Pc1 measurements of EMIC waves are not significantly linked to the acceleration of auroral protons in the cusp.

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Abstract

We present three pieces of observational evidence to conclude that EMIC waves are not the mechanism responsible for the acceleration of auroral protons in the polar cusp. It is widely believed that ElectroMagnetic Ion Cyclotron (EMIC) plasma waves are the mechanism responsible for the acceleration of auroral protons - however, measurements of auroral proton precipitation and Pc1 pulsations from Svalbard under the cusp region indicate that there is no significant link between the two phenomena. Spectrograph measurements of proton aurora over Svalbard are studied alongside co-located magnetometer measurements of Pc1 pulsations. No evidence of a link between proton aurora and Pc1 waves was found by three different methods. Firstly, accelerated protons and Pc1 pulsations have no coincident occurrence. Secondly, the proton energy spectrum does not change between Pc1 activity and quiet times. Finally, no imprint of the EMIC wave is found in periodicity of the intensity and blue-shift of the proton H-α line, unlike in flickering electron aurora where intensity fluctuations are caused by EMIC waves. It may be possible that EMIC waves are causing acceleration but not propagating down to cause Pc1 pulsations, however we deem this unlikely. Therefore we conclude that EMIC waves are not the mechanism responsible for accelerating auroral protons in the cusp.

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Key Points:

- We present evidence that EMIC waves are not the mechanism responsible for the acceleration of auroral protons in the cusp.
- Three separate methods using ground observations from Svalbard failed to show a link between proton acceleration and Pc1 pulsations.
- While EMIC waves are known to cause protons to precipitate, another mechanism is likely responsible for their acceleration.

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Abstract

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Plain Language Summary

Is it widely thought that a type of plasma wave called an EMIC (Electromagnetic Ion Cyclotron) wave is responsible for the observed acceleration of protons which enter the Earth's atmosphere from space at high-latitudes, in a region of the Earth's magnetic field called the cusp. When these protons reach the atmosphere they cause aurora invisible to the naked eye. This proton aurora can be observed using the Spectrographic Imaging Facility (SIF), which is situated on the Arctic archipelago of Svalbard. The EMIC plasma waves can also be measured by the low frequency pulsations they cause in the magnetic field, measured from the same location in Svalbard. In this study we compare the proton aurora's characteristics with magnetic measurements of the plasma waves by three different methods. Finding no significant evidence of a link between the two phenomena, we conclude that EMIC plasma waves are not responsible for accelerating auroral protons in the high-latitude cusp region. This means that some other acceleration mechanism must be responsible, however, there is a lack of suitable candidates which could indicate the true mechanism is something new or unexpected.

1 Introduction

Proton aurora is a natural atmospheric light, invisible to the human eye, caused by the precipitation of energetic protons into the atmosphere from space. When observed in the high Arctic under the polar cusp, proton aurora originating directly from the solar wind can be observed. The cusp proton aurora is typically observed with a blue-shifted spectrum with super-solar wind velocities (430 - 1400 $\mathrm{km\,s^{-1}}$; Lummerzheim & Galand 2001; Galand et al. 2001; compared to around 400 $\mathrm{km\,s^{-1}}$ in the slow solar wind; Hundhausen 1970), indicating that some acceleration process occurs within the polar cusp (Galperin, 1963). This acceleration process is typically assumed to be by Landau damping of ElectroMagnetic Ion Cyclotron (EMIC) waves (Engebretson et al., 2013; Xiao et al., 2013; Khazanov et al., 2015; Ozaki et al., 2018). However, observational evidence that EMIC waves are the acceleration mechanism of proton aurora has never been shown definitively, and there are no observational studies of proton acceleration in the cusp. This paper presents observations of accelerated proton aurora and Pc1 pulsations from Svalbard and shows that there is no discernible link between the two phenomena, contrary to expectations.

EMIC plasma waves are left-circularly polarised electromagnetic waves which propagate quasi-parallel along magnetic field lines, oscillating transverse to the magnetic field. The wave-particle interactions of EMIC waves are one of the main precipitation mechanisms for protons trapped in the magnetosphere, resulting in proton aurora equatorward of the auroral oval. EMIC waves are typically generated at equatorial latitudes as a result of a fundamental plasma instability (e.g. due to the mixing of hot and cold plasmas) and propagate along field-lines to their foot-points at higher latitudes, where they manifest as structured geomagnetic Pc1 (period of 0.2-1 Hz; Glaßmeier (2007)) pulsations at the ground (Varlamov et al., 2021; Yahnin & Yahnina, 2007; Yahnina et al., 2000; Francia et al., 2020). However, high-latitude and cusp EMIC waves are generally observed as unstructured Pc1 pulsations, suggesting that their origin lies in the outer magnetosphere (Menk et al., 1993; Mursula et al., 1994; Regi et al., 2017).

EMIC waves have been observed to precipitate protons in several studies (e.g. Xiao et al., 2013; Ozaki et al., 2018; Liang et al., 2022; Tian et al., 2023). The polar cusp contains a minimum magnetic potential, around which protons with high field-perpendicular velocities can become trapped. EMIC waves have been shown by Xiao et al. (2013) to be capable of violating the invariance of the magnetic moment and scattering protons into the atmosphere, leading to cusp proton aurora.

