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Global inventory of Helium-3 in lunar regoliths estimated by a multi-channel microwave radiometer on the Chang-E 1 lunar satellite

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Helium-3 (^{3}He) implanted by solar wind in the lunar regolith is a valuable resource because of its potential as a fusion fuel. On the basis of the Apollo regolith samples, a linear relationship between ^{3}He abundance and solar wind flux, optical maturity and TiO_2 content has been presented. China successfully launched its first lunar exploration satellite Chang-E 1 (CE-1) on October 24, 2007. A multi-channeled microwave radiometer was aboard the satellite with the purpose of measuring microwave thermal emission from the lunar surface layer. From the multi-channel brightness temperature (T_b) observed by CE-1, the global distribution of the regolith thickness was inverted from the multi-channel T_b, and was used to evaluate the total amount of ^{3}He per unit area in the lunar regolith. The global inventory of ^{3}He was estimated as being 6.6×10^8 kg; 3.7×10^8 kg for the lunar nearside and 2.9×10^8 kg for the lunar farside.

^{3}He abundance, regolith thickness, Chang-E 1

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Helium-3 (^{3}He) is a clean, safe and non-radioactive fusion fuel. Compared with traditional fusion reaction of using ^{3}H, the reaction involving ^{3}He does not generate any high-energy neutrons and does not produce prolonged radioactivity, and hence is not dangerous to a reactor or the environment. Terrestrial sources of ^{3}He are extremely rare and the total inventory is only about 2.0×10^4 kg [1]. Because there is neither a geomagnetic field nor an atmosphere on the Moon, solar wind particles can impinge directly upon the lunar surface and hence be captured by lunar regolith particles. As a consequence, a significant amount of solar wind elements (such as helium) have accumulated in the regolith during the long geological history of the Moon [1,2].

Significant work has been done to estimate the ^{3}He implantation and abundance in the lunar regolith during the last few decades, based on the returned regolith samples from the Apollo and Luna missions (for a thorough review, see [3] and [4–8]). However, there has been a need to have a precise lunar regolith thickness distribution map of the whole lunar surface to determine the quantities of ^{3}He present.

China successfully launched its first lunar exploration satellite Chang-E 1 (CE-1) on October 24, 2007 [9]. A multichannel microwave radiometer was aboard the satellite and had the purpose of measuring microwave thermal emissions from the lunar surface layer [10,11]. From the analysis of the primary CE-1 observations, consisting of the brightness temperature (T_b) (from November 2007 to February 2008), Fa and Jin [11] successfully inverted the global distribution of regolith thickness. This newly acquired dataset provided an opportunity to quantitatively estimate the global inventory of the ^{3}He accumulated in the whole regolith. Other studies on the CE-1 observations can be found in [12–17].

In this study, by combining the models of normalized solar wind flux over the lunar surface, the global distribu-

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tion of TiO_2 content and the surface optical maturity derived from Clementine UV VIS multispectral data, a linear relationship between ^{3}He abundance, TiO_2 content and surface optical maturity can be derived for the global distribution of ^{3}He in the lunar near-surface layer (thickness less than 1 μm). Using the newly acquired global distribution of the regolith thickness obtained from CE-1 multi-channel radiometer observations [11], the total amount of ^{3}He per unit area in lunar regolith can then be obtained.

1 ^{3}He distribution over the lunar surface

The abundance of ^{3}He in the lunar regolith is mainly governed by two processes: implantation by the solar winds and outgassing of the lunar regolith. If not all grain surfaces are saturated with solar wind particles, then ^{3}He abundance should be dependent on the solar wind flux over the lunar surface. The ^{3}He abundance in the regolith is governed by the efficiency with which implanted ^{3}He is retained, i.e. the process of regolith outgassing, which is determined by the structure and chemical composition of the regolith itself.

Because the solar wind is the only source of ^{3}He in the lunar regolith, its concentration should exhibit a global latitudinal variation; while at the lunar surface tilted to the solar rays, it receives a smaller flux of solar wind particles. As the Moon moves in the tail of the Earth's magnetotail and deflects the solar wind, the lunar nearside receives less solar wind exposure than the farside, which further causes a longitudinal variation in ^{3}He. In this study, the solar wind flux distribution model, which was first proposed by Johnson et al. [7] and further modified by Fa and Jin [3], was used to calculate the normalized solar wind flux over the lunar surface.

