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Lightning-induced neutrons as a possible source of charged particles in the Earth's inner radiation belt

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Key Points:

- The possibility of lightning-induced neutrons as a source of charged particles in the Earth's inner radiation belt is proposed.
- The methods for determining the contribution of lightning neutrons to charged particles in the inner radiation belt are summarized.

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Abstract: The Van Allen radiation belts are doughnut-shaped zones surrounding Earth, filled with highly energetic charged particles whose sources or loss mechanisms have been investigated for decades. As for the inner belt, cosmic ray albedo neutron decay (CRAND), radial diffusion, and local acceleration have been considered principal sources of electrons, whereas protons are predominantly from CRAND and solar protons. In this article, lightning-induced neutrons from Earth's upper atmosphere are suggested as a possible source of protons and electrons in the inner radiation belt. These terrestrial neutrons can contribute to the inner belt population by undergoing nuclear decay. Several approaches are proposed and discussed to evaluate the potential contribution of lightning-induced neutrons to the inner belt, including magnitude estimation, Monte Carlo simulations, and *in situ* observations. This article discusses some avenues of further study to determine the contribution of lightning-induced neutrons to the inner radiation belt.

Keywords: Van Allen radiation belts; cosmic ray albedo neutron decay (CRAND); lightning; neutrons

1. Introduction

At the end of the 1950s, from Explorer I spacecraft observations, James Van Allen discovered the presence of elevated fluxes of charged particles enveloping the Earth in what are now known as the Van Allen radiation belts (Van Allen et al., 1958). These belts are composed of energetic electrons (~100 keV to several MeV) and ions (~100 keV to hundreds of MeV) trapped in the magnetosphere, occupying a spatial range from $1.1 < L < 7\ R_E$ (Earth radii) (Van Allen and Frank, 1959). They are divided into inner and outer radiation belts according to their altitude. The inner belt is characterized by a dense population of protons (10–100 MeV) and electrons (tens to hundreds of keV) within the bounds of $1.1 < L < 2.5$, a region historically regarded as comparatively stable (Williams and Smith, 1965; Pfitzer and Winckler, 1968). This stability is in stark contrast to the notably variable outer belt (Arnoldy et al., 1960; Rothwell and McIlwain, 1960; Craven, 1966; Jelly and Brice, 1967).

The origins of particles in the inner radiation belt have been extensively investigated (Li YX et al., 2023, and references therein). Various mechanisms, such as cosmic ray albedo neutron decay (CRAND) (e.g., Singer, 1958; Li XL et al., 2017; Xiang Z et al., 2019; Zhang K et al., 2019), injection from the outer radiation belt via radial diffusion (e.g., Lyons and Thorne, 1973; Zhao H and Li X, 2013), and local acceleration (e.g., Zhao H et al., 2014; Zhang ZX et al., 2021b), have been identified as principal sources of electrons in the inner belt. Specifically, the CRAND mechanism involves the production of neutrons generated during nuclear interactions between galactic cosmic ray (GCR) particles and the Earth's atmosphere, which then decay into protons, electrons, and antineutrinos on a time scale of about 15 min (Pattie et al., 2018; Serebrov et al., 2018). These decay products are believed to contribute to the inner belt. Observations of electrons from the Colorado Student Space Weather Experiment (CSSWE) CubeSat have confirmed that CRAND electrons dominate at the inner edge of the inner belt (Li XL et al., 2017), with the neutron density in near-Earth space estimated as $2 \times 10^{-9}/\text{cm}^3$ in their analysis. Fluxes of neutrons generated in the atmosphere have also been provided by other models and measurements (e.g., Morris et al., 1995; Selesnick, 2015; Selesnick and Looper, 2022). Notably, Xiang Z et al. (2020) developed a drift-collision-source model, which revealed that CRAND is a substantial source of hundreds of keV trapped electrons at $L <$

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1.3 during quiet periods. Radial diffusion has long been recognized as one of the most crucial acceleration mechanisms for radiation belt electrons (Lyons and Thorne, 1973; Zhao H and Li X, 2013). Injections of keV (Turner et al., 2015; Su YJ et al., 2016) and MeV (Li X et al., 1993; Loto'aniu et al., 2006; Claudepierre et al., 2017; Kim et al., 2021) electrons from the outer radiation belt through radial transport have been extensively analyzed.

