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Lunar cosmic ray radiation environments during Luna and Lunar Reconnaissance Orbiter missions

Jongdae Sohn [a], Suyeon Oh [b], Yu Yi [a,*]

[a] Department of Astronomy and Space Science, Chungnam National University, Daejeon, South Korea
[b] Department of Earth Science Education, Chonnam National University, Gwangju, South Korea

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Abstract

The RV-2N-series instruments onboard Luna missions and the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument onboard Lunar Reconnaissance Orbiter (LRO) were designed to characterize the global lunar radiation environment and its biological impacts by measuring cosmic ray (CR) intensity. In this study, we have shown that the RV-2N-series instruments onboard of Russian Luna missions and the CRaTER reliably detect both background CRs and solar proton events (SPEs) in the lunar radiation environment using the proton intensity measured by the RV-2N-series onboard Luna missions out of the Russian Luna program for the exploration of the Moon (November 1970–August 1975) and the CR intensity on the Moon observed by the CRaTER (June 2009–March 2011). Those were compared with the CR intensities observed by neutron monitors (McMurdo, Thule, Oulu) on the Earth. The sunspot number is used as the index of solar activity (NOAA National Geophysical Data Center). As a result, the background CR intensities on the Moon turned out to have a good anti-correlation with the solar activity. We have also identified the proton intensity increasing events on the Moon which have the similar profiles to those observed by neutron monitors on the Earth. Most of these events show the significant increase of proton intensities in the lunar radiation environment when the SPEs associated with solar eruptions are verified. Therefore, most of the proton intensity increasing events are associated with the energetic solar particles in the lunar environment.

Keywords: Cosmic ray; RV-2N-series; Solar activity; CRaTER; CR intensity

1. Introduction

The RV-2N-series instruments onboard of Russian Luna missions (Luna 17, 19, 21, and 22) were designed as a monitor of charged particles traveling in the interplanetary space. They were delivered by a robotic rover (Lunokhod 1 and 2) in Luna 17 and Luna 21 missions. In 19 and 22 missions, they gathered the data by orbiting the Moon (Karachevtseva et al., 2013; Chuchkov et al., 1975; Vernov et al., 1977). The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument onboard Lunar Reconnaissance Orbiter (LRO, Tooley et al., 2010) was designed to identify the global lunar radiation environment and its biological impacts. The CRaTER investigates the lunar and deep space radiation environments (solar energetic protons (SEPs) and galactic cosmic rays (GCRs)) and the response of tissue equivalent plastic (TEP) to radiation and makes the map of radiation reflected from the lunar surfaces. The CRaTER also measures the effects of ionizing energy loss in matter due to penetrating through silicon solid-state detectors and the TEP (Spence et al., 2010).

Cosmic ray (CR) intensity is modulated in various timescales due to solar activity in the heliosphere. Forbush

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* Corresponding author.
E-mail address: euyiyu@cnu.ac.kr (Y. Yi).

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(1954) was the first one who showed that CRs are anti-correlated with solar activity. The CR intensity suddenly changes due to the solar eruptions such as solar flares and coronal mass ejections (CMEs) or the interactions with the Earth's magnetosphere. The representative variations of CR intensity are Forbush decrease (FD) with the sudden decrease (Forbush, 1937) and Ground Level Enhancement (GLE) events with the sharp and short-lived increase (Forbush, 1946).

Solar cosmic rays have attracted considerable interest since their discovery in the early 1940s (Forbush, 1946). Those are called solar energetic particles (SEPs). They consist of protons, electrons, helium ions, and high charge and energy (HZE) ions with energy ranging from a few tens of keV–GeV. SEPs have a strong influence on spacecraft systems as well as spacecraft crews as a potential threat. The study of SEPs helps to understand the particle accelerations near the Sun and in the inner heliosphere, in relation to solar flares, coronal mass ejections (CMEs), solar wind structures (Bazilevskaya, 2005). Recently, Oh et al. (2010) suggested that the association with Ground Level Enhancement (GLE) is determined by the flux in GOES high-energy differential channel. When the solar proton event (SPE) shows the significant increase in flux of GOES high-energy differential channel, it is associated with GLE. The main purpose of this study is to show that the RV-2N-series instruments onboard of Russian Luna missions and the CRaTER reliably detect both background CRs and solar proton events (SPEs). SPEs can be verified by the proton intensity increasing events on the Moon.

