

Study of Low-Latitude Aurora and Aurora-Like Red Emissions over India during Rising Phase of Solar Cycle 25

Soumya Yadav, A.K. Singh 

Department of Physics, University of Lucknow, Lucknow-226007, India

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Abstract. Auroras, typically associated with polar regions, are spectacular manifestations of solar wind-magnetosphere interactions. However, under extreme solar conditions, these luminous displays can extend to mid- and low-latitudes, offering unique opportunities to study the Sun-Earth connection. This study examines the solar wind and geomagnetic storm conditions associated with rare low-latitude aurora or aurora-like optical emissions observed over India. We analysed recent visual observations, particularly from Hanle in Ladakh. Our methodology integrates historical records along with recent observations, ground-based imaging, and its relationship with geomagnetic indices such as K_p , Dst , and solar wind parameters to assess the geophysical conditions that facilitate low-latitude auroral visibility. Historical auroras, such as the one witnessed in Mumbai during the severe geomagnetic storm of February 1872, underscore the profound influence of extreme solar activity. Recent sightings during solar cycle 25, notably on 23 April 2023, 5 November 2023, 10 May 2024, 10 October 2024, and 1 January 2025 (according to UT), reveal a resurgence of such phenomena, often marked by vivid red auroras across northern India. These events were primarily driven by intense CMEs and solar flares, leading to significant magnetospheric disturbances. Our findings contribute to a refined understanding of low-latitude auroral processes, emphasize the need for continuous solar monitoring, and support the development of regional space weather forecasting models tailored to the Indian sub-continent.

KEY WORDS: Low-latitude aurora; IMF B_z ; Dst index; K_p index; Geomagnetic storm; CMEs

1 Introduction

Auroras, globally recognized as the Northern and Southern Lights, are spectacular natural light displays that primarily manifest within the high-latitude polar regions. These captivating phenomena are the direct consequence of complex interactions between energetic charged particles from the solar wind and Earth's magnetosphere and upper atmosphere [1]. When these particles, predominantly electrons and protons, are channelled along geomagnetic field lines towards the poles, they collide with atmospheric gases (oxygen and nitrogen atoms and molecules). These collisions excite the atmospheric constituents, leading to the emission of photons across various wavelengths, which produce the characteristic vibrant colours of the aurora, with green and red typically originating from oxygen atoms, and blue and purple hues from nitrogen. Auroras are most commonly observed in high-latitude regions located between 65° and 75° (auroral oval) geomagnetic latitude such as the Arctic and Antarctic [2]. This rarity stems from the geometry of Earth's magnetic field, which ordinarily provides a robust shield for lower latitudes against the direct impact of solar wind particles. However, during periods of intense geomagnetic storms, driven by powerful solar eruptions such as coronal mass ejections (CMEs) and solar flares, the magnetosphere can undergo significant compression and reconfiguration [3, 4]. This allows energetic particles to penetrate deeper into Earth's atmosphere along perturbed magnetic field lines, extending auroral displays far beyond their usual polar confines reaching as low as 30° – 35° latitude. Such low-latitude auroras are crucial indicators of extreme space weather events and offer invaluable insights into the global response of the magnetosphere and ionosphere to severe solar forcing. The Sun's activity follows an approximately 11-year cycle, characterized by fluctuations in sunspot numbers, solar flares, and CMEs [5, 6]. Solar Cycle 25, which began in December 2019, is currently approaching or at its solar maximum, a period anticipated to bring heightened solar activity and, consequently, increased opportunities to observe and study rare geomagnetic phenomena, including low-latitude aurora or aurora-like red emissions, with unprecedented clarity [7, 8].

The existing body of research on low-latitude auroras globally confirms their sporadic but profound significance. Numerous studies have documented instances of auroral displays extending to mid-latitudes, often directly correlated with the most powerful geomagnetic storms in recorded history. Beyond specific events in India, the scientific description of auroral phenomena has evolved over centuries. For instance, one of the earliest known scientific treatises on aurora borealis described the event of 10 September 1580, in Transylvania, providing detailed observations on its time, direction, shape, colour, and variability, and attempting to explain it through natural causes [9]. Such historical accounts from various parts of the world contribute to the broader understanding of auroral history and the long-standing human endeavour to comprehend these celestial dis-

plays. The Carrington Event of 1859 [10], a super geomagnetic storm that generated auroras visible even in tropical regions like Cuba and Hawaii, underscoring the potential global impact of extreme space weather. Similarly, the 1770 event saw widespread red auroras, notably documented in Japan, while the magnetic storm of May 1921 produced auroras observed at exceptionally low geomagnetic latitudes, including Apia, Samoa [11]. These historical records are indispensable for understanding the long-term variability of solar-terrestrial interactions and serve as crucial benchmarks for assessing the intensity of past solar activity. Regarding India which is typically outside the visible auroral zone, the literature is notably sparse due to its low geomagnetic latitude, only the brilliant auroral displays seen during the superstorm of February 4–5, 1872, were documented in history by Rao [12] in his work, making confirmed auroral sightings extremely uncommon. Despite having magnetically reliable data at Indian observatories (Colaba/Alibag), some significant storms, such as the Carrington Event (1859), the May 1921 storm, and the Halloween storms (October–November 2003), do not have confirmed visual evidence. This distinction highlights both the rarity of Indian auroral observations and the potential value of high-quality modern detections. More recently, contemporary papers by researchers like Vichare [13] have begun documenting recent sightings from high-altitude locations in northern India, particularly the Ladakh region, during 2023 and 2024, offering a modern perspective on these rare occurrences.

Despite these historical accounts and recent sporadic observations, a comprehensive analysis that systematically bridges historical and modern Indian auroral sightings remains largely unexplored. There is a distinct lack of detailed comparative studies that thoroughly evaluate the solar and geomagnetic conditions associated with both past and contemporary low-latitude auroras in India. Furthermore, the implications of these unique observations for refining space weather models specifically tailored to the Indian subcontinent, a region with rapidly expanding technological infrastructure vulnerable to space weather effects, are not yet fully elucidated. This paper is therefore significant for enhancing our understanding of low-latitude auroral mechanisms. The overarching purpose of this paper is to synthesize historical and recent low-latitude aurora observations in India, offering a unique perspective on solar-terrestrial interactions from a magnetically challenging region. Using archival sources, our research aims to fill these gaps by documenting and characterising recent aurora sightings in India during Solar Cycle 25, including their visual characteristics and observational contexts, the solar activity and geomagnetic storm intensity conditions of recent events, and identifying the solar and magnetospheric drivers responsible for low-latitude aurora or aurora-like red emissions in the Indian region.

