Linking Solar Minimum, Space Weather, and Night Sky Brightness

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Linking Solar Minimum, Space Weather, and Night Sky Brightness

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Abstract

New observations indicate previously unrecognized significant sources of night sky brightness variations, not involving corresponding changes in the Sun's EUV flux, occur during deep solar minimum. Our data was taken at 5 sites spanning more than 8,500 km during the deep minimum of Solar Cycle 24 into the beginning of Solar Cycle 25.

It shows;

1) Semi-annual night sky brightness variations are produced by interactions between the Earth's magnetic field and the interplanetary magnetic field.
2) Solar wind plasma streams from solar coronal holes produce major night sky brightness increase events.
3) Some night sky brightness events are relatively local.
   Others extend at least 8,500 km along the Earth's surface.
4) It is plausible, terrestrial night airglow and geomagnetic indices have similar responses to the solar energy input into Earth's magnetosphere.

Our empirical results contribute to a quantitative basis for understanding and predicting night sky brightness variations. They are applicable in astronomical, space weather, light pollution, biological, and recreational studies.
We report significant changes in night sky airglow not involving corresponding changes in the Sun's EUV flux. Observations from five sites separated by more than 8,500 km along the Earth's surface reveal the clear astronomically dark night sky is rarely, if ever, constant in brightness. The natural night sky is a unique laboratory providing a rich tapestry of solar and terrestrial phenomena. The Methods section provides a detailed discussion of quantities used in this paper.

A quantitative understanding of natural night sky airglow is essential to inform the search for Earth approaching asteroids. Observations by telescopes like the Vera C. Rubin Observatory (VRO or LSST), astrophotography opportunities, stargazing worldwide, and the study of anthropogenic skylight require this information. Empirical evidence is necessary to guide theories and modeling of night sky brightness variations. Changes in natural night sky brightness provide clues about ionospheric and space weather processes. Extreme events in this realm have a significant impact on electrical grids, electronic communication, and navigation satellites.

The lack of a consistent data set spanning time and geographic location has made understanding night sky airglow variations difficult. Despite this, researchers have correlated natural night airglow with day-time atmospheric photoionization and subsequent night-time recombination’s response to changes in the Sun's extreme ultraviolet (EUV) flux.

Satellite observations suggest historical bright nights are the result of zonal wave superposition. Walker, Krisciunas, and others have correlated observed variations in night sky brightness with prior changes in EUV from the Sun as measured by the 10.7 cm (2.8 GHz) solar flux. The hypothesis is, changes in photoionization on the Earth's day-side produce subsequent variable night time airglow by re-radiation from atoms and molecules in a complex chemical environment. This concept can be used to relate changes in solar EUV, estimated from the 10.7 cm solar flux, to daily and yearly night sky brightness changes throughout a solar cycle.

The night sky brightness changes we observed are not correlated with changes in solar EUV flux. During the period of our observations, the solar EUV measured by the 10.7 cm solar flux was at a low, relatively constant, level (average = 69.77 sfu, stdev = 2.45, 1 sfu = 10$^{-4}$ Jy).

Fig. 1 is a plot of 948 nightly airglow brightness measurements obtained from 37,437 individual observations made at 5 locations, 4 September 2018 through 30 April 2020. Each point is the nightly average of airglow brightness, $\Delta MC-N(t)$, above its quiescent level. The celestial and anthropogenic sources have been removed as outlined in the Methods section of this paper. An expanded form of Fig. 1 shows an apparent periodicity of the 26.24 day synodic solar rotation cycle relative to the Earth. The interpretation of this temporal spacing is complicated by the lunar cycle and weather events producing the gaps in the data acquisition stream.
Fig. 1 shows during a deep solar minimum natural night airglow brightness varies by more than 0.5 mag/arcsec$^2$ (45%). Local night sky airglow brightness events span a distance of a few hundred km. Others can extend 8,500 or more km along the Earth’s surface (see Methods Section for a plot and details).

Three very broad increases in airglow brightness were measured at all sites. The $\Delta$MC-N(t) values plotted on the vertical axis of Fig. 1 are the nightly average increases of the measured airglow above its quiescent level. (see Methods) Peaks in $\Delta$MC-N(t) occurred near JD 2458435 (12 November 2018), JD 2458589 (16 April 2019), and JD 2458786 (29 October 2019). These dates were obtained by fitting the $\Delta$MC-N(t) data to a quadratic formula extending 1 or 2 lunations either side of the peak. The significance of these night airglow brightness increases are the subject of this paper.

