Postprint: Analysis of Cosmic Ray Events in Moon-Based Optical Telescope Images During the September 28, 2015 Total Lunar Eclipse

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Abstract

On September 28, 2015, the lunar-based optical telescope experienced the only complete lunar eclipse during its mission, providing a rare opportunity to investigate whether the geometric occlusion of sunlight by Earth would affect the lunar surface radiation environment. First, using continuous CCD astronomical observation images with a total duration of 2 hours and 27 minutes during the eclipse, we statistically analyzed the cosmic ray event counts during the lunar eclipse and found no significant variation; the average cosmic ray event count was 129.27 ($±15.78)*withina*30 − *secondexposuretime*.*Second*, *wealsoanalyzedthecosmicrayeventcountsinCCDdark*− *frameimagescollectedinAugustandfromOctobertoDecember*, *whichwere*119.92(±6.37), 117.00(±10.90), 118.6
error range, indicating that the geometric occlusion of the Sun by Earth did not produce a noticeable effect on the lunar surface radiation environment. Finally, the article presents an analysis and discussion of these results.

Full Text

Research on Cosmic Ray Events in Lunar-based Ultraviolet Telescope Images During the September 28, 2015 Lunar Eclipse

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Abstract

On September 28, 2015, the Lunar-based Ultraviolet Telescope (LUT) experienced the only complete lunar eclipse during its mission, providing a rare opportunity to investigate whether Earth' s geometric shielding of solar radiation affects the lunar radiation environment. First, using continuous CCD astronomical observation images spanning 2 hours and 27 minutes during the eclipse, we statistically analyzed cosmic ray event counts and found no significant variation. Within a 30-second exposure time, the average cosmic ray event count was 129.27 ($\pm$15.78).*Second, weanalyzedcosmicrayeventcountsindarkfieldimagescollectedinAugustandfromOctoberto* error, these counts are consistent with those during the eclipse, indicating that Earth' s geometric shielding of the Sun had no significant effect on the lunar radiation environment. Finally, these results are discussed and analyzed.

Keywords: lunar surface radiation environment; lunar-based ultraviolet telescope; cosmic rays

0 Introduction

The Lunar-based Ultraviolet Telescope (LUT) is a scientific payload installed on the Chang' e-3 lander. Its primary scientific objective is to conduct long-term continuous monitoring of brightness variations from various astronomical variable sources in the near-ultraviolet band, taking advantage of the Moon' s extremely slow rotation and ultra-high vacuum environment [1]. Since commencing operations on December 16, 2013, LUT successfully completed three years of astronomical observations and an additional two years of extended experiments, accumulating massive amounts of raw image data. In addition to observation targets, LUT images contain numerous cosmic ray events characterized by high brightness and profiles generally larger than stellar images. Operating on the lunar surface, LUT' s detector is directly exposed to bombardment by galactic cosmic rays, solar cosmic rays, and solar wind particles [2]. When these charged particles strike the CCD target surface, they generate electron-hole pairs that are collected and read out like those produced by photons, manifesting as "linear" or "point-like" structures in images, some morphologically similar to stellar sources, thereby interfering with subsequent image processing.

The Chang' e-3 lander derives its operating power from solar illumination, restricting LUT observations to lunar daytime periods. On September 28, 2015, a total lunar eclipse occurred—the only complete lunar eclipse experienced by LUT during its mission. During totality, Earth' s geometric shielding prevented direct solar radiation from reaching LUT. This paper investigates whether Earth' s geometric shielding of solar wind particles and solar cosmic rays causes variations in the lunar radiation environment by analyzing cosmic ray event counts in CCD images during and around the eclipse. Based on literature review, this appears to be the first study using lunar surface astronomical CCD images to investigate the lunar radiation environment.

In recent years, Chinese researchers have made significant contributions to lunar surface environment studies through the Chang' e lunar exploration program. Ouyang Ziyuan, Ye Peijian, and Chu Guibai provided comprehensive reviews of the lunar surface and near-lunar space environment [3-5]. The near-lunar space radiation environment comprises solar electromagnetic radiation and charged particle radiation. Charged particle radiation encountered on the lunar surface primarily originates from solar cosmic rays, galactic cosmic rays, and solar wind. Solar wind particles persist even without solar illumination, capable of charging lunar dust. Xue Yuxiong et al. [6] analyzed the radiation environment experienced by lunar detectors after landing, finding that during lunar daytime, the radiation environment is essentially similar to that in lunar orbit, mainly comprising solar wind and galactic cosmic rays, with solar cosmic rays present during solar flare eruptions. During lunar night, due to the Moon' s geometric shielding, detectors encounter only galactic cosmic rays. Wang Xinyue et al. [7] analyzed data from the High-energetic Particles Detectors (HPD) and Solar Wind Ion Detectors (SWIDs), discovering that during solar minimum with relatively low space environment disturbance levels and the Moon in the solar wind, the basic characteristics of the near-lunar charged particle environment show little change compared to interplanetary space. Wang Xiaodong et al. [8] used Chang' e-1 SWID data to discover solar wind ion scattering near the lunar terminator and acceleration by convection electric fields. Wang Jie and Qin Gang [9] analyzed Earth' s magnetospheric shielding effects on lunar orbit using Chang' e-1 HPD data, finding no significant magnetospheric shielding effect when the Moon is within Earth' s magnetosphere.

