



嫦娥五号月尘纳微米矿物学特征及其成因意义

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摘要 嫦娥五号从月球中纬度地区以铲取和钻取相结合的方式($\sim 43^\circ\text{N}$)采回了1.731 kg月球样品, 是我国在深空探测和月球科学研究领域的重要里程碑. 嫦娥五号采集的月壤样品中, 微细颗粒月尘(粒径小于1 mm)占有相当大的比例, 对传统固体地球科学研究带来了挑战. 本文采用纳米矿物学分析技术, 对微细月尘颗粒进行了系统分析(分析颗粒粒径 $0.1\sim 3\ \mu\text{m}$), 所有月尘颗粒都具有明显的太空风化特征, 表面被非晶态物质和纳米级自然铁覆盖. 其中, 约59%的颗粒成分变化显著, 且失去原有晶体结构, 归为太空风化非晶碎屑; 约41%的颗粒仍保留其矿物结构, 归为矿物碎屑. 矿物碎屑包括自然元素矿物(如自然铁)、辉石族矿物、长石族矿物、橄榄石族矿物和钛铁矿, 还有少量的磷灰石和陨硫铁. 太空风化非晶碎屑则主要由非晶态物质和纳米级自然铁组成. 这些结果指示月尘颗粒受陨石撞击和太空风化控制, 显著影响了月壤整体的物理化学性质, 并且非晶态物质含量较高, 能储存大量太阳风物质(如 ^3He), 具有一定的资源潜力.

关键词 嫦娥五号, 月尘, 太空风化, 纳米矿物学, 颗粒特征

月球样品对于揭示行星的起源和演化至关重要, 是我们了解月球的主要信息来源^[1]. 嫦娥五号带回的月壤样品是人类45年来再次获取的月球返回样品. 此前, 阿波罗号(美国)和月球号(苏联)共进行了9次采样, 这些任务主要集中在月球正面的低纬度地区(小于 30°), 覆盖面积不足月表的8%^[2]. 嫦娥五号返回的样品是人类首次获取的中纬度($\sim 43^\circ\text{N}$)月壤样品, 位于风暴洋北部, 属于最年轻的月海玄武岩单元之一, 受远程溅射物污染较少^[3]. 由于缺乏大气层和全球性磁场的保护, 月球表面长期受到太空风化的影响, 包括微陨石撞击、太阳风粒子的注入、昼夜温差引起的热疲劳, 以及银河宇宙射线的辐射^[4-6]. 这些过程导致月表物质破碎、

混合, 并使其发生熔融胶结、辐射损伤和气化沉积等, 从而改变了月表物质的粒径、微观形貌、化学成分和晶体结构^[7-12], 例如, 产生微陨石撞击坑、辐射径迹、玻璃胶结物以及矿物表面的纳米级自然铁等^[2,13].

广义的月壤(lunar regolith)通常是指覆盖于月球表面的风化物质, 月海的月壤厚度约5.30 m, 而高地的月壤平均厚度可达10.7 m^[14,15]. 美国Apollo计划返回的月球样品按照颗粒尺寸划分: 直径 $\geq 1\ \text{cm}$ 的颗粒物归为月岩(lunar rocks); 1 mm $\sim$ 1 cm直径的颗粒为狭义的月壤(lunar soil); 而直径 $< 1\ \text{mm}$ 的颗粒物则归为月尘(lunar dust或lunar fines)^[14]. 嫦娥五号返回样品的分析结果显示, 95%的颗粒粒度分布于1.40 $\sim$ 9.35 μm (远小于

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1 mm), 指示月尘在月球返回样品的占有相当大的比重^[3]. 本文将月尘进一步划分为微米尺度颗粒(1~1000 μm)、亚微米尺度(0.1~1 μm)和纳米尺度颗粒(1~100 nm). 纳微米粒级的月尘颗粒是嫦娥五号月球返回样品的主体, 传统的固体地球科学的研究方法在识别和分析纳微米级颗粒方面仍存在诸多挑战, 大多数关于月球返回样品的研究仍限于显微及微米尺度, 这导致对月尘粉体样品中的纳微米尺度矿物组成特征的认识十分有限. TEM具有纳米及原子级的空间分辨率, 不仅能够分析纳微米颗粒的二维及三维形貌特征, 还能获得成分和结构信息, 特别是在纳米颗粒的结构分析方面, 能够准确的识别因太空风化或陨石撞击等造成的结构变化^[16~19].

本文通过透射电子显微镜(transmission electron microscope, TEM)对嫦娥五号月尘中的纳微米级颗粒进行物相、成分及粒度统计分析, 并对主要矿物组成、非晶态组分、气相沉积颗粒等进行了观察和描述, 探讨了嫦娥五号返回样品中的纳微米尺度矿物组成特征, 为了解月尘的基本物理性质提供重要参考.

1 样品采集及研究方法

月球可分为两个基本地理区域: 暗色的月海和浅色的高地^[20]. 随着对月球地形地貌、矿物和元素组成的详细探测^[21,22], 科学家将月球划分为三大地质单元: 风暴洋克里普岩地体、长石质高地地体和南极艾特肯地体. 嫦娥五号着陆于风暴洋东北部(43.058°N, 51.916°W)(图1(a)), 远离美国阿波罗号和苏联月球号的采样区^[3,23,24]. 采样点表面为月球表土(广义的月壤), 还有少量大小不一的岩屑分布(图1(b)). 月壤样品由嫦娥五号着陆器以两种方式进行采集, 分为铲取样品(编号以“CE5C”为首)和钻取样品(编号以“CE5Z”为首). 2020年12月17日, 嫦娥五号顺利返回月壤样品, 并储存于中国科学院国家天文台月球样品实验室. 为了保持月壤样品的原始特征, 避免受到地球大气的污染, 所有的解封、处理和分装操作均是在充满高纯氮气的密闭操作台(水和氧的含量均小于1 ppm)完成^[3,25].

本研究使用自国家航天局申请的铲取样(CE5C-1000YJFM00302和CE5C0400YJFM00408)和钻取样(CE5Z0702YJFM002). 样品从国家航天局取回后, 直接存放于中国科学院广州地球化学研究所行星前沿科学中心的手套箱中, 手套箱充满氮气, 水和氧的含量均小于1 ppm. 本文利用TEM分析纳微米尺度月尘颗粒的特

征. 为避免化学污染和离子轰击引起的非晶化, 样品在手套箱中制备. 少量月尘轻撒于附有超薄碳膜的铜网上后, 使用真空转移样品杆将铜网转移至TEM中进行纳米尺度分析. 为了确保分析结果具有统计学意义, 我们对多个铜网上选定区域内的所有颗粒进行了全分析. 所分析的颗粒粒径从纳米级到微米级不等, 覆盖了不同的形貌特征, 能够较好地代表月尘样品的组成与特征. 所有TEM图像(如高角环形暗场像扫描TEM图(HAADF-STEM))、能谱和选区电子衍射图均由FEI Talos F200S透射电子显微镜采集. 所有分析工作在中国科学院广州地球化学研究所行星前沿科学中心完成, 且尽可能避免了地球环境的污染, 保持了月壤样品的原貌.

