asteroid classification based on SDSS may lead to underestimation of the number of A-type asteroids, with some A-type asteroids possibly misclassified as Q-type asteroids.

This study investigated the alteration processes of space weathering on silicate asteroid reflectance spectra by analyzing laser irradiation experimental data from meteorites, single minerals, and mineral mixtures, and comparing them with asteroid spectral classification data. The main conclusions are: (1) Space weathering does not cause significant shifts in the 1 (cid:22)m absorption center, with shifts basically maintained within $±$10 nm, providing a reference for fluctuations in the absorption center of silicate asteroid spectra caused by space weathering; (2) Olivine has weaker weathering resistance than pyroxene, and space weathering causes BAR to increase but has minimal impact on overall mineralogical classification; (3) In principal component analysis plots, A-type asteroids have a weathering trend nearly parallel to the (cid:11) line, while other silicate asteroids have a “Q-Sq-S” weathering trend, and asteroids dominated by olivine may cross the (cid:11) line after experiencing sufficiently long space weathering; (4) The asteroid classification system based on SDSS data may underestimate the number of A-type asteroids and confuse them with Q-type asteroids.

Detailed analysis of the spectral alteration effects of space weathering on silicate asteroids with different mineral compositions is of great significance for accurate interpretation of asteroid remote sensing data. This study can provide support for understanding material distribution in the solar system, surface evolution history and mechanisms of asteroids, and China's asteroid exploration missions.

Acknowledgments

We thank the reviewers for their valuable suggestions on the article.

References

[1] DeMeo F E, Carry B. Icarus, 2013, 226: 723 [2] DeMeo F E, Carry B. Nature, 2014, 505: 629 [3] Binzel R P, DeMeo F E, Turtelboom E V, et al. Icarus, 2019, 324: 41 [4] Zellner B, Tholen D J, Tedesco E F. Icarus, 1985, 61: 355 [5] Bell J F, Owensby P D, Hawke B R, et al. LPSC, 1988, 19: 57 [6] Xu S, Binzel R P, Burbine T H, et al. Icarus, 1995, 115: [7] Clark B E, Bell J F, Fanale F P, et al. Icarus, 1995, 113: [8] Carvano J M, Hasselmann P H, Lazzaro D, et al. A&A, 2010, 510: A43 [9] Chapman C R, Morrison D, Zellner B. Icarus, 1975, 25: [10] Tholen D J. Asteroid Taxonomy from Cluster Analysis [35] Vernazza P, Binzel R P, Rossi A, et al. Nature, 2009, 458: of Photometry. Tucson: University of Arizona, 1984: 54 [11] Bus S J, Binzel R P. Icarus, 2002, 158: 106 [36] Sasaki S, Nakamura K, Hamabe Y, et al. Nature, 2001, [12] Bus S J, Binzel R P. Icarus, 2002, 158: 146 410: 555 [13] DeMeo F E, Binzel R P, Slivan S M, et al. Icarus, 2009, [37] Brunetto R, Strazzulla G. Icarus, 2005, 265: 273 202: 160 [38] Sasaki S, Kurahashi E, Yamanaka C, et al. AdSpR, 2003, [14] Mahlke M, Carry B, Mattei P A. A&A, 2022, 665: A26 31: 2537 [15] Cloutis E A, Binzel R P, Gaffey M J. Eleme, 2014, 10: [39] Weber I, Stojic A N, Morlok A, et al. E&PSL, 2020, 530: [16] DeMeo F E, Burt B J, Marsset M, et al. Icarus, 2022, [40] Brunetto R, Romano F, Blanco A, et al. Icarus, 2006, 380: 114971 180: 546 [17] Hapke B. JGRE, 2001, 106: 10039 [41] Han H J, Lu X P, Jiang T, et al. RAA, 2021, 21: 127 [18] Pieters C M, Noble S K. JGRE, 2016, 121: 1865 [42] Lindsay S S, Marchis F, Emery J P, et al. Icarus, 2015, [19] Noble S K, Pieters C M, Keller L P. Icarus, 2007, 192: 247: 53 [43] Nesvorny D, Jedicke R, Whiteley R J, et al. Icarus, 2005, [20] Lucey P G, Noble S K. Icarus, 2008, 197: 348 173: 132 [21] Abe M, Takagi Y, Kitazato K, et al. Science, 2006, 312: [44] Dunn T L, McCoy T J, Sunshine J M, et al. Icarus, 2010, 208: 789 [22] Hiroi T, Abe M, Kitazato K, et al. Nature, 2006, 443: 56 [45] Marchi S, Brunetto R, Magrin S, et al. A&A, 2005, 443: [23] Ishiguro M, Hiroi T, Tholen D J, et al. M&PS, 2007, 42: [46] Taylor L A, Pieters C M, Keller L P, et al. JGRE, 2001, [24] Pieters C M, Ammannito E, Blewett D T, et al. Nature, 106: 27985