Our methodology employs a multi-faceted approach, involving the meticulous analysis of archival records, contemporary observational data (e.g., from Hanle), and its association with space weather indices to precisely pinpoint the conditions precipitating these rare events. Our key findings highlight the confirmed,

although exceptional, nature of historical sightings, exemplified by the documented events from India, which serves as a testament to periods of extreme past solar activity. Crucially, observations during Solar Cycle 25 emphasize the increasing frequency and clarity of recent sightings, including prominent red auroras in May 2024 and January 2025 from Ladakh, validating the anticipated solar maximum. The study specifically highlights major events on 23 April 2023, 5 November 2023, 10 May 2024, 10 October 2024, and 1 January 2025, all characterized by intensified solar wind and dramatic magnetospheric reconfigurations. A commonality across these events is the consistent observation of red aurora. This research further delves into the primary drivers of low-latitude auroras, with particular emphasis on geomagnetic indices (Dst index and K_p index) and their association with coronal mass ejects (CMEs) and solar flares, while also discussing geomagnetic storm intensity and regional geophysical factors. The significance of these observations is profound and they enhance our understanding of low-latitude auroral mechanisms, validate space weather models specifically tailored for the Indian subcontinent, and underscore the imperative for continuous monitoring of solar activity and its terrestrial impacts. The primary goal of this study is not to replicate global analyses of individual geomagnetic storms, but rather to compare the geomagnetic and solar wind conditions associated with multiple low-latitude auroral or aurora-like optical events observed over India during Solar Cycle 25.

The data sources and methodology used in this paper are listed in Section 2. The historical records of low-latitude auroras are discussed in Section 3, and the analysis of recent observations during Solar Cycle 25 is discussed in Section 4. Conclusions are summarised in Section 5. By studying historical and modern data, this research brings understanding of auroral dynamics, offering new insights into one of nature's most remarkable phenomena.

2 Data Sources and Methodology

To investigate the scientific credibility of auroras in Ladakh, we took a multifaceted approach. We gathered geomagnetic indices (K_p and Dst), solar wind speed and interplanetary magnetic field (IMF) measurements via the OMNIWeb Explorer (<https://omniweb.gsfc.nasa.gov/form/dx1.html>). The data for CME speed, flare class, its solar source location and NOAA active region number are taken from CDAW data centre (https://cdaw.gsfc.nasa.gov/CME_list/). For ground-based observations, we collected visual reports and photographic evidence of auroras from both the Hanle Observatory where their instrumentation included 360-degree all-sky cameras and civilian observers in Leh and surrounding areas. We also reviewed local news reports listed on the IIA website (<https://www.iiap.res.in/articles/press-releases/>). All-sky camera (ASC) images are recorded in fish-eye projection and represent the sky in instrument coordinates. Mapping these images into magnetic latitude (MLAT) and magnetic local

time (MLT) requires detailed camera calibration parameters, including optical distortion characteristics and azimuth–elevation conversion, as well as assumptions regarding emission altitude. Since such calibration information is not available for all ASC datasets analysed in this study, a full geometric inversion was not performed. Consequently, the ASC images are used qualitatively to confirm the presence, morphology, and storm-time occurrence of optical emissions, while their geophysical context is established using geomagnetic indices and solar wind parameters.

3 Historical Low-Latitude Auroras

Historically, auroral activity has been reported at unusually low latitudes during powerful geomagnetic storms, frequently associated with significant solar eruptions and geomagnetic activity. The occurrence of Aurora Borealis in India is an extremely rare event, making recorded sightings particularly noteworthy and scientifically significant [12]. Modern research, while not directly about historical events, provides a contemporary scientific understanding of how extreme space weather conditions can lead to ionospheric disturbances and auroral phenomena extending to such low magnetic latitudes. The following major events serve as precedence for the observations discussed in this study:

3.1 Carrington event (1859)

The magnetic storm of 1–2 September 1859 stands as the most intense geomagnetic storm ever recorded. Auroral displays during the event were observed as far south as 23° magnetic latitude, including locations such as Hawaii and Santiago, Chile magnitude. The storm's estimated intensity reached an exceptional -1760 nT, a value supported by the magnetic field decrease of approximately -1600 nT recorded at the Colaba observatory in India [10, 14, 15]. However, no confirmed auroral sightings from the Indian subcontinent have been found in peer-reviewed historical records, despite the country's closeness to the equatorward edge of the auroral oval during such extreme conditions. Therefore, although the Carrington event, remains the benchmark in considering for extreme space weather conditions that impact India, its usefulness is derived from magnetometer standards rather than visual auroral confirmation. A number of variables, including the lack of systematic sky monitoring in 1859 and most intense auroral phases coincided with daytime local hours, when optical emissions would not have been visible to observers, may be responsible for the absence of optical accounts. This underlines the value of recent observations from Solar Cycle 25, where calibrated imaging allows clear documentation of auroral activity over India.

3.2 February 1872 storm

Similar in strength to the Carrington event, this storm featured widespread auroral displays across Asia. One of the earliest and most significant events was the severe magnetic storm of 4 February 1872. During this event, observers in Kolkata described a vivid red glow in the night sky, attributed to a powerful geomagnetic disturbance [12]. Uberoi [16] in his paper mentioned that Moos, who witnessed the aurora from Bombay in February 1872, classified the associated geomagnetic storm responsible for significant disruption to telegraph lines as “intense,” though he noted it was less severe than the historic 1859 event [17, 18]. This assessment was later confirmed by Lakhina [19], who analyzed observatory records and estimated the storm’s intensity to be approximately 1020 nT. The Aurora Borealis was brilliantly seen in India during this severe magnetic storm, with specific observations noted in low-latitude locations such as Bombay and Alibag, highlighting the very rare phenomenon of auroral visibility at such low magnetic latitudes. This event coincided with one of the most intense solar storms of the 19th century, highlighting the global impact of extreme solar activity. The visibility of auroras in India during this period underscores the potential for geomagnetic disturbances to extend auroral activity beyond traditional boundaries.