2 粒度与粒形分析

纳微米颗粒的粒度分布是月尘的基本物理参数, 直接影响其光学特性、强度、可压缩性和抗剪强度等^[24]. 随着月表暴露时间的增加, 月壤经历了不成熟、亚成熟到成熟的演变. 在陨石撞击和太空风化作用下, 粗颗粒岩屑逐渐减少, 而细颗粒和玻璃质物质逐渐增多^[13]. 阿波罗月壤样品分析表明, 不成熟月壤的粒度分布呈双峰, 而亚成熟和成熟月壤则表现为单峰, 且粒度峰值逐渐变窄^[26]. 嫦娥五号任务采集的月壤样品显示, 整体呈单峰粒度分布, 平均粒径为3.96 μm , 95%的颗粒尺寸分布在1.40~9.35 μm 之间^[3].

本文使用TEM对三种不同编号的月尘样品(包括铲取样和钻取样)进行观察, 并对颗粒进行测量和统计分析(共178颗纳微米颗粒; 图1(c)). 通过测量颗粒的长径 A 和短径 B , 计算了其等效直径 $D(D=\sqrt{A \times B})$. 结果显示, 嫦娥五号月尘样品粒度分布呈明显的单峰特征. 月尘颗粒的等效直径 D 主要分布在112~3206 nm, 平均为858 nm, 并且具有向细粒方向偏移的特征(图1(c)). 这些结果表明, 月尘是经历长时间风化作用的成熟月壤产物, 可能记录了月表最全面的太空风化历史.

为了分析月尘纳微米颗粒的整体粒形特征, 我们计算了每个颗粒的圆度(B/A), 圆度值越接近1, 颗粒越接近圆形, 并绘制了圆度分布图(图1(d)). 需要注意的是, 由于月球表面缺乏大气和水流等动力地质作用, 这一圆度值仅反映颗粒形态, 而非地球上因风力或水流作用形成的磨圆度. 统计结果显示(图1(d)), 月尘颗粒可分为两类: 近球形颗粒约占16.3%, 碎屑颗粒占83.7%. 整体月尘颗粒的平均圆度为0.66.

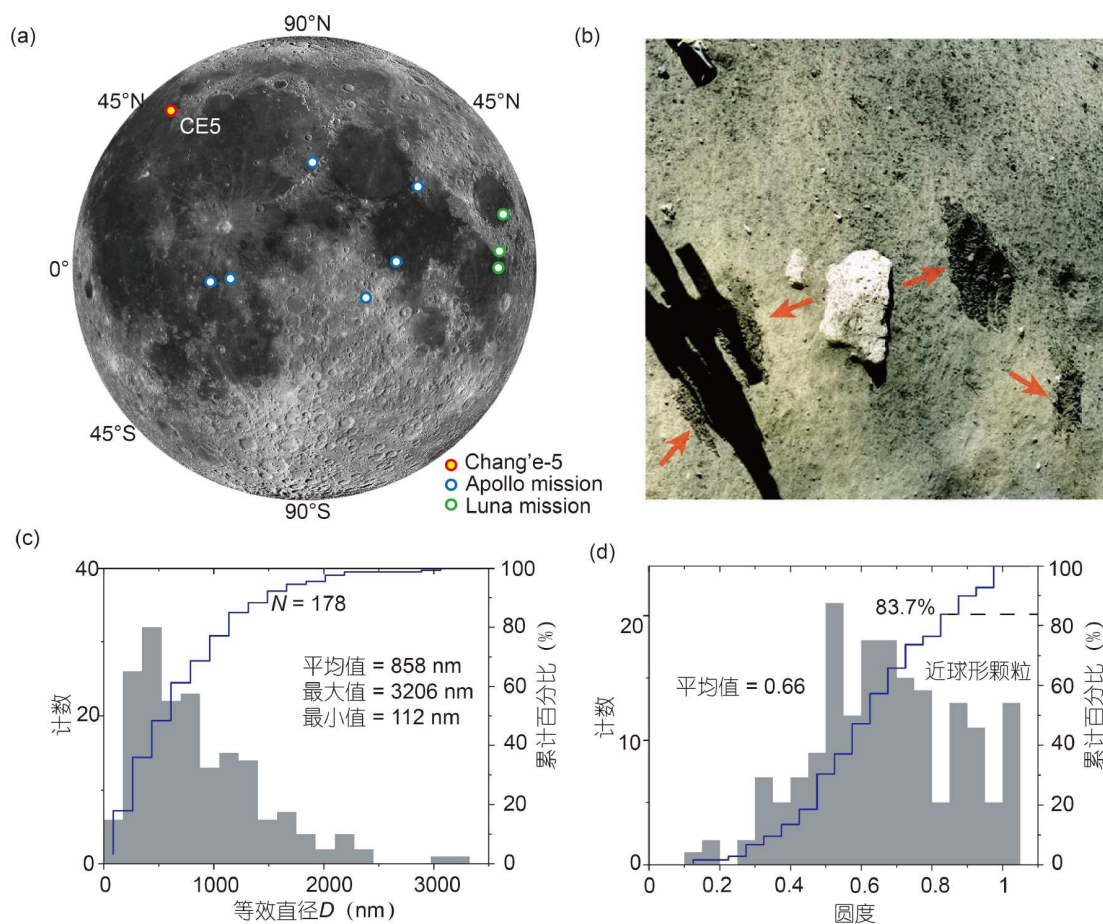


图 1 (网络版彩色)嫦娥五号采样点及其月尘颗粒特征。(a) 月壤采样位置分布。美国阿波罗号和苏联月球号采样点分布于低纬度地区,而嫦娥五号采样点位于中纬度地区。(b) 嫦娥五号着陆器铲取采样影像图。箭头指向为铲取采样痕迹。图片来自月球与行星数据发布系统网站(<https://moon.bao.ac.cn>)。(c, d) 月尘纳微米颗粒粒度和圆度分析

Figure 1 (Color online) Sampling site of Chang'e-5 (CE5) and characteristics of its lunar dust. (a) Distribution of lunar soil sampling locations. The sampling points of the Apollo and the Luna are distributed in low-latitude regions, while the CE5 sampling points are located in mid-latitude regions. (b) Image of the CE5 lander's scoop sampling. Arrows indicate the sampling traces. Image is from the Lunar and Planetary Data Release System Website (<https://moon.bao.ac.cn>). (c, d) Size and roundness distribution of Nano- and Micro-scale particles in CE5 lunar dust