The main sources of protons in the inner radiation belt include CRAND (Dragt et al., 1966; Abel and Thorne, 1998) and interplanetary solar protons (Selesnick et al., 2007, 2010, 2014). Particularly at low L ranges, solar protons and protons generated by CRAND are more prone to being trapped, whereas at higher altitudes, protons may also diffuse inward and amalgamate with preexisting trapped protons. Over extended periods, the proton density in the inner belt remains notably stable, and its anticorrelation with solar activity on long time scales has been widely documented through observations from the National Oceanic and Atmospheric Administration (NOAA) Polar Orbiting Environmental Satellites (POES), the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX), the Hisaki satellite, and the Van Allen Probes (Miyoshi et al., 2000; Tu WC et al., 2010; Selesnick and Albert, 2019; Li XL et al., 2020; Yoshioka et al., 2021). However, inner belt protons can show variations on shorter time scales attributable to geomagnetic activity, possibly through the action of various loss mechanisms (Selesnick et al., 2010; Zou H et al., 2011, 2015; Engel et al., 2015; Zhang ZX et al., 2021a). These mechanisms include magnetic field curvature scattering (Hudson et al., 1995; Young et al., 2008; Selesnick et al., 2010), elastic Coulomb scattering with the neutral atmosphere (Looper et al., 2005; Sutton et al., 2005), and source loss induced by CRAND (Albert et al., 1998).

As discussed previously, CRAND is believed to play a pivotal role in serving as a source of protons and electrons in the inner radiation belt. However, observations in recent years have revealed that a large number of neutrons can be generated during lightning events (e.g. Shah et al., 1985; Babich and Roussel-Dupré, 2007; Carlson et al., 2010; Martin and Alves, 2010; Enoto et al., 2017) and may reach near-Earth space (e.g., Bratolyubova-Tsulukidze et al., 2004; Paiva, 2009; Drozdov et al., 2010b; Grigoriev et al., 2010; Drozdov and Grigoriev, 2013a). Presently, photonuclear reactions between atmospheric nuclei and high-energy gamma rays generated during lightning events have been suggested as a theoretically plausible neutron production mechanism (Babich, 2006, 2007, 2019; Babich et al., 2010a, b, 2014; Carlson et al., 2010; Drozdov and Grigoriev, 2013b; Toropov et al., 2013; Dwyer et al., 2015; Enoto et al., 2017). Nevertheless, experimental differentiation between the radiation signatures of photonuclear reactions and nuclear fusion (deuteron–deuteron reactions; Fleischer, 1975; Shah et al., 1985; Shyam and Kaushik, 1999; Ishtiaq et al., 2016) is challenging and has led to an ongoing controversy regarding the generation mechanism of lightning neutrons. Lightning neutrons have been observed by some ground-based detectors (e.g., Shah et al., 1985; Chilingarian et al., 2010; Martin and Alves, 2010; Toropov et al., 2013; Ishtiaq et al., 2016; Enoto et al., 2017). Extensive theoretical calculations and Monte Carlo simulations have been conducted to study the spectra of neutrons generated in the atmosphere by GCRs (Armstrong et al., 1973; Clem et al., 2004; Lei F et al., 2004, 2006; Sato and Niita, 2006; Selesnick et al., 2007; Cheminet et al., 2013; Kole et al., 2015; Nesterenok and Naidenov, 2015; Pazianotto et al., 2018) and lightning (Babich et al., 2010a, b; Carlson et al., 2010; Malyshkin et al., 2010; Drozdov et al., 2013). Theoretical analysis by Grigoriev et al. (2010) revealed that the flux of lightning neutrons arriving at a specified orbital altitude is critically dependent on the altitude of the neutron source.

In addition to simulations, numerous neutron detection missions and instruments have been deployed in near-Earth space over recent decades, such as detectors onboard U.S. Space Shuttle flights (Keith et al., 1992), the Mir orbital station (Dudkin et al., 1990, 1992; Lyagushin et al., 2001), the International Space Station (ISS; Matsumoto et al., 2001), the Kolibri-2000 satellite (Klimov et al., 2005), and the Compton Gamma-Ray Observatory (CGRO) spacecraft (Gehrels et al., 1993, 1994). After comparing the global distribution of lightning flashes observed by the Optical Transient Detector (Christian et al., 1999) and the neutron flux distribution in low Earth orbit measured by detectors on the Mir orbital station (Dudkin et al., 1992), ISS (Matsumoto et al., 2001), and Kolibri-2000 satellite (Klimov et al., 2005), Bratolyubova-Tsulukidze et al. (2004) observed a longitudinal dependence in the spatial distribution of high background neutron fluxes and proposed that lightning neutrons may contribute to the neutron flux at $L < 1.2$. Open questions on the lightning neutrons have led to several new satellite mission proposals, including a new space experiment presented by Drozdov et al. (2010a) aiming to detect thunderstorm neutrons at various orbital altitudes and map their distribution in correlation with thunderstorm activity. In addition, a new multi-satellite project named Universat-SOCRAT was proposed by Panasyuk et al. (2019) to study transient phenomena in the upper atmosphere. It will incorporate neutron detection as part of its objectives.