3.3 May 1921 storm

Another noteworthy historical event is the geomagnetic storm of May 1921, which caused widespread auroral displays in mid-latitude regions. On May 13th, a significant sudden commencement of 130 nT was observed at 13:11 GMT+4hr 51min “Bombay time” at the Alibag station in India (18.6°N, 72.9°E). Further intense storm activity was recorded after 22:00 on May 14th, with a 230 nT sudden commencement occurring at 22:15. During this period, the horizontal component (H) of the magnetic field went off-chart from 03:25 to 05:50 the following day, even with the use of a deflector magnet [11]. While this storm is widely regarded as one of the most disruptive of the century, no confirmed optical auroral sightings from India have been documented.

3.4 October–November 2003 (Halloween storms)

The October–November 2003 (Halloween storms) was a series of intense solar events that occurred during Solar Cycle 23. These storms were associated with several X-class solar flares, multiple CMEs, and GLE 67 (Ground Level Enhancement). On 28 October, an X17.2-class flare erupted from AR 486 (S16E08), launching a full halo CME at 2459 km/s. The shock arrived at Earth in less than 19 hours, causing a Dst of -363 nT. On 29 October, another X10-class flare from the same region launched a 2000 km/s CME, resulting in a Dst of -401 nT. Both events triggered intense geomagnetic storms, widespread auroras

at mid to low latitudes, and disruptions to satellites and radio communications. The strongest storm of the cycle occurred on 20 November, when AR 484, having rotated back as AR 501 (S03W18), produced a CME with a fully southward magnetic cloud. It resulted in a Dst of -472 nT, the most intense geomagnetic storm recorded during the cycle. These eruptions were among only 15 historical events with CME-driven shocks reaching Earth in less than 24 hours. With CME speeds exceeding 2000 km/s, and central disk origins, the Oct-Nov 2003 storms serve as benchmark events for extreme space weather forecasting and impact assessment [20]. India did not report any confirmed visual auroral sightings, despite the severity of these storms and their worldwide auroral impact.

Taken together, these historical examples demonstrate that although India lays far equatorward of the nominal auroral zone, intense geomagnetic disturbances can produce either direct low-latitude auroral visibility or geophysically significant storm-time red optical emissions under exceptional solar wind forcing. This historical context strengthens the plausibility of the recent Ladakh observations and motivates a focused examination of the Solar Cycle 25 events discussed in the next section.

4 Rare Low-Latitude Auroral and Aurora-Like Optical Events in Hanle, Ladakh: A Case Study of Solar Cycle 25

Solar Cycle 25, which began in December 2019, has brought renewed attention to auroral studies due to increased solar activity and its associated geomagnetic storms. In India, the Ladakh region has emerged as a focal point for observing rare low-latitude aurora or aurora-like red emissions. In remarkable and infrequent celestial occurrence, the Hanle region of Ladakh, India, witnessed visible auroral display during high solar activity particularly in 2023 and 2024. These events were significant because auroras are exceedingly rare at such low latitudes. Hanle is a village located in Ladakh, India, at an elevation of 14,764 feet above sea level and lacking artificial city lights. The geographic coordinates for Hanle are as follows: geographical latitude (GGLat) = 32.8°N , geographical longitude (GGLon) = 79°E , geomagnetic latitude (GMLat) = 24.4°N , and geomagnetic longitude (GMLon) = 154°E [13]. The Indian Astronomical Observatory, perched at an impressive altitude of 4,500 meters, played a crucial role in documenting this spectacular phenomenon. They utilized a specialized 360-degree camera system, meticulously designed for continuous night-sky monitoring, to capture the ephemeral lights. These observations provide critical insights into how auroras manifest outside traditional polar regions during periods of extreme solar activity. Solar Cycle 25 has demonstrated considerable activity in its solar maxima. Several major solar eruptions have produced the necessary space weather conditions for low-latitude aurora or aurora-like red emissions, especially in the Ladakh region. Table 1 summarizes key solar events, specifically flare classes and CME speeds, alongside their measured geomagnetic effects, including IMF B_z , K_p index, and Dst index values, and the associated aurora

Table 1. Chronological summary of solar flares, coronal mass ejections, geomagnetic indices, and associated aurora or aurora-like optical event displays observed in India (April 2023 - January 2025)

Date	Location	Flare class	CME speed (km/s)	IMF B_z (nT)	K_p index	Dst (nT)	Aurora colour
2023 Apr. 23	Hanle, Ladakh	M1.7	1284	-15.7	8.3	-213	Diffuse faint red hues
2023 Nov. 05	Leh and Kargil, Ladakh	M1.4	1238	-23.4	7.3	-163	Vibrant red
2024 May 10	Ladakh (Hanle, Merak)	X1.0	530	-35	8.7	-339	Primarily intense red-coloured light rays (SAR arcs); bright
2024 Oct. 10	Northern India, Ladakh region	X1.8	1435	-42.2	8.7	-333	Intense red auroras
2025 Jan. 01	Hanle, Ladakh; Northern India	M2.0	764	-21.5	8	-210	Stunning vibrant aurora in Ladakh

observations in various regions of India from April 2023 to January 2025. In the current work, we concentrate on complementing observations unique to India rather than trying to recreate the entire global-scale analysis that has already been published.

Red optical emissions seen at sub-auroral and low magnetic latitudes can originate from different physical processes, most commonly from either auroral particle precipitation or Stable Auroral Red (SAR) arcs. SAR arcs are produced mainly by thermal excitation of atomic oxygen (630.0 nm) linked to storm-time energy transfer from the ring current into the plasmasphere, and they usually appear as smooth, stable, and long-lasting red arcs during the recovery phase of geomagnetic storms. In contrast, true low-latitude auroral emissions occur mainly during the main phase of strong storms, when prolonged southward IMF B_z allows the auroral oval to expand rapidly toward lower latitudes. The events examined in this study occurred during severe geomagnetic activity ($Dst < -150$ nT, $K_p = 7-9$) and were accompanied by extreme southward IMF B_z and enhanced solar-wind speeds. The observed emissions also showed structured, arc-like forms and clear temporal changes, rather than the steady and