3 月尘主要颗粒类型及其成因

先前的研究报道了嫦娥五号返回样品的矿物组成,包括长石族矿物(~30%),辉石族矿物(主要为普通辉石和易变辉石;~40%),橄榄石族矿物(5%~6%),钛铁矿(4%~5%)^[3]。本文对嫦娥五号月尘颗粒(包括矿物碎屑和非晶态物质)进行了观察,发现月尘颗粒整体分散性良好,均为纳微米单颗粒,黏结物较少。TEM能谱和物相分析显示,约59%的颗粒成分变化较大且非晶化程度高,因为陨石和微陨石撞击以及太空风化作用导致成分发生混合和叠加,难以辨识矿物相,我们归为太空风化非晶碎屑;~41%的颗粒仍保持矿物结构,主要为长石族矿物(~60%)、辉石族矿物(~10%)、橄榄石族矿物

(~14%)、钛铁矿(~9%),还有少量自然铁、磷灰石和陨硫铁等,这些颗粒归为矿物碎屑。特别地,长石族矿物在矿物碎屑中的比例较高(~60%),明显高于先前毫米-微米尺度的分析结果^[3],这可能是因为斜长石比其他含铁矿物更耐太空风化。综合来看,本文将纳微米粒级月尘颗粒分为太空风化非晶碎屑和矿物碎屑两类,二者均呈现较高圆度,并附着有富Si非晶层和纳米自然铁。

3.1 矿物碎屑

3.1.1 自然元素矿物

由于月球的极还原条件以及频繁的陨石撞击和太

空风化作用, 月球样品中存在自然元素矿物. 例如, 嫦娥五号返回样品中发现石墨烯^[27]; 气相沉积成因的自然铜和FeCo合金^[28]; 以及发现气相沉积成因的铜合金颗粒. 而纳米级自然铁是月尘中的主要自然元素矿物^[9,10,29].

纳米级的自然铁矿物(nanophase iron particles, npFe⁰), 又称纳米单质铁, 广泛分布于月壤颗粒表层, 是太空风化作用的特征标志之一^[9,11,29]. 纳米自然铁的形成是月壤中二价铁通过多种方式获得自由电子被还原的过程, 主要有3种假说: (1) 陨石和微陨石撞击导致月表物质发生气相沉积作用和热分解, 形成了阳离子、阴离子以及自由电子在内的等离子体, 在这个过程中二价铁离子捕获自由电子形成了自然铁^[5,29-31]; (2) 太阳风H⁺注入也是导致的二价铁还原成自然铁的原因之一^[18,32,33]; (3) 陨石和微陨石撞击过程产生的高压能够促使二价铁发生歧化反应而形成纳米级自然铁^[10,11].

纳米自然铁的广泛存在对月壤的反射光谱具有显著的影响, 包括降低反射率、减弱矿物特征峰强度等^[4,34].

TEM分析表明, 几乎所有矿物碎屑(包括辉石族、橄榄石族、长石族和钛铁矿等)以及太空风化非晶碎屑中均富集有大量纳米级自然铁. 不同成因的自然铁可能表现出不同的粒径特征, 例如: 由歧化反应或热解作用形成的自然铁粒径通常约为10~35 nm, 而由气相沉积形成的自然铁粒径则约为3 nm^[29]. 此外, 月尘中还观察到三种不同形态的自然铁: 铁晶须、非晶态球体中的自然铁和泪滴形自然铁(图2). 图2(a)展示的铁晶须表面覆盖富Si的非晶层, 可能源自气相沉积. 铁晶须通常见于铁硫化物表面, 如日本“隼鸟”号采集的ItoKawa小行星样品^[35]及嫦娥五号样品^[18]中观察到类似结构. 图2(c)展示的非晶态球体直径约139 nm, 包裹着纳米级自然铁球, 可能由陨石撞击或高温气体冷凝形成^[36]. 图2(f)展示的泪滴形纳米自然铁表面有富Si非晶

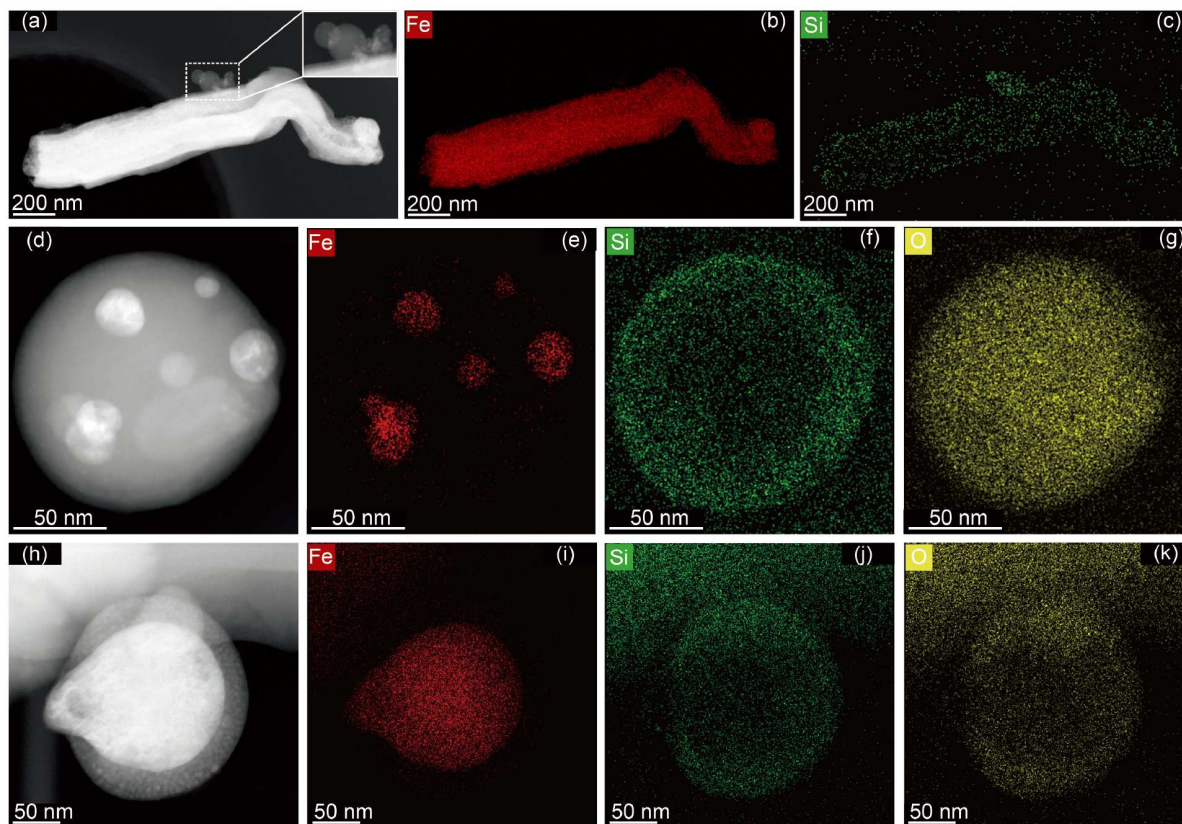


图2 月尘中的自然铁. (a~c) 铁晶须HAADF-STEM图像和Fe、Si元素面分布图; (d~g) 气相沉积非晶态物质及纳米自然铁HAADF-STEM图像和Fe、Al、Si和O元素面分布图; (h~k) 泪滴形自然铁及表面附着富Si非晶层HAADF-STEM图像和Fe、Ni、Si和O元素面分布图

Figure 2 Natural iron in lunar dust. (a~c) HAADF-STEM images and Fe, Si elemental distribution maps of iron whiskers; (d~g) HAADF-STEM images and Fe, Al, Si, and O elemental distribution maps of vapor-deposited amorphous materials and Nano-scale natural iron; (h~k) HAADF-STEM images and Fe, Ni, Si, and O elemental distribution maps of teardrop-shaped natural iron with a surface-attached Si-rich amorphous layer

层,这类颗粒(包括球形、哑铃形和泪滴形的玻璃和自然铁)通常由飞行过程中熔体快速冷凝形成^[37].

