Repetitive Occurrence of Intense and Gigantic Polar Rain Aurora

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Auroras are luminous phenomena that occur when charged particles precipitate into the upper atmosphere (altitude ~100-300 km) along the magnetic field lines, where they excite and subsequently de-excite atmospheric oxygen atoms and nitrogen molecules, emitting light. The electrons responsible for auroras do not always come directly from the Sun but are often accelerated in the Earth's magnetotail (plasma sheet). These electrons precipitate into the polar region along closed magnetic field lines, forming a ring-shaped auroral oval centered on the magnetic pole. As a result, during moderately disturbed conditions, auroras are absent in the polar cap region. However, on December 25, 2022, during an interval of exceptionally low solar wind density (~0.5 cm^{-3} or lower), a large auroral structure covering the entire polar region was observed (Hosokawa et al., 2024). The unique mechanism causing this phenomenon was suggested to be the polar rain precipitation, generated by a direct influx of solar wind electrons into the polar ionosphere. This type of aurora is observed near the geomagnetic poles and is called polar rain aurora (PRA: Zhang et al., 2007). High-energy (~keV) electrons in the solar wind, known as "Strahl," directly precipitate along open magnetic field lines, producing spatially uniform emissions in the polar cap. Under typical solar wind conditions, auroras do not appear in the polar cap. PRA becomes evident only when the solar wind density is exceptionally low and the Interplanetary Magnetic Field (IMF) is directly connected to the Earth's magnetic field. Because PRA is an extremely rare phenomenon, with fewer than ten reported cases, it has not been widely recognized as a major auroral category.

To investigate the characteristics and origin of this unique aurora, we conducted a long-term statistical analysis using SSUSI data from the DMSP F16, F17, and F18 satellites. The study covers the period from 2005 to 2023. We analyzed trans-polar auroral images obtained in the Lyman-Birge-Hopfield short-wavelength channel (140-150 nm) through line-scanning observations in imaging mode. The DMSP satellites operate in a Sun-synchronous polar orbit at an altitude of ~850 km, completing a full orbit in ~97 minutes. During the analysis period, at least two of the three DMSP satellites were operational simultaneously, allowing us to obtain large-scale images of auroras in the polar cap at ~50-minute intervals. From the dataset, we identified PRA events characterized by intense, widespread emissions in the polar cap. We examined their occurrence frequency, hemispheric distribution, and corresponding solar wind plasma and IMF conditions using NASA's OMNIWeb database. As a result, we detected 14 PRA events over the past two decades, ranging from weak, localized occurrences to strong events covering the entire polar cap. Furthermore, for the first time, we identified a repetitive occurrence of PRA with a cycle of ~25-30 days. PRA events were particularly concentrated during periods of significantly reduced solar wind density, and their ~27-day recurrence pattern suggests a potential relationship with Corotating Interaction Regions (CIR). Notably, two past PRA cases reported by Foster et al. (1976) also exhibited the same periodicity. Additionally, our statistical analysis confirmed that the IMF_x component (aligned with the Sun-Earth direction) influences the hemispheric asymmetry in PRA occurrence. However, PRA was not always observed even when the solar wind density was low, indicating that low-density conditions alone are not a sufficient criterion for PRA occurrence. We further examined the potential relationship between PRA and the IMF B_x/B_y angle, which determines the degree of perpendicular IMF entry into the magnetosphere. However, no clear correlation was found. Future studies will focus on identifying the necessary and sufficient conditions for PRA occurrence.

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