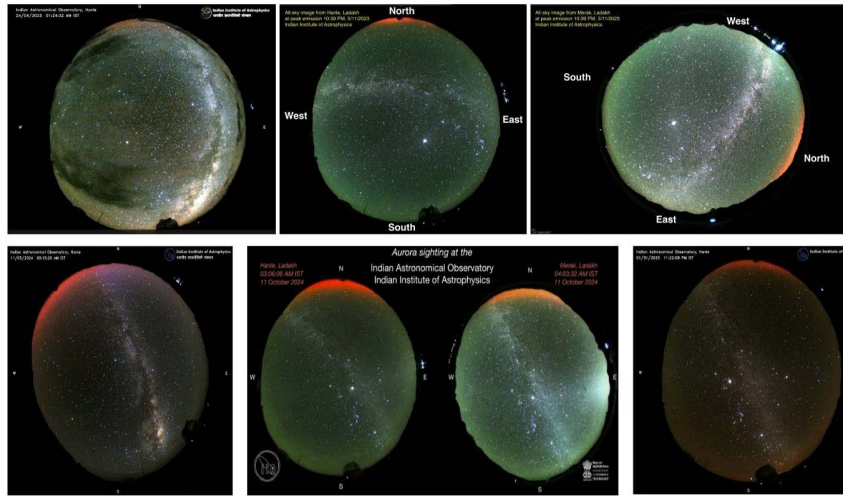


Figure 1. Composite collage of five auroral displays observed from Hanle, Ladakh, during the geomagnetic storm events of 23 April 2023, 5 November 2023, 10 May 2024, 10 October 2024, and 1 January 2025. The all-sky images show red auroral emissions and auroral arcs near the northern horizon during intense storm-time conditions, illustrating repeated low-latitude auroral visibility over India (Source: <https://www.iiap.res.in/articles/press-releases/>).

persistent behaviour typical of SAR arcs. In addition, key events especially that of 23 April 2023, have been independently identified as low-latitude auroral displays by the Indian Institute of Astrophysics and in recent peer-reviewed studies [13]. Although SAR-type processes cannot be completely ruled out without spectral or particle measurements, the storm-time conditions, optical characteristics, timing, and independent classifications together support interpreting these observations as low-latitude aurora or aurora-like emissions.

To provide a consolidated visual perspective of all documented auroral events during Solar Cycle 25 over Ladakh, Figure 1 presents a composite collage of all-sky camera observations corresponding to 23 April 2023, 5 November 2023, 10 May 2024, 10 October 2024, and 1 January 2025. These images are presented together to highlight recurring morphological characteristics of low-latitude auroral emissions over India.

4.1 23 April 2023: Auroral display in Hanle, Ladakh

On 23 April 2023, a scientifically significant and rare auroral display was witnessed over Hanle, Ladakh, India, an event highly unusual given its low geomagnetic latitude (24.4°N), the first camera-based identification of low-latitude auroral emissions from India occurred during solar cycle 25. The Indian Astronomical Observatory in Hanle, situated at a high altitude of 14,764 feet (4,500

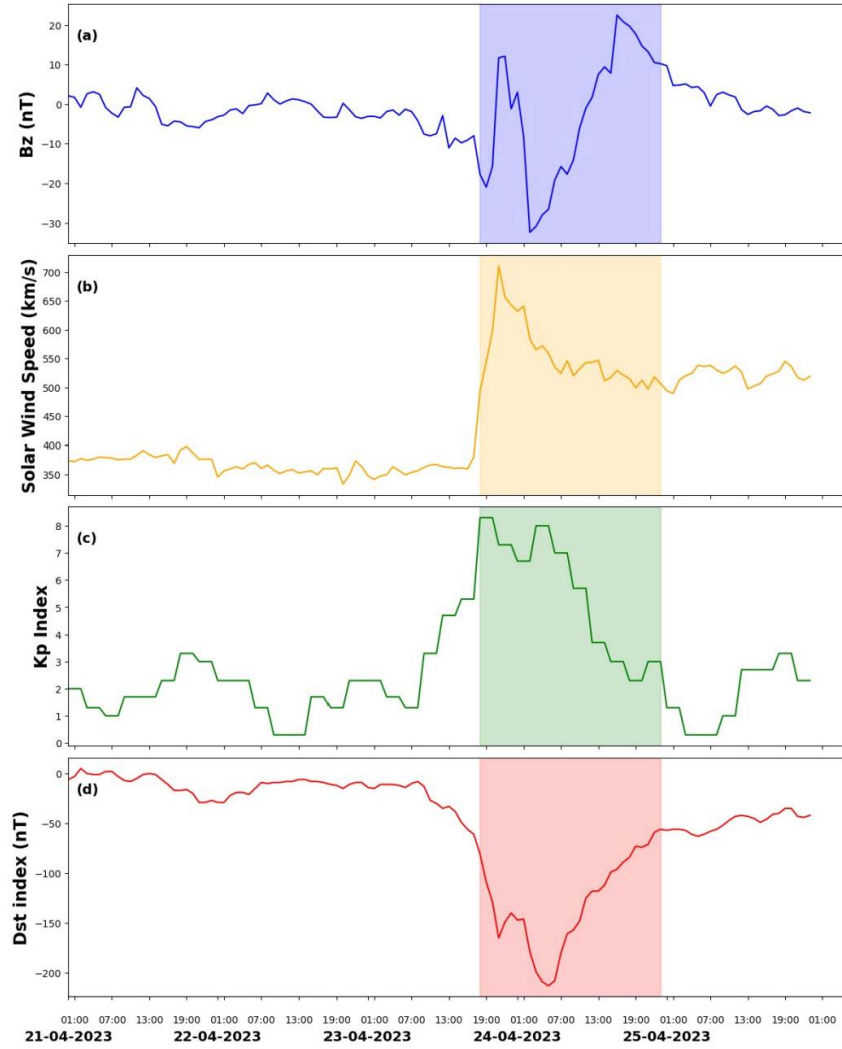


Figure 2. Temporal evolution of interplanetary and geomagnetic parameters associated with the 23 April 2023 auroral aurora-like optical event over Hanle, India. Panels show: (a) IMF B_z ; (b) solar wind speed; (c) K_p index; and (d) Dst index during 21–25 April 2023. The shaded region marks the main storm interval associated with the reported red optical emission.

meters) which offers exceptionally dark and clear skies, played a crucial role in documenting this phenomenon. This observation, captured by its specialized 360-degree camera system revealing prominent reddish hues across the night sky, is presented in Figure 2. This occurrence has already been thoroughly ex-

plored in earlier research, such as Vichare et al. [13]. The event is revisited using available optical observations and geomagnetic data to document its characteristics and evaluate the conditions that enabled auroral visibility over India. Here, using the geomagnetic data and optical observations that are currently accessible, the event is studied in order to record its features and analyse the circumstances that made auroral visibility over India possible.