An important question regarding the potential role of lightning neutrons as a source of neutrons in near-Earth space is the following: What contributions do lightning neutrons (compared with the total neutron flux) make to the population of protons and electrons within the inner radiation belt? Ways to address this question are discussed in the following section.

2. Estimating the Contribution of Lightning Neutrons to Inner Radiation Belt Protons and Electrons

In this section, we discuss several ways to determine the proportion of lightning neutrons (compared with the total neutron flux) that contribute to the population of inner radiation belt protons and electrons.

2.1 Magnitude Estimation

As a first step, a preliminary estimation should be undertaken. We refer to a number of previous estimates of lightning neutron flux that have been made based on theoretical calculations, simulations, and observations. In 1985, Shah et al. (1985) reported the first experimental evidence of lightning neutrons and estimated that 10^7–10^{10} neutrons would be produced per stroke. A neutron yield estimate of ~10^{15} per upward atmospheric discharge was obtained from theoretical calculations carried out by Babich (2006, 2007) and Babich and Roussel-Dupré (2007). Similarly, magnitudes of 1.6×10^{14} to 1.1×10^{15} per upward atmospheric discharge were obtained from numerical simulations (Babich et al., 2008). According to Carlson et al. (2010), approximately 10^{12} neutrons are produced per event by terrestrial gamma-ray flashes (TGFs), a millisecond-duration gamma-ray burst phenomenon that is believed to be associated with lightning. However, more recent observations of lightning neutrons present a serious discrepancy with the present theory of photonuclear neutron generation associated with lightning (Gurevich et al., 2012). In this study, we suggest that the flux of lightning neutrons is actually three orders of magnitude higher than the results of previous simulations or theoretical calculations in which the intensity of gamma-ray flashes is used as a proxy for neutron generation. Thus, perhaps the mechanism by which lightning neutrons are produced through photonuclear reactions needs further scrutiny to explain this discrepancy.

Global flash rates of lightning events have been estimated, calculated, or observed for decades. As early as 1925, Brooks (1925) inferred an average global flash rate of 100 flashes fl/s, and estimations of this order of magnitude persisted into the 1980s. Measurements of the global flash rate improved over the ensuing few decades, with the development of detector technology and satellite observations. Using radio frequency receivers on the ISS-b satellite, Kotaki and Katoh (1983) obtained an estimation of 63 fl/s for the global average flash rate. Mackerras et al. (1998) analyzed data from ground-based observations, the ISS-b satellite, and the Defense Meteorological Satellite Program nighttime lightning observations (Orville and Henderson, 1986) and obtained a global average flash rate of 65 fl/s. Observations from the Optical Transient Detector (OTD) onboard the MicroLab-1 satellite suggested the occurrence of approximately 44 ± 5 lightning events per second around the Earth (Christian et al., 2003). This number changed to 46 fl/s when combining OTD data with Lightning Imaging Sensor data taken from the Tropical Rainfall Measuring Mission satellite (Cecil et al., 2015).

According to these data, a reasonable estimate of up to 4.6×10^{19} (46 lightnings/s times 10^{18} neutrons/lightning) lightning neutrons per second can be derived, assuming that TGFs are indeed associated with lightning events. Assuming isotropic neutron sources distributed uniformly around the Earth at an altitude h of 10 km (Xu W et al., 2012), the proportion r of lightning neutrons escaping into space can be calculated via

$$r = \frac{4\pi - \Omega}{4\pi}, \tag{1}$$

where

$$\Omega = \iint \mathrm{d}\Omega = \int_0^{2\pi} \int_0^{\theta_{\max}} \sin\theta \mathrm{d}\theta \mathrm{d}\varphi \text{ and } \sin\theta_{\max} = \frac{R_\mathrm{E}}{R_\mathrm{E} + h}, \tag{2}$$

in which Ω represents the solid angle obscured by the Earth and $\theta_{\max}$ denotes the maximum angle at which the lightning neutron source at an altitude h can be obstructed by the Earth, as illustrated in Figure 1.