3.1.2 辉石族矿物

辉石族矿物是大多数月岩的主要矿物组分,其中月海玄武岩主要由单斜辉石亚族矿物组成,而非月海玄武岩及高地岩石则主要由斜方辉石亚族矿物组成^[14]. 先前研究表明,嫦娥五号返回样品中的辉石族矿物以普通辉石(约30%)为主,其次是易变辉石(约11%),未测得斜方辉石亚族矿物^[3]. 本次分析显示,嫦娥五号月尘矿物碎屑中的辉石族矿物占约10%. 图3(c)展示了月尘中辉石族矿物的成分变化,结果表明,嫦娥五号月尘中的纳米级辉石成分变化较大,主要偏向高钙高铁普通辉石为主. TEM分析结果显示,月尘中的纳米级辉石族矿物普遍表现出太空风化特征,表面附着非晶层,并含有多种成因的纳米级自然铁(粒径在3.09~39.0 nm之间,平均为8.63 nm).

3.1.3 橄榄石族矿物

月尘样品中,橄榄石族矿物约占分析矿物碎屑组分14%, Fo值(Mg/[Mg+Fe]摩尔比)在5.60~71.4之间,平均为50.0(图4(f)),包括铁橄榄石、镁铁橄榄石和透铁橄榄石亚种.

在嫦娥五号返回样品中,橄榄石族矿物约5%~

6%^[3]. 本次分析的嫦娥五号月尘中,橄榄石族矿物约占分析矿物碎屑组分14%. 橄榄石的成分变化受到主量元素Fe和Mg控制,先前的分析表明嫦娥五号月壤中橄榄石的成分变化比较大,橄榄石的Fo值(Mg/(Mg+Fe)摩尔比)在0.1~65.1之间^[3]. 本研究中嫦娥五号月尘的橄榄石Fo值分布于5.60~71.4之间,平均Fo值为50.0(图4(f)).

橄榄石族矿物中的铁主要以二价铁形式存在,太空风化作用使其表面形成非晶层和纳米级自然铁^[29]. 纳米级橄榄石的圆度较好,但部分颗粒仍保留一定棱角(图4(b, c)). TEM分析显示,橄榄石族矿物中分布着大量纳米级自然铁(粒径在3.75~15.1 nm之间,平均为7.73 nm; 图4(e)). 本次观察到的大粒径自然铁较少,推测以气相沉积成因的纳米级自然铁为主.

3.1.4 长石族矿物

月海玄武岩和高地岩石中长石族矿物主要是斜长石系列($\text{NaAlSi}_3\text{O}_8(\text{Ab})$ - $\text{CaAl}_2\text{Si}_2\text{O}_8(\text{An})$ 类质同象系列的长石矿物的总称),嫦娥五号月尘样品中,斜长石在识别矿物碎屑中占比较大(60%). An值在74.4~97.4范围内变化(平均为84.8),平均矿物组成为 $\text{An}_{84.8}\text{Ab}_{14.5}\text{Or}_{0.69}$,指示月尘中长石族矿物主要是倍长石和钙长石(图5(e)),该结果与月壤整体长石特征一致^[3].

TEM观察结果显示,长石表现出较好的颗粒外形,

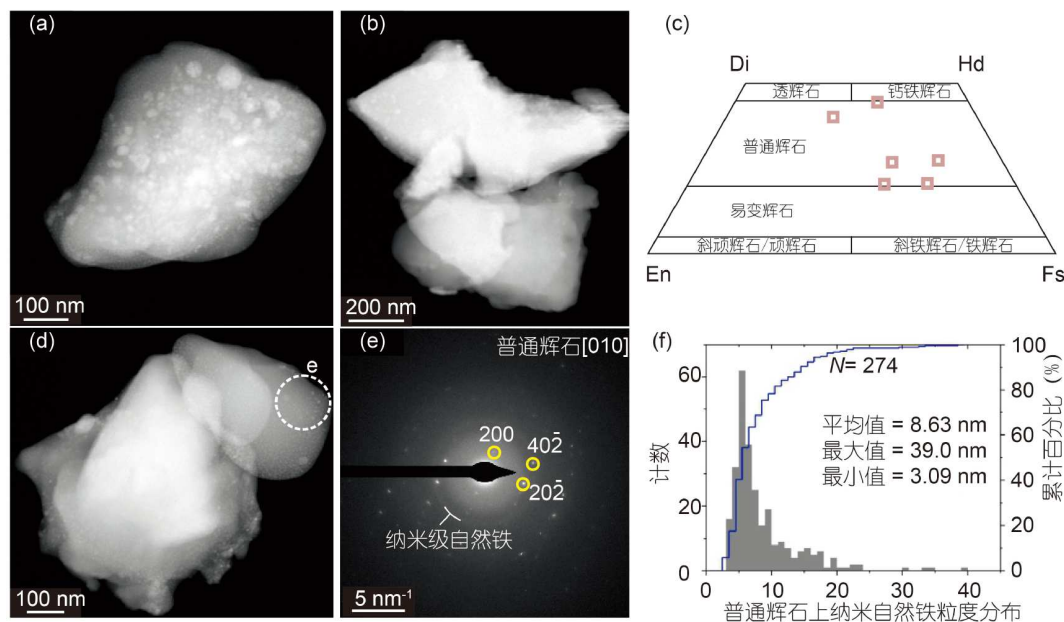


图3 (网络版彩色)月尘中的辉石族矿物. (a, b, d) 月尘中纳米级普通辉石HAADF-STEM图像; (c) 辉石族矿物成分投图; (e) 图(d)区域选区电子衍射图; (f) 普通辉石上纳米级自然铁粒度分布

Figure 3 (Color online) Pyroxene group mineral in lunar dust. (a, b, d) HAADF-STEM images of Nano-scale augite in lunar dust. (c) Pyroxene group mineral composition map; (e) SAED pattern of the region in (d); (f) size distribution of Nano-scale natural iron on augite