Geomagnetic activity has a long history of time series measurements and their analysis. Conversely, interruptions by the Sun, Moon, weather events, and the lack of a wide spread network of suitable measuring stations have left the study of natural night sky airglow brightness variations relatively undeveloped. This paper juxtaposes a limited night sky airglow brightness data set with the rich body of geomagnetic research.
The semi-annual variation in geomagnetic activity has been known for over 100 years\(^8\). In 1971, Russell and McPherron proposed a model to explain this phenomena in terms of the relationship between the z component of the interplanetary magnetic field, \(B(t)_z\text{GSM}\), and the z component of the Earth's magnetic field\(^9\) (both expressed in the Geocentric Solar Magnetospheric [GSM] coordinate system). In the Russell and McPherron model the interaction between these two magnetic fields acts like a rectifier. When \(B(t)_z\text{GSM}\) is negative, opposite Earth's magnetic field, charged particles are more likely to penetrate the ionosphere. When \(B(t)_z\text{GSM}\) is positive, in the same direction the Earth's magnetic field they are partially blocked. A negative \(B(t)_z\text{GSM}\) produces enhanced geomagnetic activity. In 2019, according to their model geomagnetic activity reaches a maximum around 4 April and 7 October. Expressed in fractions of a year, \(F\), these peaks are at \(F = 0.257\) and \(F = 0.769\). It should be emphasized this model is based on the statistics of geomagnetic events above a certain threshold. There are broad peaks and dips with a full width at half maximum of many days.

The existence of a seasonal variation in the brightness of the natural night airglow has been debated for years in the literature. Patat reviews this situation and presents new data derived from spectroscopic observations in the UBVRI passbands at the Cassegrain focus of the 8.2 m telescopes at the Paranal Observatory in Chile\(^10\). The observations were made during the decline from maximum to minimum of Solar Cycle 23. He reports a clear seasonal variation in the broadband VRI passbands with two broad maxima (April-May and October) and two broad minima (July-August and December-January).

Fig. 2 compares our March-April 2019 data with satellite, geomagnetic, and solar flux observations. It shows a widespread increase in night sky airglow during a time when \(B(t)_z\text{GSM}\) was predominately negative. Negative values of the z component of the interplanetary magnetic field diminish Earth's magnetic field allowing charged particles from the Sun to penetrate the Earth's magnetic shield. The normalized solar wind kinetic energy, NKE\((t)\) varied significantly above its median level and NAp\((t)\) shows enhanced geomagnetic activity. These quantities are defined in the Methods section of this paper. Enhanced airglow coincides with Russell-McPherron prediction of increased geomagnetic activity.

Fig. 2 suggests night sky airglow is modulated by the changing alignment of the interplanetary magnetic field relative to that of Earth in a way similar to the Russell-McPherron effect for geomagnetic activity. It should be emphasized that simple cause and effect relationships between changes in solar activity and geomagnetic activity, and/or night sky brightness variations are difficult to establish. In the Russell-McPherron effect the chaotic, highly variable, solar wind is modulated by the interplanetary magnetic field to produce a statistically discernible geomagnetic activity pattern using data encompassing a number of years. The data presented in Fig. 2 are suggestive that night sky airglow variations follow the Russell-McPherron effect, however, data from more years will be required to put this hypothesis on a solid statistical basis.
Fig. 2: The upper panel plots measures of solar and geomagnetic activity parameters versus time in JD. The lower panel plots nightly airglow brightness averages above the quiescent level, ΔMC-N(t), versus JD. The error bars are +/- 1 standard deviation. They represent real brightness variations during the night produced by changes in the solar wind and the interplanetary magnetic field. The actual measurement errors are less than 0.03 mag/arcsec².

The dashed line is a quadratic fit to all the data. The negative values of [B(t)z]GSM (plotted in red) allowed charged particles from the solar wind to penetrate Earth’s magnetic shield enhancing geomagnetic activity and terrestrial airglow. The Russell-McPherron effect models a statistical enhancement of geomagnetic activity over a long time base. Additional night airglow data are required to firmly establish that night airglow is statistically predictable using the Russell-McPherron effect.