The second factor affecting the ^{3}He abundance is the maturity of the lunar soil, which is actually the amount of time that the lunar soil has been exposed to the environment. As the surface exposure progresses, the grain size of the soil decreases and the abundance of agglutinates increases, and ^{3}He abundance (and also other volatiles in the regolith) increases [4,6]. Several indices have been proposed to quantify the maturation process of regolith, including the Is/FeO (the ratio of ferromagnetic resonance intensity (Is) to the total Fe content), optical maturity (OMAT), grain size, abundance of agglutinates and abundance of solar wind gas [18]. In this study, the optical maturity proposed in [18,19] is used to quantify the maturation of the lunar surface.

The third factor is the TiO_2 content. Comparisons of lunar ilmenite, olivine, pyroxene and plagioclase show that ilmenites in the same grain-size ranged from the same soil, may contain 10–100 times as much ^{3}He as [4,6]. Since most lunar TiO_2 is found in ilmenites, the TiO_2 content serves as a good tracer of ilmenite abundance, and hence ^{3}He retentivity.

Considering all these three factors that affect the abundance of ^{3}He in the lunar regolith and using the measurement of Apollo regolith samples, we present a linear relation between ^{3}He abundance C_0 of the lunar surface (in ppb, part per billion), the normalized solar wind flux F, the TiO_2 content S_{Ti} and the OMAT as

$$C_0 = 0.56\times\left[S_{Ti}\times F/\mathrm{OMAT}\right]+1.62. \tag{1}$$

Figure 1 shows a regression function between ^{3}He abundance, normalized solar wind flux, TiO_2 content, and OMAT that was derived from the Apollo regolith samples by Fa and Jin [3].

Using the normalized solar wind flux calculated from Jin and Fa [3], and the distribution of OMAT and TiO_2 content from [18,19], the global distribution of ^{3}He abundance over lunar surface can be obtained (Figure 6 in [3]). Due to the high TiO_2 content, the maria in the lunar nearside may have a large value of ^{3}He even as they receive less solar wind flux because of shielding from the Earth's magnetotail. The highest ^{3}He occurs in Mare Tranquillitatis and Oceanus Procellarum, with the ^{3}He abundance being as high as 30 ppb. Compared with highlands on the lunar nearside, the highlands on lunar farside have higher ^{3}He than the highlands on nearside, mainly because of the farside undergoing more solar wind flux. The lunar polar areas have less ^{3}He, which is mainly because of the less incident solar wind in those areas.

2 Mapping regolith thickness using the CE-1 radiometer

Previous investigations show that almost the entire lunar surface is covered with a regolith which consists of fragmented materials such as surface layer dust, unconsolidated

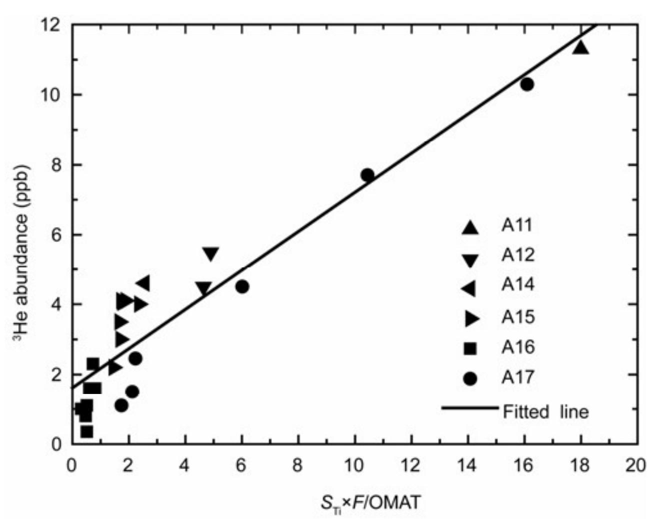

Figure 1 Regression analysis between ^{3}He abundance, solar wind flux, TiO_2 content, and OMAT for the Apollo regolith sample [3].