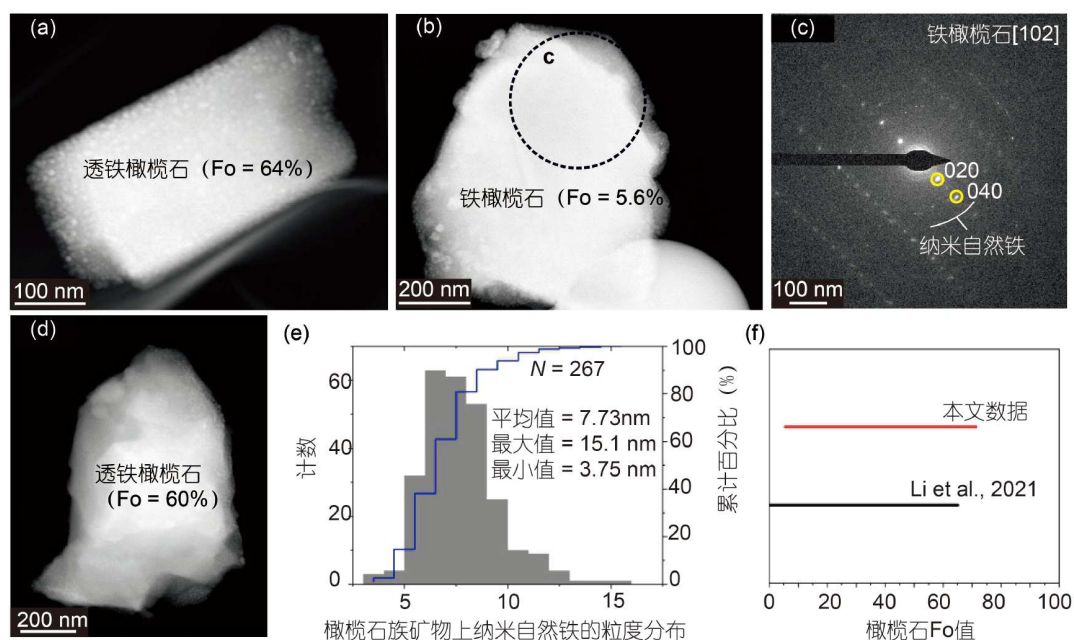


图 4 (网络版彩色)月尘中的橄榄石. (a, b, d) 月尘中纳米级橄榄石族矿物HAADF-STEM图; (c) 图(b)区域选区电子衍射图; (e) 月尘橄榄石上纳米级自然铁粒度分布; (f) 橄榄石族矿物Fo值图, 嫦娥五号月壤数据来自文献[3]

Figure 4 (Color online) Olivine in lunar dust. (a, b, d) HAADF-STEM images of Nano-scale olivine group minerals in lunar dust; (c) SAED pattern of the region in (b); (e) distribution of Nano-scale natural iron particles on olivine; (f) Fo values of olivine group minerals. Chang'e-5 lunar soil data from Ref. [3]

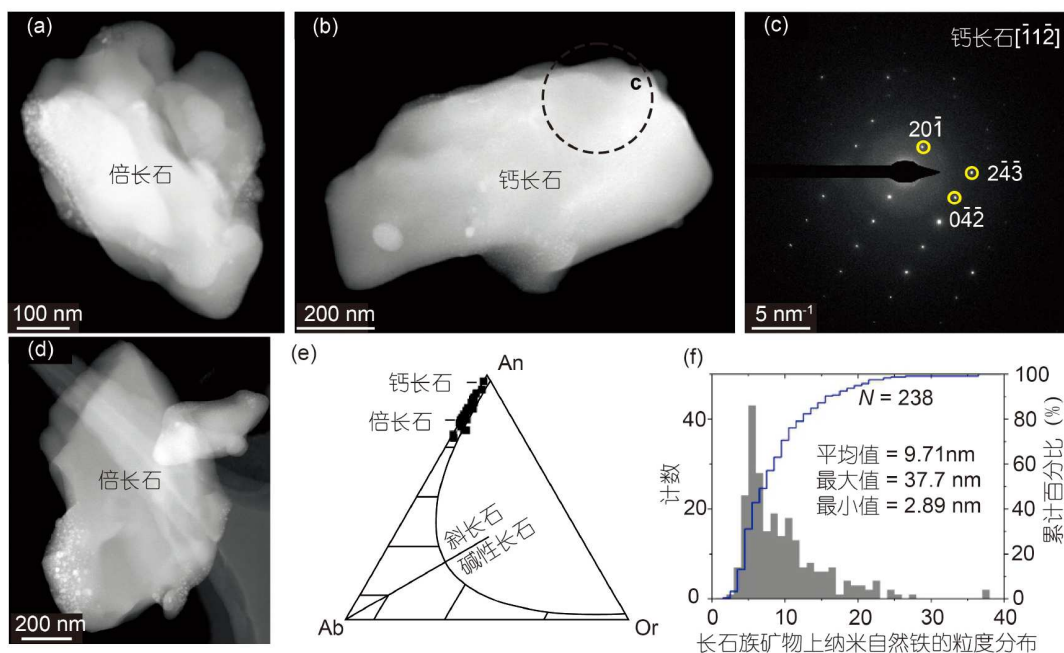


图 5 (网络版彩色)月尘中的长石族矿物. (a, b, d) 月尘中长石族矿物HAADF-STEM图; (c) 图(b)区域选区电子衍射图; (e) 斜长石成分分布图; (f) 长石附着纳米级自然铁粒度分布图. An: 钙长石; Ab: 钠长石; Or: 钾长石

Figure 5 (Color online) Feldspar in lunar dust. (a, b, d) HAADF-STEM images of feldspar minerals in lunar dust; (c) SAED image of region (b); (e) the mineral composition of plagioclase; (f) size distribution map of Nano-scale natural iron particles on feldspar. An: anorthite; Ab: albite; Or: orthoclase

在太空风化的作用下还保持较好的晶体结构(图5(c)). 斜长石仅部分区域附着少量纳米级自然铁, 颗粒表面整体相比于其他含铁矿物表面较为干净. 表面附着自然铁粒径分布于2.89~37.7 nm, 平均为9.71 nm, 以气相沉积成因为主.

3.1.5 钛铁矿

与地球相比, 月球的玄武岩含有更高比例的钛铁矿, 约为10%~12%, 而地球的玄武岩中通常低于5%^[14]. 本次分析月尘样品中钛铁矿颗粒数约占矿物碎屑组分的9%. TEM分析显示(图6), 钛铁矿颗粒受太空风化作用影响, 被太空风化非晶层包裹, 并且表面附着大量的纳米级自然铁. 这些颗粒的粒径为2.24~22.1 nm, 平均为8.20 nm(图6(e)).

3.1.6 磷灰石和陨硫铁

在地外样品中, 磷灰石是重要的含羟基(水)矿物和主要的定年矿物, 含有F、Cl和OH等挥发分, 因此其水

含量、挥发分、年代学分析和同位素组成一直是月球科学研究的焦点^[38~40]. 嫦娥五号返回样品中磷灰石占比为1.4%^[14]. 图7(a~c)展示的磷灰石颗粒表面附着富Si的非晶层, 可能来自于微陨石撞击造成的溅射或气相沉积(图7(a~c)).