From July to November 2018 the same large coronal hole was observed on the Sun. It pointed in our direction every solar synodic period. After each such alignment, several days later Earth was engulfed in a high speed stream in the solar wind. This set of circumstances produced airglow and geomagnetic events world wide and was imaged by astronauts on the International Space Station. This series of events produced the broad peak in night sky brightness near JD 2458435 (12 November 2018), see Fig.1. The wide vertical distribution of points in Fig. 1 is the result of real changes in the night airglow.

During the summer and fall of 2019 large coronal holes repeatedly pointed toward Earth producing the broad peak in night sky brightness near JD 2458786 (29 October 2019) in Fig. 1. Fig. 3 plots solar activity and night airglow brightness from JD 2458776 (19 October 2019) to JD 2458789 (1 November 2019). During this time large coronal holes were observed moving across the visible face of the Sun. This solar phenomena produced an overall increase in night sky brightness punctuated by spikes created when particularly energetic streams in the solar wind impacted Earth’s magnetosphere. The top panel is a plot of normalized solar wind and geomagnetic parameters versus the time in JD (days). The bottom panel is a plot of the airglow above the quiescent level, ΔMC(t), for each site in mag/arcsec² versus the time in JD (days). (See Methods)
Zoltán Kolláth’s image (Fig. 4) was captured on 20.10.2019 at 03:53 UT (2458776.66181 JD) at the beginning of an extended night sky brightness episode. Fig. 3 shows the image’s temporal relationship to the other data. Green (558nm) oxygen and orange (589nm) sodium airglow are visible over the entire sky. The R,G, and B channels in the digital camera data provide estimates of the strength and spatial structure of the oxygen and sodium lines.

Fig. 3 shows this period of time was characterized by predominately negative $[B(t)z]_{GSM}$ and NKE(t) which varied significantly above its median value. Near 2458780.75 JD (24 October 2019) a high speed stream in the solar wind produced a shock wave at Earth’s bow shock nose. This produced a dramatic increase in geomagnetic activity, NAp(t). A pulse in NKE(t) deposited energy into the Earth’s magnetosphere. Meanwhile, the solar EUV as indicated by the N10.7cm(t) flux was low and constant and is uncorrelated with airglow brightness changes. The period of negative $[B(t)z]_{GSM}$ which followed allowed energetic charged particles to penetrate deep into Earth’s ionosphere. The shock wave triggered large variations in airglow brightness during the night reaching peak brightnesses near local midnight.

We observed several other episodes of substantial brightness variations in night airglow. In some cases, after a maximum near local midnight, a decline in airglow brightness was followed by a substantial brightening several hours later. Insufficient data prevented us from determining if these features were the result of atmospheric airglow waves, energy being released from Earth’s magnetospheric tail, or an unknown physical process.

Fig. 3: Top panel: The normalized geomagnetic index, NAp(t), normalized solar wind kinetic energy, NKE(t), normalized N10.7cm(t) solar radio flux along with the positive and negative z components of the interplanetary magnetic field in the GSM coordinate system are plotted versus JD (days). The shockwave arriving about on about 2458781 features a dramatic sign change in $[B(t)z]_{GSM}$ and pulse in NKE(t) appears to trigger geomagnetic and airglow variations. Similar events are observed on other occasions.

Bottom Panel: The night airglow above the quiescent level, ΔMC(t), for each site is plotted versus Julian Date (JD). It is interesting to note airglow is increasing in brightness before the arrival of the shockwave. This suggests preconditioning of the magnetosphere-ionosphere system may allow a shock wave to trigger a night sky brightness increase event.
Fig. 4: On the night of October 19-20, 2019 Zoltán Kolláth captured this true color image at CCIDSS as part of a survey of dark sky sites in the American southwest. North is at the top of the image. He reported the airglow was unusually bright that night. He states for this night “The airglow gives an increase in sky brightness ~0.3 mpsas at the zenith and ~0.7 mpsas around 40 deg. In red the increase is ~0.5 and ~0.9 mpsas.” These data are in agreement with the SQM-LU-DL data simultaneously recorded at CCIDSS.