This paper utilizes LUT observation data during the lunar eclipse to investigate potential radiation environment changes. Combined with dark field data from months before and after the eclipse, we further compare and study whether Earth' s geometric shielding of sunlight affects the lunar radiation environment. For eclipse observations, we employed astronomical position calibration to identify and extract cosmic rays. For dark field images, we used direct identification and extraction. Finally, we conducted comparative analysis of cosmic ray event probabilities considering solar activity during image acquisition to discuss Earth' s geometric shielding effects on the lunar radiation environment.

1 Overview of the Lunar-based Ultraviolet Telescope System

[Figure 1: see original paper] shows the optical path design and cross-sectional view of the LUT telescope. The telescope employs an R-C system design with a focal ratio of F/3.75 and a primary mirror diameter of 150 mm. To reduce overall instrument length, a plane mirror reflects light to the Nasmyth focus where the CCD is installed. The CCD is a frame transfer model CCD47-20 produced by E2V, containing 1024$×1024*pixelswithapixelsizeof*13×$13 m. The CCD can be cooled to -40°C. LUT' s main technical specifications are listed in Table 1 [10].

2 Data Selection and Processing Flow

On September 28, 2015, LUT experienced a complete lunar eclipse during sky survey observations. LUT captured 374 frames during the approximately four-hour eclipse period. We analyzed sky background brightness variations throughout the process, with results shown in Figure 2 [Figure 2: see original paper]. The horizontal axis represents UT time, and the vertical axis shows background brightness counts per pixel. The figure reveals that LUT observation images underwent a bright-to-dark-to-bright transition during the eclipse. From 01:27:49.23 UT to 03:55:03.95 UT on September 28, 2015—a total of 2 hours and 27 minutes—the sky background brightness was at its minimum, with the Chang' e-3 landing site fully within the eclipse shadow. We selected 230 frames captured during this period as eclipse observation data to analyze cosmic ray event variations.

As control samples, we also selected dark field images captured by LUT in August, October, November, and December 2015 to compare Earth' s shielding effects on the lunar surface cosmic ray environment. Dark field images were chosen because LUT' s door is closed during acquisition, creating a dark environment unaffected by lunar daytime sunlight or stars, most closely resembling the dark background during total eclipse. Additionally, the door is thin and does not significantly affect cosmic ray penetration. Detailed information on the selected data is provided in Table 2 .

2.1 Processing of Eclipse Observation Images

LUT observation data contain many cosmic ray events with morphological profiles similar to stellar images. Traditional cosmic ray identification algorithms (e.g., median filtering, Laplacian edge detection, histogram-based fast algorithms, and universal noise elimination algorithms) [11] show low identification efficiency for such events with certain misidentification rates. This paper employs a detection method based on astronomical position calibration to extract cosmic ray events from images. Compared with other methods, this approach more effectively identifies cosmic ray events from single-exposure images. Detailed processing procedures are described in reference [12].

The cosmic ray detection algorithm based on astronomical position calibration proceeds as follows:

(1) **Image preprocessing**: Preprocessing of LUT eclipse images primarily includes calibration of bias fields, flat fields, and dark fields. Bias fields calibrate the DC zero point under zero-time measurement, flat fields calibrate non-uniform quantum efficiency of CCD devices, and dark fields calibrate dark current noise under non-illuminated conditions.

(2) **Background subtraction**: During the eclipse, LUT operated in sky survey mode, with stellar positions shifting by several pixels between adjacent images. To obtain background-fitted images, we first grouped the

sequential observation images. For each frame, we median-combined other images from the same group (excluding itself) to generate corresponding background-fitted images. Each frame then subtracted its corresponding background-fitted image, simultaneously removing "hot pixels" and "bad pixels." Background-subtracted images retain stellar images and cosmic rays [13].

(3) **Astronomical position calibration**: For each background-subtracted image, we extracted 5-10 bright stars to obtain their positions and brightness information, then performed dual-layer matching with the Tycho-2.0 catalog for position and brightness. Using Tycho-2.0' s high-precision J2000 astronomical coordinates, we achieved astronomical position calibration with approximately 1 arcsecond precision.