月球中的硫化物矿物主要以陨硫铁为主, 还有近年来首次发现的气相沉积成因的蓝辉铜矿颗粒($\text{Cu}_{1.8}\text{S}$)^[41]. 图7(e~g)展示了月尘中的纳米级陨硫铁颗粒, 表面粗糙, 表明其在太阳风粒子作用下发生了结构破坏. 此外, 月壤中的硫化物微陨石撞击条件下能通过共析反应产生纳米级磁铁矿, 这对于月表磁异常研究具有重要意义^[42,43].

3.2 太空风化非晶碎屑

本文对嫦娥五号月尘中的纳微米颗粒进行了形貌、成分和结构分析, 发现几乎所有颗粒都受到太空

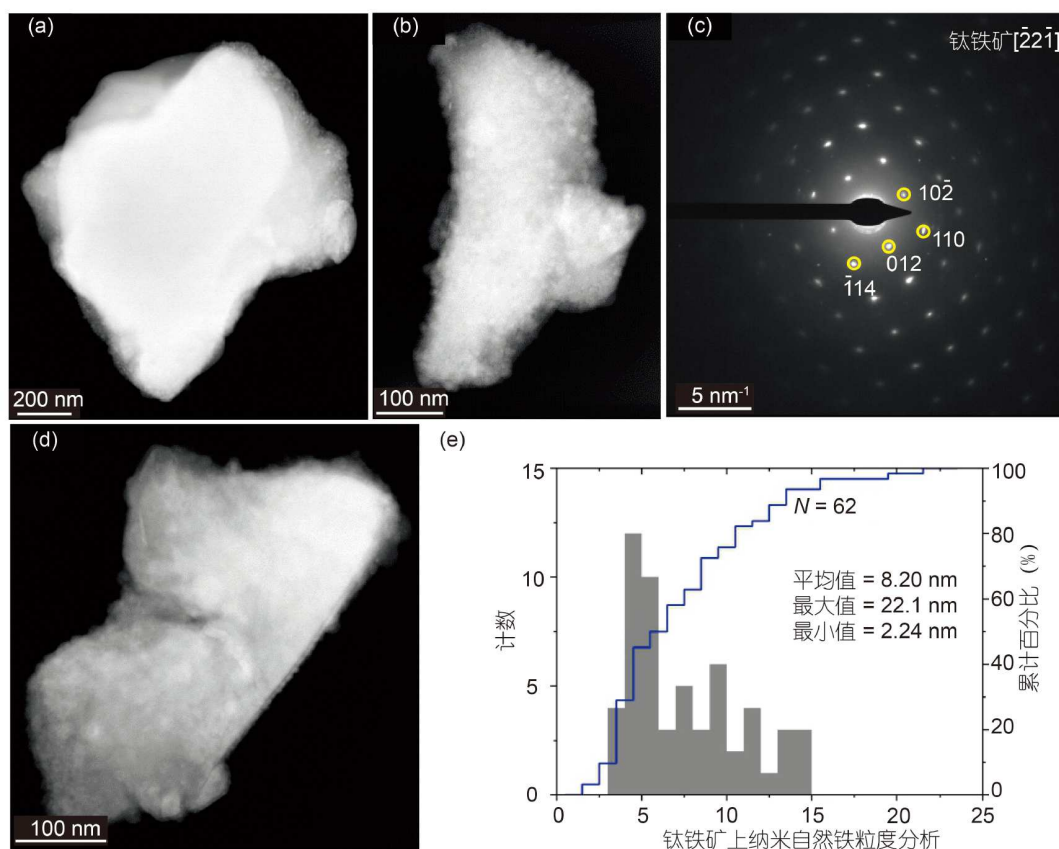


图6 (网络版彩色)月尘中的钛铁矿. (a, b, d) 月尘中纳米钛铁矿HAADF-STEM图; (c) 图(b)区域选区电子衍射图; (e) 钛铁矿上纳米级自然铁粒度分布图

Figure 6 (Color online) Ilmenite in lunar dust. (a, b, d) HAADF-STEM images of Nano-scale ilmenite in lunar dust; (c) SAED pattern of the region in (b); (e) distribution of Nano-scale natural iron particles on ilmenite

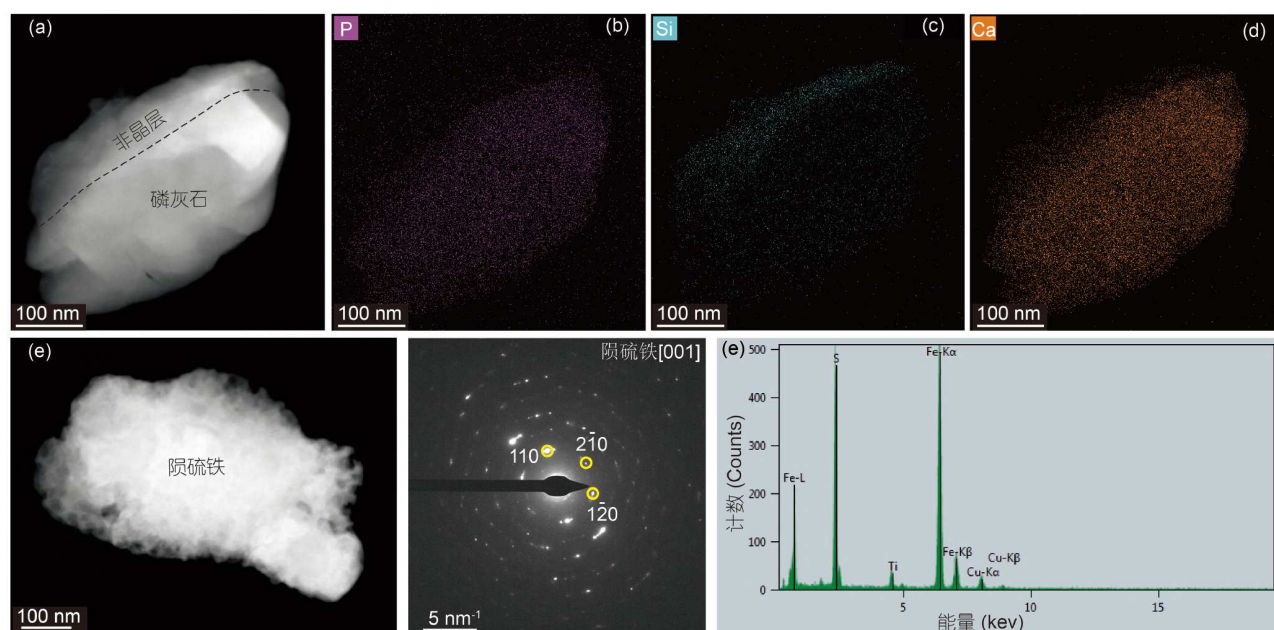


图7 月尘中的磷灰石和陨硫铁。(a~d) 纳米级磷灰石HAADF-STEM图及能谱P、Si和Ca元素面分布图；(e~g) 纳米级陨硫铁HAADF-STEM图、选区电子衍射图及能谱分析结果