The genesis of this auroral event traces back to 21 April 2023, with an M1.7-class solar flare erupting from NOAA Active Region 13283 (S22W11). This flare was accompanied by a full halo CME, observed by SOHO/LASCO at 18:12 UT, exhibiting an estimated velocity of 1284 km/s. Classified as a fast, Earth-directed event, its potential for significant geomagnetic disturbance was high, further amplified by its embedding within a pre-existing solar wind environment with a velocity of approximately 544 km/s. Upon reaching Earth CMEs magnetic structure facilitated a strong interaction with Earth's magnetosphere, leading to a severe G4-level geomagnetic storm. A critical factor was the prolonged and intense southward turning of the IMF, with the B_z component reaching a minimum of -15.7 nT (in GSM coordinates) at approximately 20:00 UT on April 23. This deep southward orientation enabled efficient magnetic reconnection and energy transfer into the magnetosphere. The storm's intensity was quantified by a planetary K_p index peak of 8.3 and a Dst index minimum of -129 nT, which further descended to a lowest point of -213 nT. Figure 2 clearly illustrates the temporal evolution of these key solar wind and geomagnetic parameters, highlighting the abrupt onset of G4-level storm conditions coinciding with the solar wind arrival.

The substantial equatorward displacement of the auroral oval, combined with Ladakh's unique high-altitude environment that reduces atmospheric scattering, allowed for this rare low-latitude visibility. This occurrence provides crucial empirical data for low-latitude auroral research, demonstrating how a combination of CME velocity, IMF orientation, and regional geography can enable auroral visibility well beyond traditional high-latitude zones. Furthermore, it underscores a critical gap in current space weather preparedness, as low-latitude regions are often assumed to be shielded from severe geomagnetic impacts, thus making the Ladakh sighting a compelling case for establishing enhanced, long-term monitoring stations in the Indian Himalayas.

4.2 November 2023: Heightened solar activity and auroral visibility

First seen at 23:14 UT on 2 November 2023, a full halo CME with a speed of 1238 km/s was created by an M1.4-class solar flare that erupted from the NOAA Active Region near S19W31. On November 5, this made its way to Earth, triggering a powerful geomagnetic storm. As the IMF B_z shifted strongly southward, reaching -23.4 nT and rising to -16 nT at 17:00 UT (GSM coordinates), solar wind conditions quickly escalated, increasing in speed from 370 km/s to

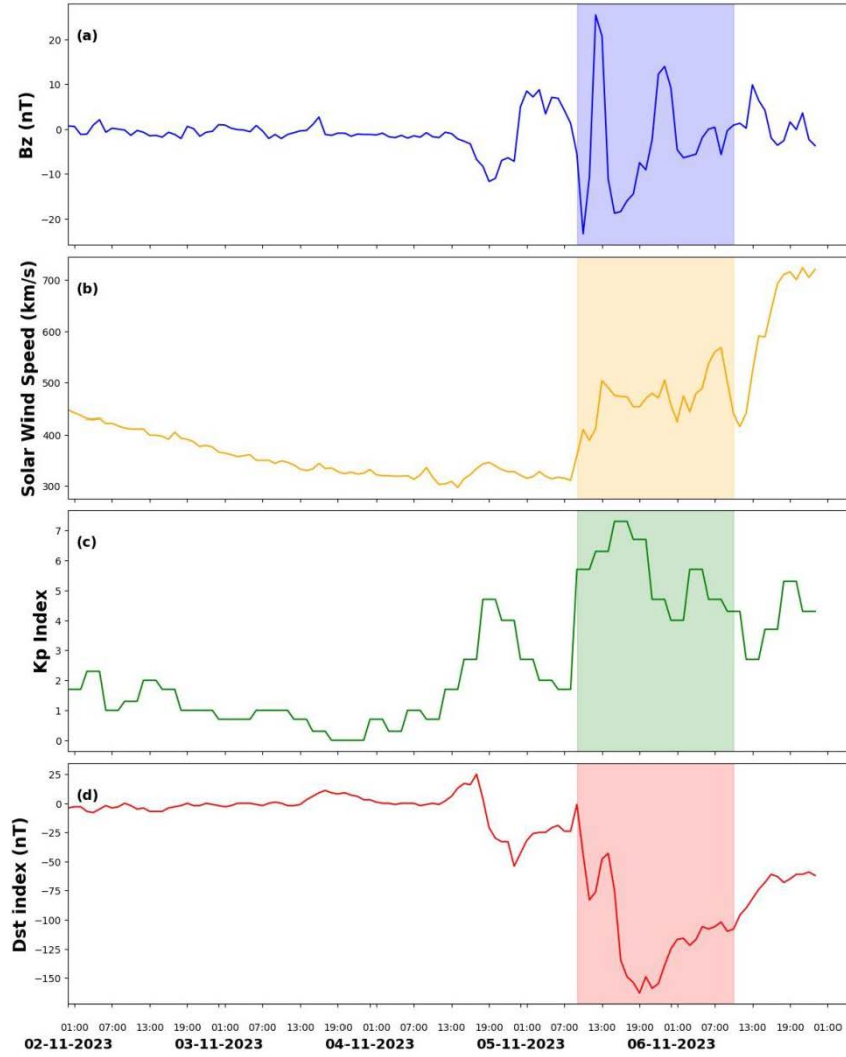


Figure 3. Temporal evolution of interplanetary and geomagnetic parameters associated with the 5 November 2023 auroral or aurora-like optical event over Hanle, India. Panels show: (a) IMF B_z ; (b) solar wind speed; (c) K_p index; and (d) Dst index during 2-6 November 2023. The shaded region marks the main storm interval associated with the reported optical manifestation.

nearly 650 km/s. Strong magnetospheric coupling and storm-time energy input were triggered by these circumstances. Consequently, the Dst index decreased to -163 nT, indicating the development of deep ring currents, while the planetary K_p index peaked at 7.3, indicating that the storm was of G3 intensity. These

dynamics are clearly illustrated in the multi-panel time-series of IMF B_z , solar wind speed, K_p , and Dst indices from 2-6 November 2023 shown in Figure 3. This event demonstrates the ability of even moderate solar eruptions to produce significant space weather impacts under favourable solar wind conditions. It also emphasizes the importance of high-altitude, low-latitude observational sites like Ladakh for monitoring auroral phenomena at the margins of typical visibility zones.