In a series of papers, Lockwood et al. investigate the semiannual, annual, and Universal Time variations in the magnetosphere and geomagnetic activity. A key element in their research is an estimation of the power input into the magnetosphere, $P_\alpha$. They calculate $P_\alpha$, employing interplanetary measurements, with the formula originally derived, theoretically, by Vasyliunas et al. $P_\alpha$ has only 1 free parameter, the coupling factor $\alpha$. It is driven by the speed, number density, ion mass measures of the solar wind, and modulated by the interplanetary magnetic field’s strength and orientation. In general, geomagnetic parameters have fractional variational amplitudes larger than the corresponding temporal fractional changes in $P_\alpha$. This amplification can be seen by comparing the am geomagnetic index with $P_\alpha$. This research group shows the Russell-McPherron Effect is the principal driver of semi-annual geomagnetic activity even though it has a small impact on $P_\alpha$. Interestingly, they report the intensity of geomagnetic activity produced by the Russell-McPherron Effect is apparently amplified by the release of energy stored in the Earth’s magnetospheric tail.
It is plausible the brightness of night side airglow, like geomagnetic indices, is driven by $P_\alpha$. Airglow is likely to possess an amplitude of variation and delayed response produced by non-linear processes in the Earth's magnetosphere. To investigate this possibility, Fig. 5 is a graph of 948 nightly airglow averages obtained at five sites, 4 September 2018 through 30 April 2020. On the vertical axis, each point is the nightly average of airglow brightness, $\Delta MC-N(t)$. The celestial and anthropogenic sources have been removed as outlined in the Methods section of this paper. The horizontal axis is the time in fractions of a year (F). The data were sorted into 36 bins with an F width of 0.0278. The smoothed data curve was obtained from the 36 data bins using a 5 point triangular weighting function. The smoothed, binned, data curve of Fig. 5 shows a semi-annual variation in airglow brightness with broad peaks near 0.273 F and 0.837 F. The peak near 0.837 F has an amplitude and location strongly influenced by high speed streams in the solar wind from coronal holes on the face of the Sun. The wave form of the smoothed binned data of Fig. 5 is similar to the am geomagnetic index amplified response to $P_\alpha$ as calculated by Lockwood et al. 17. This similarity suggests the night side airglow is coupled to the energy input into the Earth's magnetosphere in a way similar to the am geomagnetic index.

Fig. 5: The vertical axis are the $\Delta MC-N(t)$ nightly average airglow data from Fig. 1. All 5 sites are plotted with the same symbol. The binned data and smoothed, binned, data are described in the text. The horizontal axis is F, the fraction of a year. The error bars are +/- 1 standard deviation and represent real changes during the night. This plot clearly shows the semi-annual variation in night sky brightness. Given the random nature of solar events, the precise amplitude and the location of the maximums and minimums are likely to shift as the temporal time base increases in length. This wave form is similar to the am geomagnetic index17.
In conclusion, during solar minimum, significant episodes of increased night sky airglow are not produced by changes in solar EUV flux. They appear to be the result of two processes; 1) Changing orientation of the interplanetary magnetic field relative to Earth's magnetic field and 2) Earth entering streams of energetic solar wind.

Some night sky brightness events are relatively local. Others extend at least 8,500 km along the Earth's surface (see Methods for a plot).

Our data suggests the terrestrial night airglow responds to the energy input into the Earth's magnetosphere in a fashion similar to the geomagnetic indices.

We strongly advocate the establishment of a global network of photometers, in places where anthropogenic skyglow is at a minimum. They would track brightness variations of the natural night sky. Established astronomical observatories are the places to start. These measurements will have a significant impact on the studies of astronomy, space weather, light pollution, biology, and recreation.
Methods

We measure changes in terrestrial zenith night airglow relative to celestial sources. This procedure minimizes errors encountered using data from several different instruments and individual instrument drift in sensitivity if it exists. Our photometers are used to measure differences in brightness of the same place on the celestial sphere along the zenith declination.

In the past, most night sky brightness measurements published in the scientific literature were made by astronomical research-grade instruments occasionally scheduled for this task\(^5,6\). Our research is enabled by accurate, low cost, scientific quality SQM-LU-DL\(^20\) and TESS-W\(^21\) photometers. They provide continuous measures of zenith night sky brightness dusk to dawn every night. These two photometers use the same detector, have slightly different fields of view, and different red responses. Their differential photometric measurements produce similar results. In the differential photometry mode we employ, they are more accurate (error < 0.03 mag/arcsec\(^2\)) compared to when used as calibrated absolute photometers (error ~ 0.1 mag/arcsec\(^2\)).\(^20\) The irradiance-to-frequency semiconductor detector employed by both the SQM-LU-DL and TESS-W instruments is calibrated to report the measurements in mag/arcsec\(^2\).\(^22\) On clear astronomically dark nights, these single channel photometers, pointed at zenith, measure light accumulated from terrestrial airglow, stars, planets, scattered star light, zodiacal light, nebulae, galaxies, other faint astronomical sources, and anthropogenic skyglow if present.