Figure 7 Apatite and troilite in lunar dust. (a~d) HAADF-STEM images of Nano-scale apatite and elemental distribution maps of P, Si, and Ca; (e~g) HAADF-STEM image, SAED pattern and EDS result of Nano-scale troilite

风化影响。其中，59%的颗粒显示显著的成分变化和结构非晶化，归类为太空风化非晶碎屑。月尘中矿物碎屑和太空风化非晶碎屑的 Al_2O_3 和 FeO 含量协变图(图8(a, b))表明，太空风化非晶碎屑的分布范围与矿物碎屑相似，表明其主要为矿物碎屑的风化产物。它们主要由非晶质和纳米级自然铁组成，其中，纳米级自然铁粒径为2.75~39.1 nm，平均粒径为6.79 nm，以气相沉积成因为主(图8(j))。

月尘中的太空风化非晶质碎屑记录了陨石和微陨石撞击以及太空风化等过程，同时能长期储存太阳风注入的水、 ^3He 和太空风化形成的纳米级自然铁等物质资源^[44~47]。月尘中的非晶质碎屑种类多样，主要包括火山玻璃、撞击玻璃、胶结玻璃和颗粒表面的非晶态物质。火山玻璃由月球火山喷发的微小液滴快速冷却形成^[48]，撞击玻璃则是由陨石高速撞击月表，产生的高温将月球矿物融化甚至气化，这些融化的月表物质飞溅形成的微小熔融液滴快速冷却而成^[49]。这两类玻璃颗粒通常为球形，尺寸从几十纳米到几厘米不等，难以仅凭形态区分。研究表明，撞击玻璃通常具有较低的Mg/Al比值，作为区分火山玻璃的特征之一^[37,50]。在嫦娥五号月尘中观察到许多亚微米尺寸的玻璃球

(图8(c, f))，且具有较低的Mg/Al比值，推测主要为撞击玻璃。此外，玻璃球表面还观察到气相沉积的纳米级自然铁(图8(f))，进一步表明气相沉积的纳米铁在月尘中的普遍分布。胶结玻璃是撞击产生的熔体将月壤碎屑黏结形成的物质，或熔体溅射到月壤碎屑表面形成的黏结物^[44]。这种玻璃被认为是月壤的重要组成部分，平均占月壤的30%^[44]。本文观察到的大量不规则的纳米级太空风化非晶碎屑可能是胶结玻璃破碎的结果^[47,51,52]。

月尘中几乎所有颗粒表面均覆盖一层厚度约几十纳米的非晶态物质，且含有纳米级自然铁。这些非晶层主要有两种形成机制：一是太阳风粒子注入矿物颗粒，结合昼夜温差导致的热疲劳，不断破坏矿物表面的晶体结构，最终形成非晶层，且其成分与基底矿物相似^[53,54]。这种非晶层受太阳风粒子作用，可能产生纳米级自然铁和羟基等物质，并储存 ^3He ^[47]；另一种是气相沉积形成的非晶层，陨石和微陨石撞击产生的高温将月球矿物气化，蒸发的气体沉积在周围碎屑表面，形成气化沉积的非晶层，其成分与基底矿物不同^[31,55]。气相沉积非晶层广泛分布，其中含有大量纳米级自然铁，如图8(f)中观察到含有气孔的纳米铁，这被认为是气相沉积的标志^[29]。图8(g)展示了一颗由挥发分(F、S、C、P