(4) **Extraction of cosmic ray candidates**: We used SExtractor software to extract cosmic ray candidates from LUT images based on two criteria: (1) single-pixel counts greater than 5 times the background noise; (2) connected pixels greater than or equal to 4. Using astronomical position calibration parameters, we calculated corresponding J2000 astronomical coordinates for each candidate.

(5) **Identification of cosmic ray samples**: Cosmic ray candidates include some stellar images that must be removed. We cross-matched candidates with the Tycho-2.0 and USNO_{B1}.0 catalogs to eliminate stellar images and obtain cosmic ray samples.

Figure 3 [Figure 3: see original paper] shows sample LUT eclipse observation images. Figure 3(a) displays the original image, while Figure 3(b) shows the preprocessed image after background subtraction. Compared with Figure 3(a), Figure 3(b) demonstrates excellent background and noise removal. Figure 3(c) presents cosmic ray identification results for Figure 3(b), with cosmic ray events marked by blue circles and stellar images by red circles.

2.2 Processing of LUT Dark Field Images

Dark field images are obtained by exposing CCD devices in complete darkness for a specified time. Theoretically, dark field images contain two components: bias voltage readings from the offset field, and thermal noise from dark current generated between pixels during exposure. Examination of LUT dark field images reveals some pixels with brightness values significantly exceeding the average. These super-bright pixels occurring in every frame are typically considered "hot pixels" or "bad pixels," while those occurring sporadically are generally recognized as cosmic ray events. We identified and extracted cosmic ray events from dark field images using the following method:

(1) **Image preprocessing**: Similar to eclipse data processing, we performed bias subtraction preprocessing on dark field images.

(2) **Dark current noise subtraction**: Preprocessed dark field images underwent median combination across multiple frames to remove sporadic cosmic ray events, yielding average dark current images for each set. Each dark field image then subtracted its corresponding average dark current image. Dark current noise-subtracted images retain cosmic ray events while simultaneously removing "hot pixels" and "bad pixels."

(3) **Extraction of cosmic ray samples**: To ensure sample consistency, we applied identical identification criteria. To determine brightness thresholds for cosmic ray events, we first calculated background noise for monthly dark field images and eclipse images, with results shown in Table 3 . Dark field image background noise across four months ranged between 5.81-5.92 ADU, lower than the 6.87 ADU during eclipse. Therefore, the brightness threshold was uniformly set to 5$×$6.87 ADU. Cosmic ray identification criteria included: (1) brightness threshold greater than 34.35 ADU; (2) connected pixels greater than or equal to 4.

Figure 4 [Figure 4: see original paper] illustrates the LUT dark field image processing workflow. Figure 4(a) shows the original dark field image, Figure 4(b) displays the preprocessed image after dark current noise subtraction, demonstrating removal of systematic noise. Figure 4(c) presents cosmic ray identification results for Figure 4(b), with cosmic ray events marked by blue circles.

3 Results and Analysis

3.1 Statistical Analysis of Cosmic Ray Events During Eclipse

Applying the astronomical position calibration method, we identified and extracted cosmic ray events from 230 frames captured by LUT during the eclipse, with results shown in Figure 5 [Figure 5: see original paper]. The horizontal axis represents UT time of each frame' s exposure start, and the vertical axis shows the number of cosmic ray events per frame. Our algorithm identified 29,731 cosmic ray events, with a statistical average of 129.27 ($±$15.78).

To investigate potential variations in the lunar radiation environment during the eclipse, we performed grouped statistical analysis of cosmic ray event counts in chronological order. The 230 frames were divided into seven groups: six groups containing 33 frames each and a seventh group containing 32 frames. Grouped statistical results are presented in Table 4 and Figure 6 [Figure 6: see original paper]. In Figure 6, the horizontal axis shows each group' s exposure start/end UT time, and the vertical axis displays the mean number and 1σ error of cosmic ray events per group. Clearly, within 1σ error, cosmic ray events showed no variation during the eclipse, indicating no significant change in the lunar radiation environment.

3.2 Comparative Analysis of Cosmic Ray Events Before, During, and After Eclipse

To investigate whether Earth' s geometric shielding of the Sun affects the lunar radiation environment, we compared cosmic ray event variations during and around the eclipse.

We further conducted statistical analysis of cosmic ray events in dark field images captured monthly by LUT in August and October-December 2015, with results shown in Figure 7 [Figure 7: see original paper]. The horizontal axis represents sequential image numbers for each dark field group, and the vertical axis shows cosmic ray event counts per dark field frame.

Average cosmic ray event counts per frame in LUT dark field images were 399.72 (\$±21.25)$inAugust, 390.00(\pm36.32)inOctober, 395.36(\pm29.81)inNovember, and413.00(\pm$\$29.72) in December. Given that eclipse images had 30-second exposures while dark field images had 100-second exposures, we normalized the statistics to a 30-second interval for direct comparison. The resulting cosmic ray event counts per 30 seconds are shown in Table 5 .