Data are collected at Cosmic Campground International Dark Sky Sanctuary (CCIDSS) and Catalina Sky Survey Mt. Lemmon Station (CSSMLS). Data from TESS-W photometers located at Spain Observatorio Astrofísico de Javalambre- Arcos de las Salinas/Teruel (Stars18), Centre d’Observació del’Univers, Àger, Lleida, Spain (Stars62), and Observatorio del Teide, Izaña, Tenerife, Spain. (Stars211) were downloaded from the TESS Data Monthly data files using IAU-IDA format\(^23\).

| Site      | Instrument | Latitude | Longitude | Elevation | Artificial Level \(^24\) |
|-----------|------------|----------|-----------|-----------|-------------------------|
| CCIDSS    | SQM-LU-DL  | 33.4793 ° N | 108.9226 ° W | 1634 m | 0.632 \(\mu\)cd/m\(^2\) |
| CSSMLS    | SQM-LU-DL  | 32.4420 ° N | 110.7893 ° W | 2791 m | 132 \(\mu\)cd/m\(^2\) |
| Stars18   | TESS-W     | 40.0371 ° N | 1.001815 ° W | 1589 m | 31.8 \(\mu\)cd/m\(^2\) |
| Stars62   | TESS-W     | 42.0246 ° N | 0.73479 ° W | 810 m | 37.0 \(\mu\)cd/m\(^2\) |
| Stars211  | TESS-W     | 28.2983 ° N | 16.5105 ° W | 2106 m | 123 \(\mu\)cd/m\(^2\) |

Methods Table 1: The sites and instrumentation used in this study.

The artificial levels in Methods Table 1 are estimates from satellite data adjusted by SQM observations on the ground\(^24\). CCIDSS is a unique standard more than 60 km away from any significant source of artificial light. Analysis of all sky images\(^14\) and the satellite estimate, of less than \(\frac{1}{2}\%\) artificial light\(^24\), indicates anthropogenic skyglow is unmeasurable at zenith at CCIDSS.
Methods (Continued)

We have developed techniques and software to process the data. Our software selects individual instrumental measurements, $M(t)$, taken at time $t$, when the Sun was more than 18 degrees below the horizon, the Moon was more than 10 degrees below the horizon, and the sky was clear. Sky clearness is measured by computing Chi Squared from a straight line fit to the data extending for 45 minutes on either side of the point in question. A Chi Squared of less than 0.009 rejects cloudiness but not the rising Milky Way. As an additional check the TESS-W near IR sensor is employed to estimate cloud cover. At Stars211 in only one case out of 198 nights, did the Chi Squared fit indicate clear skies while the IR sensor indicated cloudiness. For the TESS-W data, the original 1 min data are averaged over 5 minute intervals to produce 5 minute samples. Our software calculates the Right Ascension (R.A.), Declination (Dec.), Julian Date (JD), Local Sidereal Time (LST), Solar and Lunar Altitudes and other parameters for each $M(t)$ data point.

Methods Fig. 1 is a plot of the 12,892, $M(t)$, data points, sorted into $\frac{1}{2}$ h bins in R.A., obtained at CCIDSS September 2018 through April 2020. The vertical distribution of sky brightness, at each sky position of R.A., is due to changes in terrestrial airglow.

Methods Fig. 1 and similar plots for the other sites observationally establish a quiescent value of airglow for each location on the celestial sphere. One could, also, establish a value for the quiescent airglow level by adding up the minimum values for all known sources of diffuse night sky brightness.

Methods Fig. 1: The vertical axis is the instrumental sky brightness, $M(t)$, in mag/arcsec$^2$. It shows changes in airglow due to solar activity at each sky position. The horizontal axis is the position in the sky in hours of R.A. (the data being sorted into $\frac{1}{2}$ h bins). The continuous light curve of quiescent airglow was calculated using the faintest 10% of the $M(t)$ in each $\frac{1}{2}$ h R.A. bin. It is the sky brightness when the terrestrial airglow is at minimum.
Methods (Continued)