2012, 491: 79 [47] Noble S K, Pieters C M, Hiroi T, et al. JGRE, 2006, 111: [25] Arakawa M, Saiki T, Wada K, et al. Science, 2020, 368: [48] Adams J B. JGRE, 1974, 79: 4829 [26] Lauretta D S, Adam C D, Allen A J, et al. Science, 2022, [49] Minitti M E, Mustard J F, Rutherford M J. JGRE, 2002, 377: 285 107: E5 [27] Lantz C, Brunetto R, Barucci M A, et al. Icarus, 2017, [50] Horgan B H, Cloutis E A, Mann P, et al. Icarus, 2014, 285: 43 234: 132 [28] Lantz C, Binzel R P, DeMeo F E. Icarus, 2018, 302: 10 [51] Kohout T, ˇCuda J, Filip J, et al. Icarus, 2014, 237: 75 [29] Thompson M S, Morris R V, Clemett S J, et al. Icarus, [52] Chrbolkov´a K, Brunetto R, ˇDurech J, et al. A&A, 2021, 2020, 346: 113775 654: A143 [30] Matsuoka M, Nakamura T, Hiroi T, et al. ApJ, 2020, 890: [53] Chrbolkov´a K, Halodov´a P, Kohout T, et al. A&A, 2022, 665: A14 [31] Zhang P, Tai K, Li Y, et al. A&A, 2022, 659: A78 [54] DeMeo F E, Marsset M, Polishook D, et al. Icarus, 2023, [32] 周婷, 唐红, 缪秉魁, 等. 空间科学学报, 2023, 43: 647 389: 115264 [33] Wu Y Z, Wang Z C, Lu Y. RAA, 2019, 19: 051 [55] Kohout T, Penttil¨a, Mann P, et al. PSJ, 2020, 1: 37 [34] Hasegawa S, DeMeo F E, Marsset M, et al. ApJ, 2022, [56] DeMeo F E, Polishook D, Carry B, et al. Icarus, 2019, 939: L9 322: 13

The In(cid:13)uence of Space Weathering on the Re(cid:13)ectance Spectra of Silicate Asteroids ZHANG Qin-wei1;2 ZHANG Peng-fei3 WANG Peng-yue4 JIANG Te5 LU Yu1 HAN Hui-jie4 PANG Rong-hua3 LI Yang3 ZHANG Hao5 JIN Yan6 WU Yun-zhao1;4 (1 Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023) (2 School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026) (3 Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081) (4 State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Macau 999078) (5 Planetary Science Institute, China University of Geosciences, Wuhan 430074) (6 Earth Observation System and Data Center, China National Space Administration, Beijing 100101) ABSTRACT Research on space weathering is of great significance for the remote sensing inversion of the surface environment and composition of asteroids. Currently, research results on the spectral changes of asteroids caused by space weathering are not consistent, and there is a lack of systematic understanding of weathering patterns for silicate asteroids. Based on the idea of large-sample research, laser irradiation experiments were conducted on 4 ordinary chondrites (H, L, and LL types), 7 types of silicate minerals, and 6 groups of olivine-pyroxene mixtures with different proportions. The visible- near-infrared reflectance spectra (0.45–2.5 (cid:22)m) of the samples before and after laser experiments were analyzed, and the impact of space weathering on the reflectance spectra of silicate asteroids was studied in combination with the spectral classification of asteroids. Our results showed that space weathering can increase the band area ratio, but it does not cause a significant shift in the 1 (cid:22)m absorption center. The use of the “1 (cid:22)m absorption center - band area ratio” diagram is still effective in distinguishing different types of meteorites. Moreover, space weathering has little impact on overall mineralogical classification. In the principal component analysis plot, A-type asteroids have a space weathering trend almost parallel to

the (cid:11) line, while the rest of the silicate asteroids have a “Q-Sq-S” space weathering trend. The asteroid classification system based on Sloan Digital Sky Survey (SDSS) data may confuse the classification of olivine-rich asteroids and may underestimate the number of A-type asteroids. This study systematically analyzes the weathering models and spectral changes of silicate asteroids, which is scientifically significant for a better understanding of the space weathering effect on asteroid spectra and has practical value for remote sensing quantitative inversion. Key words planets and satellites: surfaces, moon, asteroids: general