4.3 10 May 2024: The most intense storm of Solar Cycle 25

Numerous in-depth researches have been conducted on the geomagnetic storm of intensity G5 that occurred on May 10–11, 2024, which is widely acknowledged as one of the most intense events of Solar Cycle 25 [21–23]. These studies have examined global ionospheric disturbances, the auroral oval's equatorward expansion, and the remarkable optical visibility of auroral emissions at exceptionally low latitudes on plenty of countries, including India. Here we concentrate on complementing observations unique to India rather than trying to recreate the entire global-scale analysis that has already been published.

An X1.0-class solar flare occurred on May 8, 2024, from NOAA Active Region 13664, which is located at S22W11 on the solar disc. The flare created a full halo CME, which was first seen at 21:08 UT and had a speed of about 530 km/s. On May 10, 2024, an interplanetary CME (ICME) struck Earth's magnetosphere, causing a major geomagnetic storm. Upstream solar wind conditions rapidly worsened, with a sudden increase in solar wind speed to 703 km/s and a sharp southward turn of the IMF B_z component to -35 nT in GSM coordinates near 21:00 UT. The magnetospheric response was rapid and intense. The Dst index decreased abruptly from -149 nT to -339 nT, suggesting a substantial ring current injection, while the planetary K_p index peaked at 8.7, indicating a G4 (severe) geomagnetic storm. These signs are clearly visible in Figure 4, which depicts the entire course of the disturbance using time-series data of IMF B_z , solar wind speed, K_p , and Dst from 8-12 May 2024. The storm's primary phase included a rare low-latitude auroral show. Due to the storm's strong magnetospheric compression and extended southward IMF, this observation shows how the auroral oval expanded equatorward onto the Indian subcontinent. This event highlights the geo-effectiveness of Earth-directed X-class flares with even moderate CME speeds under strong southward IMF conditions. The May 2024 superstorm has already been extensively investigated in previous global and regional studies, therefore, the present discussion is limited to its relevance for low-latitude optical observations over the Indian sector.

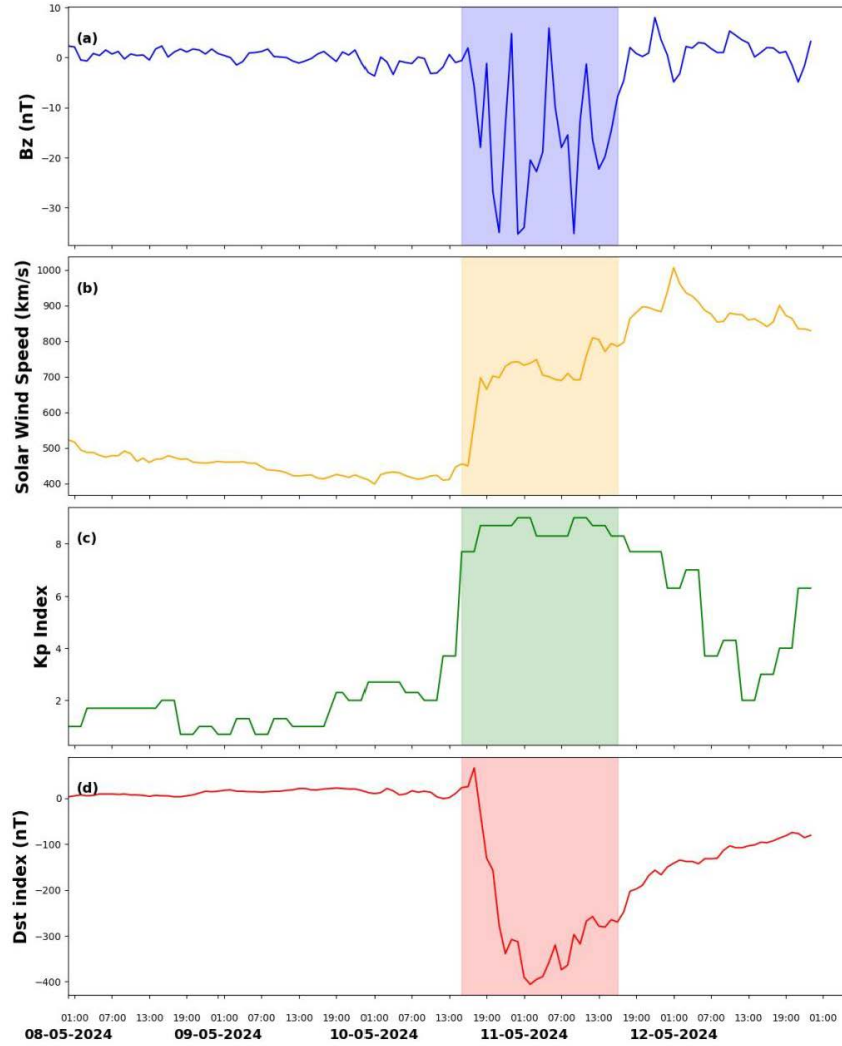


Figure 4. Temporal evolution of interplanetary and geomagnetic parameters associated with the 10 May 2024 auroral or aurora-like optical event over Hanle, India. Panels show: (a) IMF B_z ; (b) solar wind speed; (c) K_p index; and (d) Dst index during 8–12 May 2024. The shaded region marks the principal storm phase associated with the reported red optical emission.

4.4 10 Oct 2024: Auroral event

An Earth-directed CME caused a significant geomagnetic storm on October 10, 2024, which resulted in a rare low-latitude auroral show over Ladakh, India. It