2. Data and methods

The RV-2N-series onboard Luna 17, 19, 21 consist of three sensors: a gas-discharge counter D1 of the STS-5 series, and two SSD (Si) detectors: D2 and D3 of ~35 μm thickness. The RV-2N-series onboard Luna 17 and 21 are mounted on the robotic rovers of Lunokhod 1 and Lunokhod 2, respectively. Luna 22 carries four sensors: one gas-discharge counter D1 of the STS-5 series, and three SSD (Si) detectors: D2, D3 and D4 of ~50 and ~300 μm thicknesses. The spacecraft memory is used for the data storage; there are various time resolutions such as about 22 min, 1 h, and 1 day. All sensors measure proton intensity continuously. However, there exist short, discontinuous, and irregular time intervals as well as missing data in the Luna data. Thus, the data of protons (D1 channel: $E > 30$ MeV) were converted to daily averaged data for the background CR intensity. Table 1 explains the information on Luna data used in this paper. As shown in Table 1, The RV-2N-series instruments onboard of Luna missions monitor charged particles traveling the lunar radiation environment.

The CRaTER data consist of three levels such as primary science, secondary science, and house-keeping parameters. We use the data of Level 2 secondary science (detector singles count rates, configuration, spacecrafts position) provided from Planetary Plasma Interactions (http://ppi.pds.nasa.gov). The CRaTER produces the daily file with one second resolution. Daily files report the number of 'singles' (silicon detector; D1, D2, D3, D4, D5, and D6) as well as the number of 'good', 'rejected', and 'total' records observed by the CRaTER during the monitoring period. We use the total count rates via six channels ($E > 10$ MeV) from June 2009 to March 2011. The count rates are converted to daily averaged data for the background CR intensity.

In order to examine the variation of CR intensity in the lunar radiation environment, we compare the CR intensities observed by lunar missions and the sunspot number (NOAA National Geophysical Data Center) is used as the index of solar activity. Using the solar flare list and solar proton event list at NOAA Space Environment Services Center (SESC), we have identified the proton increasing events associated with SPEs. As the reference of variation in CR intensity, we have used the CR data observed by neutron monitors on the Earth (Climax, McMurdo and Thule neutron monitors). They have small cutoff rigidities close to 0 GV and can detect the low energy parts of CR from the space. To identify the proton intensity increasing event on the Moon associated with GLE on the Earth, we used the GLE list of Oulu neutron monitor (http://cosmicrays.oulu.fi/GLE.html). The proton intensities in the lunar environment are compared with the background CR intensities and the proton intensity increasing events associated with SPEs.

3. Results

Fig. 1 shows the time profiles of background CR intensity measured by the RV-2N-series onboard Luna missions on the Moon, the CR intensity at McMurdo neutron monitor on the Earth, and the sunspot number from January 1964 until December 1975. The time profile of background CR intensity in the lunar radiation environment is similar to the CR intensity of McMurdo neutron monitor on the Earth. Similar to the CR intensities on the Earth, the background CR intensities on the Moon have a good anti-correlation with the sunspot numbers.

As in Figs. 1 and 2 compares the CR intensities measured by the CRaTER onboard LRO and observed by neutron monitors on the Earth (McMurdo and Thule neutron monitors) with the solar activity from January 2009 until March 2011. The profiles of CR intensities on the Moon and the Earth show a similar trend. They also show a good anti-correlation with the sunspot number related to the solar activity.

We could confirm the similarity of the time profiles for the background CR intensity at the lunar radiation environment and those for the CR intensity on the Earth. The time profiles of the background CR intensities at the lunar radiation environment have a good correlation with those on the Earth. The background CR intensities on the Moon have a good anti-correlation with the solar activity.