Given sufficient time for the majority of neutrons to reach a specified altitude (Grigoriev et al., 2010) — and neglecting attenuation by neutron decay — it can be deduced that approximately 50% of lightning neutrons will successfully reach the altitude of the inner radiation belt, providing a flux of approximately 2.3×10^{19}/s.

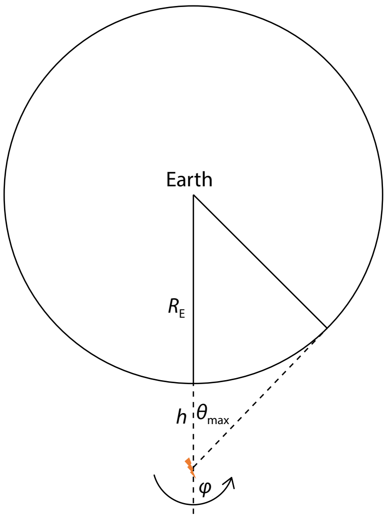

Figure 1. Diagram of an isotropic lightning neutron source with an altitude of h.

As for neutrons generated by GCRs, extensive simulations have been carried out to elucidate their characteristics. For example, the QinetiQ atmospheric radiation model (QARM; Lei F et al., 2004, 2005) has been used for this purpose in the European Cooperation for Space Standardization (ESSC) standards (ECSS, 2008). The results derived from the QARM agree with various experimental results (Ait-Ouamer et al., 1988; Morris et al., 1995; Lei F et al., 2004, 2005) and other Monte Carlo simulations (Armstrong and Colborn, 1992; Fioretti et al., 2012; Kole et al., 2015). According to the QARM result (ECSS, 2008), the integral flux of GCR-induced neutrons is approximately 3.1×10^{18}/s at solar maximum conditions with a cutoff rigidity of 5 GV, corresponding to the radiation environment at an altitude of 500 km (Galgóczi et al., 2021). Evidently, the estimation indicates that the population of lightning neutrons is about an order of magnitude higher than GCR-induced albedo neutrons at most.

2.2 Monte Carlo Simulation

Monte Carlo simulations present a viable approach to addressing this inquiry comprehensively. Extensive Monte Carlo simulations have been conducted to study lightning-induced neutrons. For instance, Drozdov and Grigoriev (2013b) compared the spectra of lightning neutrons and albedo neutrons by using simulations, and they found a discrepancy showing that the albedo spectrum becomes more distinct with increasing lightning altitude. Through simulations, Carlson et al. (2010) predicted an average of ~10^{12} neutrons produced per TGF; they also provided the energy, time, and space distributions of lightning-induced neutrons reaching ground and satellite altitudes. Furthermore, Malyshkin et al. (2010) simulated the altitude distribution of lightning-induced neutrons by using the improved TGF-source characteristics and discussed the influence of the neutron source structure on neutron flux on orbit.

Achieving more realism in simulation results necessitates an enhanced dataset pertaining to lightning observations. The characteristics of photons, such as their spectral characteristics, altitude of occurrence, and intensity, are intricately linked to the specific nature of lightning events. Therefore, a more comprehensive understanding of these aspects would contribute substantially to the fidelity of the simulations. Moreover, it is crucial to acknowledge that neutron generation during lightning may be influenced by additional physical processes beyond photonuclear reactions. As such, incorporating a nuanced consideration of these diverse mechanisms in the simulations is imperative for a thorough exploration of the neutron generation dynamics associated with lightning events. The refinement of simulations through continuous integration of updated observational data and a nuanced understanding of the multifaceted processes involved is essential for advancing the accuracy and applicability of the results obtained.

Initiated with initial lightning photon point sources emitting around the Earth, these simulations can incorporate an energy spectrum referenced from pertinent calculations or observational data. The simulation framework should encompass the Earth's atmosphere, magnetic field, water-rich clouds, and observed global distributions of lightning events, as documented in studies such as those by Molinié and Pontikis (1995) and Christian et al. (2003), along with other influential factors to ensure a comprehensive and accurate representation of the scenario. Furthermore, it is imperative to include GCRs in the simulations for comparative analysis. Ultimately, such simulations can yield the flux proportions of neutrons reaching the altitude of the inner radiation belt, differentiating contributions from various sources and thus offering a more nuanced understanding of the relative impact of lightning neutrons in comparison with other factors.