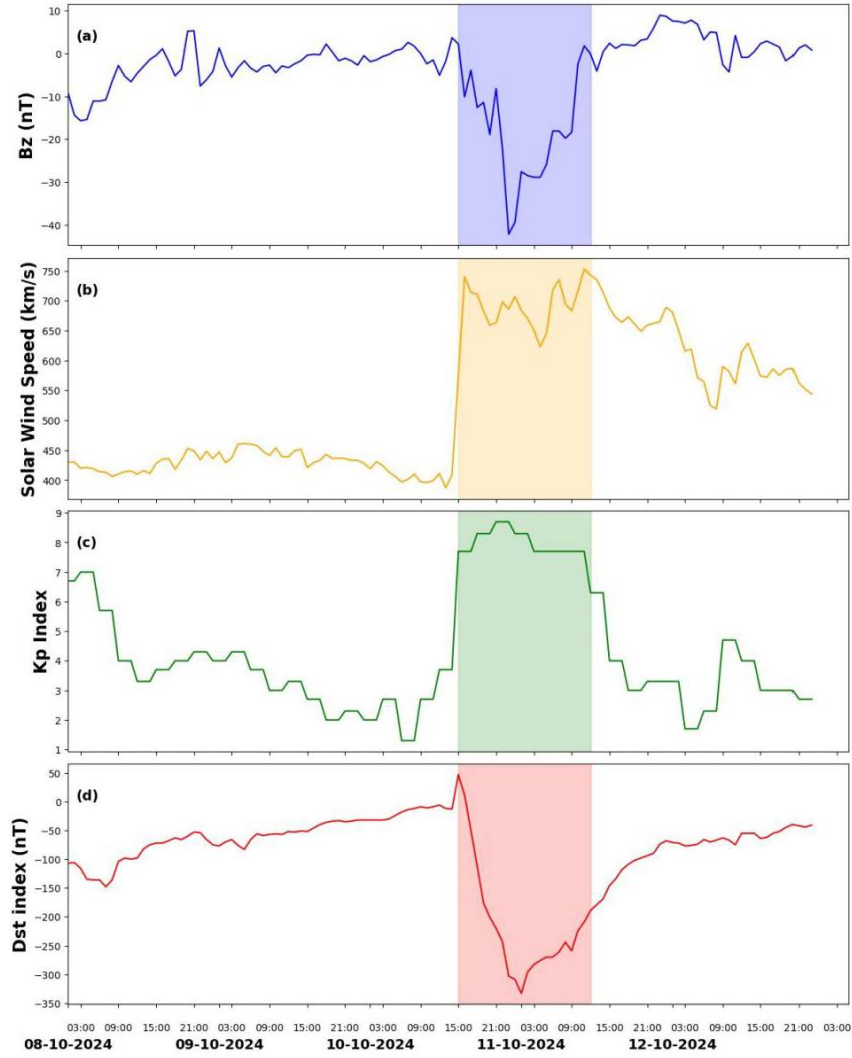


Figure 5. Temporal evolution of interplanetary and geomagnetic parameters associated with the 10 October 2024 auroral or aurora-like optical event over Hanle, India. Panels show: (a) IMF B_z ; (b) solar wind speed; (c) K_p index; and (d) Dst index during 8–12 October 2024. The shaded region marks the main storm interval associated with the reported red optical manifestation.

was linked to a solar flare of the X1.8 class that erupted from an active region close to the western hemisphere on October 8, 2024, at 01:25 UT from solar coordinates N13W08. When the CME arrived, it created a powerful interplan-

etary shock and reached a maximum speed of 1435 km/s, which increased the solar wind speed to 698 km/s. Furthermore, around 22:30 UT in GSM coordinates, the IMF B_z made a dramatic southward shift, reaching an extreme value of -42.2 nT. This allowed for strong solar wind-magnetosphere interaction and subsequent enhancement of ring current. As a result, the Dst index dropped to -303 nT and then extended to -333 nT, causing a significant geomagnetic response. The event was classified as a high-end G4 (severe) geomagnetic storm when the planetary K_p index peaked at 8.7.

Abrupt solar wind disturbances and significant geomagnetic variations were characteristics of the storm, as illustrated in Figure 5. The auroral oval expanded unusually equatorward under these circumstances. This event's main cause was the southward IMF component's extraordinary intensity, showing that even M-class flares can have a major space weather impact at low-latitude locations when they are accompanied by fast CMEs and extreme magnetic configurations.

4.5 1 January 2025: New-Year severe storm

As the world ushered in the New Year, 1 January 2025, brought with it a mesmerizing and equally rare celestial phenomenon to the skies above Ladakh, India: another brilliant display of the aurora borealis. A notable low-latitude auroral display was observed from the Indian Astronomical Observatory in Hanle, Ladakh, coinciding with a severe geomagnetic storm. The storm was triggered by a halo CME having speed 764 km/s, associated with an M2.0-class flare from NOAA active region 13939, located at S17E33, which erupted on 29 December 2024 at 04:18 UT. This impacted Earth with a solar wind speed of 513 km/s, accompanied by a prolonged southward IMF B_z , reaching -21.5 nT at 17:00 UT on 1 January. These conditions facilitated strong solar wind-magnetosphere coupling, leading to an intense geomagnetic response marked by a minimum Dst index of -210 nT and a peak K_p value of 8.0, qualifying it as a G4 (severe) geomagnetic storm. As shown in Figure 6, the event was characterized by a distinct drop in IMF B_z , elevated solar wind speeds, and enhancements in geomagnetic indices, indicating significant ring current injection and auroral electrojet intensification. The resulting expansion of the auroral oval enabled optical auroral emissions to be observed over Ladakh. This case highlights the potential for auroral visibility in subauroral regions during moderate-speed CME events under sustained southward IMF conditions.

The event produced clearly detectable red optical emissions over Ladakh under severe geomagnetic storm conditions. The aurora, predominantly captured as a video by the all-sky camera at the Indian Astronomical Observatory in Hanle, was a vibrant spectacle. This observatory, along with the Kodaikanal Solar Observatory (which imaged the associated active region) and the Gauribidanur Radio Observatory (which observed low-frequency radio emissions from the CME), played a crucial role in monitoring and documenting this rare