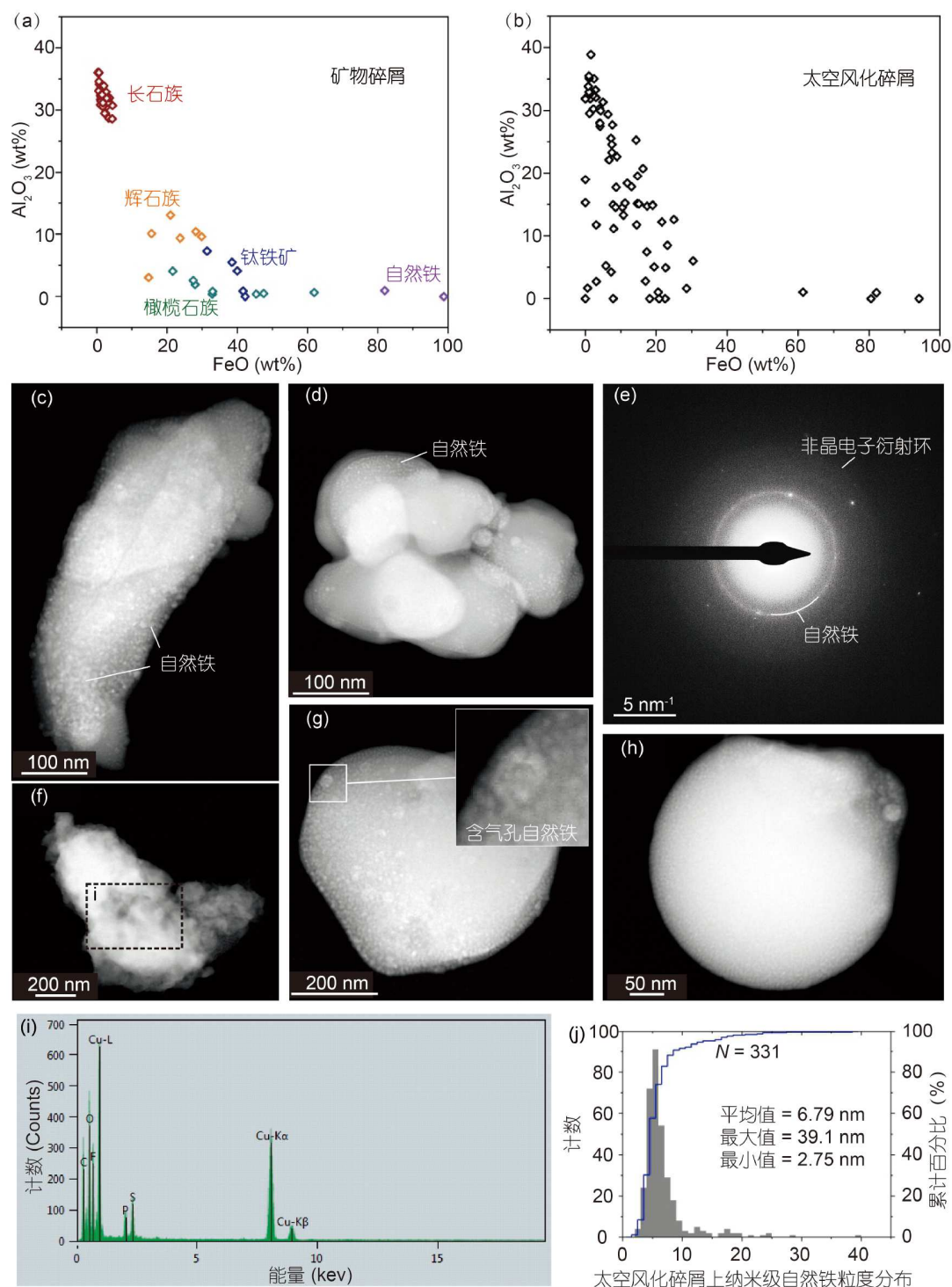


图 8 月尘中矿物碎屑和太空风化碎屑颗粒特征. (a, b) 月尘中矿物碎屑和太空风化非晶碎屑 Al_2O_3 和 FeO 含量协变图; (c, d, g, h) 太空风化非晶碎屑 HAADF-STEM 图; (e) 图(d) 太空风化非晶碎屑的选区电子衍射图; (f) 蒸汽凝结颗粒的 HAADF-STEM 图 and (i) 能谱图; (j) 太空风化非晶碎屑上纳米级自然铁粒度统计

Figure 8 Characteristics of mineral fragments and space-weathered fragments in lunar dust. (a, b) Covariance diagram of Al_2O_3 and FeO content in mineral fragments and space-weathered fragments in lunar dust; (c, d, g, h) HAADF-STEM images of space-weathered amorphous fragments; (e) SAED image of space-weathered amorphous fragments (d); (f) HAADF-STEM images, and (i) EDS of vapor-condensed particles; (j) Nano-scale natural iron particle size distribution in space-weathered fragments

等)组成的非晶态团聚体,可能是陨石和微陨石撞击气化产生的蒸汽凝结而成,这可能是月尘中挥发分的赋存形式之一。

4 结论

本文对178颗嫦娥五号纳微米粒径月尘颗粒(平均粒径为858 nm)进行了系统分析,揭示了月尘中纳微米颗粒的矿物学特征。结果显示,几乎所有月尘颗粒均受到太空风化作用的影响,被非晶层包裹,并附着大量纳米级自然铁。约59%的纳微米颗粒成分变化显著且失去原有晶体结构,归为太空风化非晶碎屑;41%的颗粒仍

保持矿物结构,归为矿物碎屑。矿物碎屑主要由自然元素矿物(主要为自然铁)、辉石族、长石族、橄榄石族、钛铁矿及少量磷灰石和陨硫铁组成。太空风化非晶碎屑则主要由非晶态物质、纳米级自然铁和挥发分凝聚物组成。自然铁矿物在月尘颗粒中广泛分布,主要为气相沉积成因的纳米自然铁,此外还包括陨硫铁太空风化形成的铁晶须和撞击成因的泪滴形自然铁,这会对月壤的物理化学性质和光谱学信息有显著影响。此外,月尘中的非晶态物质含量较高,能储存大量太阳风物质,如太阳风注入的水、 ^3He 和太空风化形成的纳米级自然铁等,值得进一步评估其资源潜力。

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Summary for “嫦娥五号月尘纳微米矿物学特征及其成因意义”

Mineralogical characteristics and genesis significance of nano- and micro-scale Chang'e-5 lunar dust

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The Chang'e-5 mission successfully retrieved 1.731 kg of lunar regolith from the Moon's mid-latitude region (~43°N) through a combination of scooping and drilling methods, marking a historic achievement in China's lunar exploration endeavors and contributing significantly to lunar science. The weathered material that covers the Moon's surface is known as lunar regolith. The thickness of lunar regolith in the mare regions is approximately 5.3 m, while in the highlands, the average thickness can reach up to 10.7 m. According to particle size classification of the lunar samples returned by the Apollo missions: particles (with diameters ≥ 1 cm) are classified as lunar rocks; particles (< 1 mm) are called lunar dust (or lunar fines).

Among the Chang'e-5 returned materials, the 95% of the particles range in size from 1.4 μm to 9.35 μm (much smaller than 1 mm), suggesting that the lunar dust constitutes a significant portion of the returned material. This study further classifies lunar dust into three size categories: microscale particles (1–1000 μm), sub-microscale particles (0.1–1 μm), and nanoscale particles (1–100 nm). These fine particles present considerable analytical challenges for conventional solid Earth geoscience techniques due to their small size and complex nanoscale features.

To address this, the present study employs advanced nano-mineralogical techniques, including high-resolution transmission electron microscopy (HRTEM) with energy-dispersive spectroscopy (EDS), to conduct a comprehensive characterization of the fine lunar dust particles (with particle sizes ranging from 0.1 μm to 3 μm). The analysis reveals that all particles exhibit distinct signatures of space weathering, most notably the presence of surface coatings composed of amorphous materials and nanoscale native iron (npFe⁰), which are indicative of prolonged exposure to the harsh space environment.

The particles were then divided into two groups based on their structural characteristics: space-weathered fragments and mineral fragments. Mineral fragments, which included phases like natural minerals (like natural iron), pyroxene, plagioclase feldspar, olivine, and ilmenite, with sporadic occurrences of apatite and troilite, accounted for about 41% of the particles, which still had some of their original crystalline structure. The varying degrees of compositional alteration seen in these mineral fragments demonstrate the widespread influence of space weathering processes. In contrast, roughly 59% of the particles showed significant amorphization and were categorized as space-weathered fragments, which mostly consisted of glassy materials with iron nanoparticles embedded in them. Nanoscale natural iron particles are widely distributed in lunar dust, primarily in the form of metallic iron formed by vapor deposition. In addition, iron whiskers resulting from the space-weathering of troilite and teardrop-shaped metallic iron produced by impact.

Owing to the absence of a protective atmosphere and a global magnetic field, the lunar surface has been exposed to prolonged space-weathering, including micrometeorite impacts, continuous solar wind irradiation, thermal fatigue resulting from extreme diurnal temperature fluctuations, and bombardment by galactic cosmic rays. These processes cause fragmentation and mixing of surface materials, along with melting, radiation-induced damage, and vapor-phase deposition, collectively inducing significant alterations in the physicochemical and spectroscopic properties of lunar surface materials.

The lunar surface has been subjected to extended space-weathering due to the lack of a protective atmosphere and a global magnetic field. This includes micrometeorite impacts, constant solar wind radiation, thermal fatigue from drastic diurnal temperature fluctuations, and galactic cosmic ray bombardment. The physicochemical and spectroscopic characteristics of lunar surface materials are significantly altered by these processes, which also result in melting, radiation-induced damage, vapor-phase deposition, and surface material fragmentation and mixing. Furthermore, the high number of amorphous phases suggests a significant ability to trap the solar wind-implanted materials, such as ³He, underscoring the potential of lunar regolith as a valuable resource from space.

Chang'e-5, lunar dust, space weathering, nano-mineralogy, particle characteristics

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