As shown in Table 5, within 1σ error, cosmic ray events showed no variation before, during, or after the eclipse, demonstrating that Earth's geometric shielding of the Sun had no significant effect on the lunar radiation environment.

3.3 Discussion

Charged particle radiation encountered on the lunar surface primarily originates from galactic cosmic rays, solar cosmic rays, and solar wind [3-5]. Our comparative analysis of cosmic ray event counts in LUT eclipse observations and dark field images from around the eclipse reveals that the lunar eclipse did not affect cosmic ray event probabilities in LUT images. We discuss the influences of galactic cosmic rays, solar cosmic rays, and solar wind particles on LUT cosmic ray events before and after the eclipse.

The spatial distribution of interplanetary galactic cosmic rays is essentially isotropic, composed primarily of low-flux charged particles with energies ranging from 10^8 to 10^{19} eV. Research indicates that Earth' s magnetosphere cannot produce significant magnetic shielding effects on cosmic ray particles near lunar orbit [14]. Therefore, we conclude that in the lunar surface environment, Earth' s geometric shielding during lunar eclipse does not cause noticeable changes in lunar galactic cosmic ray events.

Solar cosmic rays are high-energy particles with energies from 10^5 to 10^{10} eV ejected during solar flares. Lunar surfaces encounter solar cosmic ray bombardment only during solar flare eruptions [7]. We examined solar activity conditions from August to December 2015. Based on data from the Solar and Heliospheric Observatory (SOHO) satellite and the Royal Observatory of Belgium, solar spot and flare occurrences during this period are shown in Figure 8 [Figure 8: see original paper]. The figure reveals no significant changes in sunspot and flare numbers, with sunspot counts at moderate levels in the long-term cycle, indicating relatively stable solar cosmic ray events in LUT images during this period.

Solar wind consists of plasma composed of electrons and ions (primarily protons) that persists on the lunar surface regardless of solar illumination [3-5]. Quiet-period solar wind has an average velocity of approximately 400 km/s [14], with a typical timescale of 3-4 days for solar wind particles to reach the lunar surface. LUT image acquisition during the eclipse lasted only 2 hours and 27 minutes, far shorter than the solar wind particle arrival timescale, making it difficult to detect Earth' s geometric shielding effects on solar wind particles through our analysis.

LUT images from the lunar surface contain numerous high-brightness, large-area cosmic ray events with morphologies similar to stellar images. Statistical analysis of these cosmic ray event probabilities can provide data support for lunar radiation environment research. Moreover, LUT experienced only this single complete lunar eclipse during its sky survey mission on September 28, 2015. This paper employs astronomical position calibration methods tailored to cosmic ray morphological characteristics in LUT images, enabling precise discrimination between cosmic ray events of specific brightness and stellar images.

Our analysis of 230 sky survey frames captured by LUT during the September 2015 eclipse identified 29,931 cosmic ray events with connectivity $ 4andbrightnessexceeding5timesthebackgroundfluctuation.Statisticalanalysisyieldedanaveragecosmicray per frame during the eclipse, with no variation in cosmic ray event probability during the eclipse, indicating no change in the lunar radiation environment.

For comparison, we identified and extracted cosmic ray events of specific brightness from dark field images captured monthly by LUT in August and October-December 2015. Normalized to 30-second exposures, dark field images yielded average cosmic ray event counts of 119.92 ($±6.37),117.00(±10.90),118.61(±8.94),and123.90(±$8.92), respectively. These values are consistent with eclipse counts within error ranges, demonstrating that Earth' s geometric shielding had no significant effect on the lunar radiation environment.

Finally, we discuss our results from the perspectives of galactic cosmic rays, solar cosmic rays, and solar wind particles. Galactic cosmic rays are essentially isotropic in interplanetary space, and Earth' s magnetospheric shielding does not affect the lunar radiation environment, so lunar eclipse occurrence does not cause significant changes in lunar galactic cosmic ray events. Solar cosmic rays bombard the lunar surface only during solar flare eruptions, and solar flare activity remained stable during the eclipse, resulting in steady solar cosmic ray events in LUT images. For solar wind particles, their arrival timescale at the lunar surface far exceeds the LUT image acquisition duration during eclipse, preventing detection of Earth's geometric shielding effects on solar wind particles through our cosmic ray event analysis.

Unfortunately, since LUT did not encounter any intense solar eruption events during its mission, we lost the opportunity to study whether Earth' s geometric shielding during solar eruptions affects the lunar radiation environment through LUT data analysis. This paper does not discuss this scenario in depth.

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Note: Figure translations are in progress. See original paper for figures.