2.3 *In situ* Observations in Space

After the aforementioned considerations, *in situ* observations should offer a conclusive determination. Diverse methodologies for observing lightning can be deployed at various altitudes, with some of these methodologies already being operational (e.g., Shah et al., 1985; Shyam and Kaushik, 1999; Bratolyubova-Tsulukidze et al., 2004; Tsuchiya et al., 2007, 2012; Chilingarian et al., 2010, 2012a, b, 2013, 2016; Tavani et al., 2011; Kuroda et al., 2016; Bowers et al., 2017). First, ground-based detectors are capable of identifying and distinguishing lightning neutrons that reach the Earth's surface. These detectors can estimate the flux emitted away from the Earth by analyzing neutron signals detected on the ground. Second, measurements conducted via balloon platforms can furnish valuable information regarding lightning neutrons at different altitudes, offering a convenient means of discerning between various types of lightning events. Third, satellites or CubeSats, such as Weiming-1, which was developed by Peking University and Shandong University and was launched in January 2024, have the capacity to detect neutrons at higher altitudes in near-Earth space. Under the anticipated conditions, the average flux of lightning neutrons reaching orbit can be ascertained by subtracting the "background" neutron flux (induced by GCRs) from the total observed flux. The determination of this background distribution can be achieved by referencing global lightning distribution observations, thereby providing a robust baseline for interpreting the observed neutron flux in near-Earth space. Moreover, individual event analyses will be applicable with the higher detection efficiency of neutrons in the future, instead of the statistical analysis of background.

3. Discussion

The measurement fluxes of neutrons in near-Earth space are in good agreement with simulations of GCR-induced neutrons used in the aforementioned estimation. However, the measurement neutron fluxes contain neutrons originating from all theoretical sources around the Earth, including but not limited to GCR-induced neutrons, lightning neutrons, and even secondary neutrons produced during interactions between high-energy particles and the satellites or detectors themselves. Hence, the simulation flux of GCR-induced neutrons is worth further examination and calibration.

Previous studies (e.g., Qin MR et al., 2014; Lin RL et al., 2020) have found that the inner belt proton flux varies with the solar activity cycle, which was thought to be partly due to the anticorrelation between CRAND and solar activity intensity, when CRAND was considered a main source of inner belt protons. However, the inverse correlation between lightning frequency and solar activity intensity has also been found in some statistical studies (e.g., Brooks, 1934; Stringfellow, 1974; Scott et al., 2014). Related atmospheric mechanisms, such as the cosmic ray-cloud seeding effect (Svensmark and Friis-Christensen, 1997; Marsh and Svensmark, 2000; Carslaw et al., 2002), the influence of aerosols (Shi Z et al., 2015) or clouds (Thomason and Krider, 1982), and other meteorological factors (Schlegel et al., 2001) on lightning, have been discussed as well. This means the inverse correlation between the inner belt proton flux and solar activity intensity does not rule out the possibility of lightning neutron decay as one source of inner belt particles.

Regarding calculation of the proportion of lightning-induced neutrons based on *in situ* observations, an initial approach involves comparing the global distribution of lightning activity with the neutron flux, as mentioned at the end of Section 2.3. This is because lightning-induced neutrons display a strong temporal correlation with lightning events. Subsequently, the neutron flux in regions with low lightning activity can be considered as background neutron flux, primarily induced by GCRs. The lightning-induced neutron flux can then be determined by subtracting the background flux from the total neutron flux observed in near-Earth space. Furthermore, it is anticipated that, with continued advances in both the understanding of lightning physics and neutron detection technologies, distinguishing between lightning- and GCR-induced neutrons based on differences in their energy spectra will become feasible. This will allow for a more accurate estimation of the proportion of lightning-induced neutrons.

4. Summary

Previous research progress on the sources and loss mechanisms of particles in the inner radiation belts is briefly summarized. Lightning-induced neutrons as a possible source of charged particles in the inner radiation belt are proposed in this article. Several approaches for determining the potential contribution of lightning-induced neutrons to inner belt protons and electrons are discussed. Magnitude estimation results show that lightning neutrons are expected to account for a considerable portion of the neutron flux in near-Earth space. Monte Carlo simulations can further refine expectations for lightning neutron contributions. Satellites such as Weiming-1 and the following missions are expected to perform a definitive resolution one way or the other via direct *in situ* observations in near-Earth space.

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