Along the zenith declination on the celestial sphere, \( \frac{1}{2} \) h bins in R.A., are used as 48 standard candles. Each such standard candle is the average of the 10% faintest M(t) measurements at its location on the celestial sphere. A set of joined polynomials are fitted to the 48 standard candles to produce a continuous light curve of quiescent airglow brightness. Methods Fig. 1 illustrates these concepts with data from CCIDSS. Each site has a unique light curve of quiescent airglow brightness which depends on its latitude and the degree to which it is influenced by anthropogenic light. Each measured point’s brightness above the quiescent airglow, \( \Delta M(t) \), is obtained by subtracting the continuous light curve of quiescent airglow from the data, point by point. This procedure removes light from the stars, planets, Milky Way, zodiacal light, other celestial sources, and constant anthropogenic light if present. Thus, each \( \Delta M(t) \), is the differential photometric night sky brightness at time t, relative to the brightness of the same point on the celestial sphere when the airglow is at minimum. The same procedure is used to produce, \( \Delta M(t) \), a time series of airglow brightness above its quiescent level for each site. Despite our instrument’s dusk to dawn coverage every night, the observations were unavoidably interrupted by Sun, Moon, clouds, and instrument down time. For the total elapsed time during this research, 4 September 2018 through 30 April 2020, the % of time logged during clear astronomical dark conditions was for CCIDSS (7.4%), CSSMLS (5.6 %), Stars18 (1.6 %), Stars62 (3.3%), and Stars211 (5.1%). Our data must be regarded as a small sample of sky brightness during this time.

To evaluate conditions during the night at each site, we averaged the \( \Delta M(t) \) data into \( \frac{1}{2} \) h time intervals relative to local midnight. The results are plotted in Methods Fig. 2. The error bars, produced by real airglow variations, are +/- 1 standard deviation for the \( \frac{1}{2} \) h bin averages. At CCIDSS, the quiescent airglow light curve is relatively flat (average 0.18 mag/arcsec\(^2\)). The standard deviation of 0.136 mag/arcsec\(^2\) is produced by real changes in airglow. On long winter nights, before the onset of astronomical twilight, there does seem to be an increase of approximately 0.07 mag/arcsec\(^2\). The origin of this increase is unclear. There appear to be other reports of this phenomena in the literature. It is plausible natural night sky airglow has a UT dependence similar to the geomagnetic indices. At CSSMLS, \( \Delta M(t) \) is correlated with automobile driving patterns and scheduled outdoor lighting changes in and around Tucson, AZ. At Stars18, Stars62, and Stars211 there appears to be prolonged morning and evening twilight when the Sun is more than 18° below the horizon. This result could be due to the extended red response of the TESS-W photometers and/or the European pattern of artificial lighting in nearby cities.
Methods (Continued)

Methods Fig. 2: The vertical axis is brightness of the $\Delta M(t)$ time series data averaged into $\frac{1}{2}$ h time intervals relative to local midnight for each site. The horizontal axis is the time in hours relative to local solar midnight.

For each site, the $\Delta M(t)$ data versus the time relative to local midnight were fit to a quadratic function. This smooth quadratic function was used to remove the effects of anthropogenic skyglow and other factors. These corrections flatten the curves of Fig. 2, tighten the agreement between sites, and are small. In mag/arcsec$^2$, the site (median, stdev) correction values are CCIDSS (0.005, 0.008), CSSMLS (-0.018, 0.056), Stars18 (0.017, 0.048), Stars62 (0.016, 0.040), and Stars211 (-0.033, 0.029). The resulting time-series of data points, $\Delta MC(t)$, for each site are used to track the natural zenith airglow uncontaminated by celestial and other sources above its quiescent level.

We compare the zenith natural airglow above its quiescent level, $\Delta MC(t)$, during a deep solar minimum, with conditions in the near Earth environment. We employ solar wind data as compiled and presented on the NASA Omni Plus Browser$^{27}$, as well as sunspot counts, 10.7cm(t) (2.8 GHz) solar flux, and Geomagnetic indices$^{28-31}$.

We obtained the 1 h averages for $[B(t)_{z}]_{GSM}$, $[Bz(t)]$, $V(t)$ [Kp Speed], and $n(t)$ [Kp-Proton Density] from the NASA Omni Plus Browser$^{32}$. These parameters are the solar wind conditions at Earth's magnetic bow shock nose at time $t$. 
Methods (Continued)

Assuming protons are the predominate ion in the solar wind, we define a normalized measure of the solar wind kinetic energy, NKE(t), to be \( n(t) \) [proton density] times \( v(t) \) [solar wind speed] squared divided by the median of this quantity for the period 4 September 2018 through 30 April 2020. NKE(t) is similar to PSW which itself can be related to geomagnetic activity\(^\text{16,17}\). Similar calculations were made to obtain normalized solar flux, \( \text{N10.7cm}(t) \), and normalized Potsdam Geomagnetic index, \( \text{NAp}(t) \).