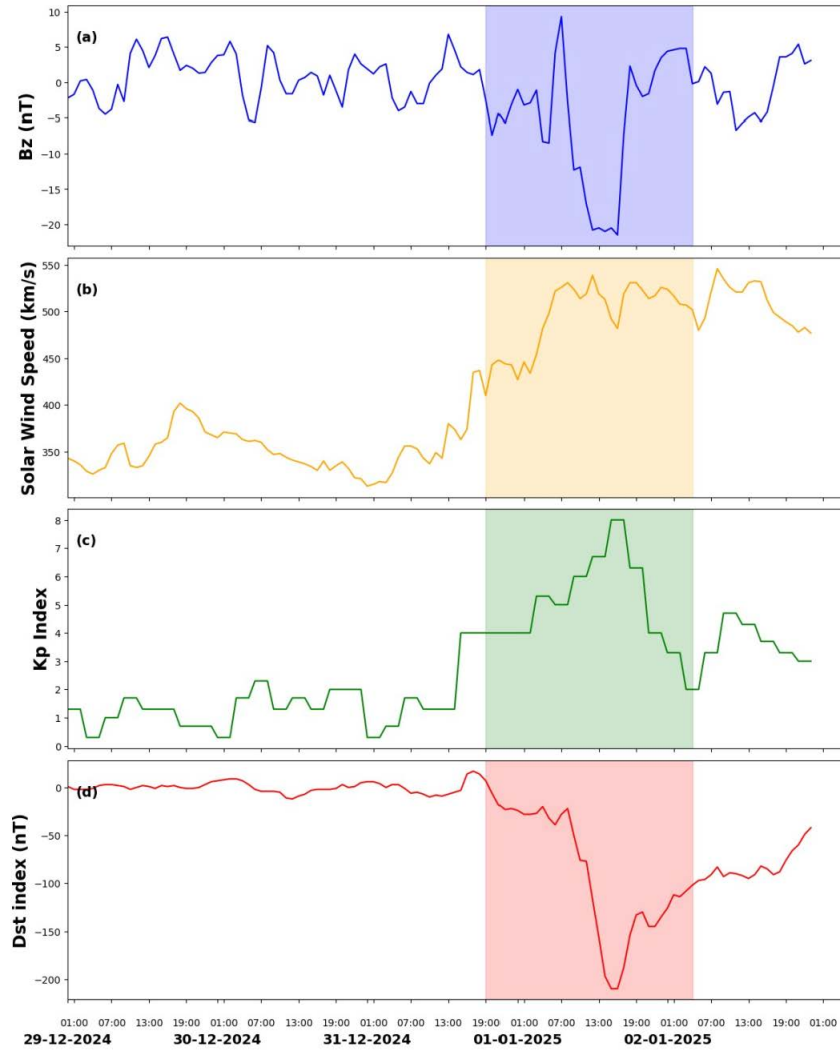


Figure 6. Temporal evolution of interplanetary and geomagnetic parameters associated with the 1 January 2025 auroral or aurora-like optical event over Hanle, India. Panels show: (a) IMF B_z ; (b) solar wind speed; (c) K_p index; and (d) Dst index during 29 December 2024–2 January 2025. The shaded region marks the principal storm interval associated with the reported optical manifestation.

occurrence. This extraordinary event marked the second major auroral sighting for India in a relatively short period, underscoring the escalating solar activity as Solar Cycle 25 approached its anticipated peak. The visibility of the aurora at such lower latitudes reaffirmed the extreme intensity of the geomagnetic storm

and served as a clear indicator of the Sun's heightened activity as it approaches solar maximum. For skywatchers and scientists in India, the New Year began with a celestial gift, reinforcing the dynamic and awe-inspiring nature of space weather.

4.6 Limitations and scope of the present study

While the present study provides a comparative analysis of five notable auroral or aurora-like optical events reported over India during Solar Cycle 25, certain limitations should be acknowledged. First, the study is primarily observational and comparative in nature, combining visual reports, all-sky imagery where available, and associated solar wind and geomagnetic parameters, but without uniform spectroscopic confirmation or calibrated photometric measurements for every event. Accordingly, although the reported red optical emissions are strongly consistent with severe geomagnetic disturbance and low-latitude auroral or sub-auroral activity, the exact physical classification of each event may not be identical.

Second, the observational basis is not uniform across all five cases. The 23 April 2023 Hanle event is comparatively well constrained because it is supported by dedicated all-sky observatory imaging and peer-reviewed reporting, whereas some of the other events rely more heavily on region-based visual reports or less uniformly calibrated imagery. Therefore, the five events should not be interpreted as having identical observational certainty, even though all are geophysically plausible and consistent with storm-time conditions.

Third, as noted in Section 2, the present study does not perform a full MLAT-MLT geometric inversion of the all-sky camera imagery because the required calibration parameters are not uniformly available. Consequently, the optical images are used qualitatively rather than as direct inversion products of emission latitude and altitude.

Despite these limitations, the consistent association between the reported optical manifestations, strong southward IMF B_z , elevated K_p , and significant Dst depression supports the scientific relevance of these events as rare low-latitude storm-time optical phenomena over the Indian sector. The present work therefore provides a useful observational baseline for future spectroscopic and multi-instrument studies of low-latitude auroral and sub-auroral emissions over India.

5 Conclusion

This study presents a comparative investigation of five rare auroral or aurora-like red optical events reported over India during Solar Cycle 25, with particular emphasis on observations from Hanle, Ladakh. Although such events are uncommon at the low geomagnetic latitudes relevant to India, the results show that

storm-time red optical emissions can become visible over the Indian sector during major to severe geomagnetic disturbances. Detailed analyses of major events in April 2023, November 2023, May 2024, October 2024, and January 2025 reveal that these occurrences are closely linked to severe and extreme geomagnetic storms, with NOAA storm intensities ranging from G3 to G5. While it is widely accepted that X-class solar flares typically drive the most extreme space weather events, this study places critical emphasis on the often-underestimated capability of M-class flares to generate strong geomagnetic storms and visible low-latitude aurora or aurora-like red emissions. Multiple events analysed in this study clearly show that CMEs associated with M-class flare, particularly those with high speed and Earth-directed trajectories, have caused significant disturbances in Earth's magnetosphere. While the most intense cases were associated with X-class flares, several M-class flare events also produced strong geomagnetic storms and plausible low-latitude auroral or aurora-like red optical manifestations when accompanied by fast, geoeffective CMEs and favourable interplanetary magnetic field conditions.

This distinction is critical as it shows that M-class flares are also capable of producing low-latitude auroras. Several M-class flare-associated events in the selected sample were accompanied by major geomagnetic disturbances, reinforcing those strong storm-time optical responses can occur even in the absence of an X-class flare. This illustrates a broader pattern where storm intensity, as measured by Dst , correlates not just with flare class but with the combined effect of CME speed, flare-associated plasma dynamics, and the direction and duration of IMF B_z . It is evident that while stronger flares, like X-class, often result in more pronounced magnetic disturbances, M-class flares can achieve similar geoeffectiveness when the CME is particularly fast and magnetically structured to promote efficient coupling with Earth's magnetic field. These fast CMEs compress the magnetosphere more effectively, allowing energetic charged particles to penetrate deeper and enabling the auroral oval to expand toward lower latitudes. This is precisely what allows auroral activity to be detected as far south as Ladakh. The favourable geographic and atmospheric conditions in Hanle such as high altitude, dry air, and minimal light pollution further support the detection of faint red auroras caused by atomic oxygen excitation at altitudes of 200–400 km. Overall, this study reinforces the need to assess space weather risk based on multiple dynamic parameters rather than flare classification alone. It also strongly advocates for the development of multi-instrument monitoring infrastructure across the Indian Himalayas to enhance predictive capabilities in a region once thought to be shielded from severe geomagnetic effects.

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