\([B(t)_{Z}]_{\text{GSM}}\) is the \( Z \) component of the interplanetary magnetic field in geocentric solar magnetospheric system (GSM) in units of nT. In GSM system the \( Z \) axis is aligned with the Earth’s northern magnetic pole. Thus, a positive \([B(t)_{Z}]_{\text{GSM}}\) enhances the Earth's magnetic field while a negative \([B(t)_{Z}]_{\text{GSM}}\) opposes it. This is a key concept in our interpretation of the data.

Methods Fig. 3 presents data obtained on the night of 2019 February 7-8 (JD 2458522). It was a rare night when zenith sky brightness reached nearly record faint levels at all sites. In the direction away from the disk of the Milky Way (LST 11-14 h) the measured sky brightnesses were: CCIDSS (22.128 mag/arcsec\(^2\), stdev = 0.016), CSSMLS (21.456 mag/arcsec\(^2\), stdev = 0.009), and Stars211 (21.469 mag/arcsec\(^2\), stdev = 0.038). The photometers at CCIDSS and CSSMLS were in sync with one another for 4 h with a delta magnitude of 0.032 mag/arcsec\(^2\) (stdev 0.014 mag/arcsec\(^2\)). In the upper panel the normalized values of NKE(t), NAp(t), and N10.7cm(t) were all steady, at or below their median values. The \([B(t)_{Z}]_{\text{GSM}}\) had relatively small variations. All of these measurements taken together indicate a state of low solar and geomagnetic activity.
Methods (Continued)

Methods Fig. 3: A dark night experienced at sites separated by more than 8,500 km. The horizontal axis is the JD – 2458000 in days, \([B(t)]_{GSM} \) in nT along with the normalized solar wind kinetic energy, NKE(t), normalized geomagnetic index, NAp(t), and the radio solar flux, N10.7cm(t) are plotted in the upper panel. The airglow brightness data points, \(\Delta MC(t)\), in mag/arcsec² are plotted in the lower panel.

At CCIDSS, September 2018 through April 2020, 15 nights were recorded to have minimum brightnesses between 22.10 and 22.18 mag/arcsec².

We calculated an average night sky brightness \(\Delta MC-N(t)\) with standard deviation for each of the 948 nights observed at CCIDSS, CSSMLS, Stars18, Stars62, and Stars211.

CCIDSS and CSSMLS had 123 clear nights in common while CCIDSS and Stars211 had 107 clear nights in common. In Methods Fig. 4 we plot the nightly average, \(\Delta MC-N(t)\), and standard deviation for CCIDSS on the horizontal axis. The nightly average, \(\Delta MC-N(t)\), and standard deviation for the nights which were in common with CCIDSS for CSSMLS and Stars211 are plotted on the vertical axis. The results for Stars18 and Stars62 are similar but not included since they are at a more northern latitude.
Methods (Continued)

Methods Fig. 4 indicates some airglow increase events are local while others extend over relatively large geographic regions. CCIDSS and CSSMLS are 209 km apart. The airglow of the nights in common between these two sites scales with a scale factor of 0.91. The data suggest the largest brightness increase events occur over geographical dimensions of more than 200 km while lesser airglow brightness events are more local. CCIDSS and Stars211 are 8519 km apart. The airglow of the nights in common between these two sites scales with a scale factor of 0.75. This suggests that some airglow increase events have dimensions of 8,500 km or more while others are more local. Widely observed night sky brightness events may be similar to large-scale structures observed on airglow maps.

Methods Fig. 4: Clear nights in common for CCIDSS-CSSMLS and CCIDSS-Stars211. The horizontal axis is the ΔMC-N(t) [nightly average] and standard deviation for CCIDSS. The vertical axis is the ΔMC-N(t) [nightly average] and standard deviation for CSSMLS (round red points) and the ΔMC-N(t) and standard deviation for Stars211 (square blue points).
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Author Contributions

ADG is responsible for manuscript content and data analysis.

PAG is responsible for manuscript content and editing changes which make the document coherent.

Competing Interests.

The authors declare no competing interests.

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Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author [ADG].
Figures

Figure 1

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Figure 2

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Figure 3

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