Outwith the cusp region, Kim et al. (2017) showed travelling convection vortices to generate EMIC waves coincident with proton auroral precipitation. In the night-side auroral oval, proton aurora is understood to be caused by precipitation from the plasma sheet. EMIC wave scattering is also associated with detached proton auroral arcs, i.e. low-latitude bands of proton aurora detached from the main auroral oval. Magnetic Pc1 pulsations consistent with EMIC waves have been detected near detached subauroral proton arc events (Immel et al., 2005; Sakaguchi et al., 2007) and isolated proton aurora (IPA) (Sakaguchi et al., 2015; Nomura et al., 2016; Kim et al., 2021; Liang et al., 2022; Nakamura et al., 2021; Ozaki et al., 2022). EMIC waves have been shown to produce detached proton aurora arcs by pitch-angle scattering of protons from the ring current into the upper atmosphere (Spasojevi et al., 2013). Geomagnetic Pc1 pulsations associated with a substorm have been observed occurring during a proton arc and Strong Thermal Emission Velocity Enhancement (STEVE) event (Varlamov et al., 2021). EMIC/Pc1 waves have also been linked to proton precipitation on the dayside on Svalbard by Engebretson et al. (2013), on closed field lines.

Weak evidence of periodic flickering of a wide-band assumed to be isolated proton aurora (IPA) was reported as evidence of EMIC acceleration by Ozaki et al. (2018) (akin to flickering electron aurora (Whiter et al., 2010)). They present a 1 Hz periodic modulation in photometer measurements correlated with Pc1 observations; however, they show no method of separating IPA from contamination by electron precipitation. In addition, their conclusions do not necessarily apply to the cusp region.

This study compares observations of the proton H-α auroral emission with observations of Pc1 pulsations in the cusp. We do not observe any temporal link between proton aurora and Pc1 waves or any effect from Pc1 waves on the velocity spectrum of the protons. We do not observe any periodic flickering in the H-α auroral emission line.

2 Instrumentation and Observations

The proton aurora H-α spectrum was observed using the High-Throughput Imaging Echelle Spectrograph (HiTIES, Chakrabarti et al. 2001). HiTIES is part of the Spectrographic Imaging Facility (SIF), located at the Kjell Henriksen Observatory (KHO) at Longyearbyen on the Arctic archipelago, Svalbard at geographic latitude 78° 8' 52.8" N, and longitude 16° 2' 34.8" E . The instrument includes an echelle spectrograph grating, an EMCCD (Electron-Multiplying Charged Coupled Device) detector, and a mosaic filter, which is used to select multiple overlapping spectral orders, enabling observation of multiple non-contiguous wavelength bands at high resolution. HiTIES is directed at magnetic zenith with a 8° by 0.05° field-of-view. The imaging cadence is 2 Hz giving a temporal Nyquist frequency of 1 Hz. This study uses the H-α filter panel, which selects the band 649 - 663 nm, and has been installed from December 2015 to the present. An example observation of the proton aurora spectrum with HiTIES is shown in Figure 1.

This work uses observations taken during the 2021-2022 observing season, from 4th December 2021 - 31 January 2022. Periodicity studies were carried out on proton aurora events with concurrent Pc1 observations on 13 December 2021 and 15 December 2021. Observations during February and March were not used since daylight limits and time-biases the observations.

The H-α spectrum is extracted from the EMCCD image of the H-α panel in the mosaic filter by integrating the pixel intensity in the spatial direction (along the slit). The spectrum is then calibrated using flat-field images taken on 4 December 2021, and dark-field images taken every 20 minutes. The wavelength of the spectrum is calibrated using the OH airglow spectrum and the solar spectrum.

A 2-axis search-coil magnetometer (Engebretson et al., 2009), co-located with HiTIES at the KHO, Svalbard was used to observe Pc1 pulsations. It consists of two sensors aligned with magnetic N-S and E-W. The Pc1 geomagnetic pulsations are observed in the 0.1 - 1 Hz range, and are used as a proxy for EMIC waves (Paulson et al., 2017; Francia et al., 2020).

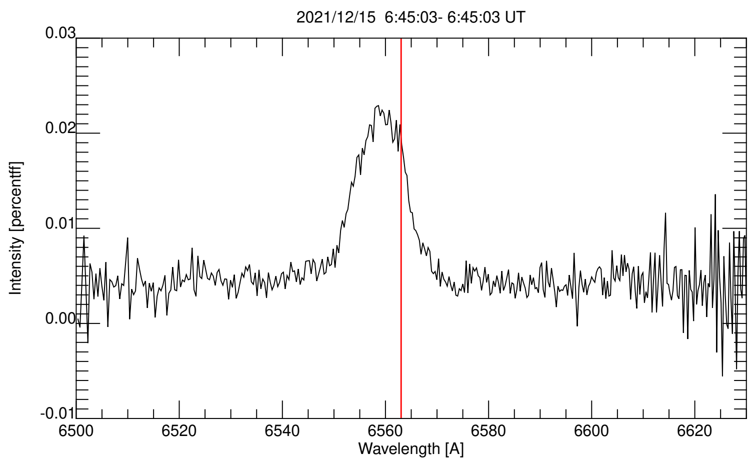

Figure 1: An example H-α spectrum as measured by the HiTIES instrument, where the vertical red line signifies the stationary H-α wavelength at 656.3 nm. The broad H-α line is clearly visible above the background showing its usual blueshifted peak. The median velocity from the blueshift of this spectrum is around 300 $\mathrm{km\,s^{-1}}$, with the top end around 600 $\mathrm{km\,s^{-1}}$.

3 Methods and Results

Three methods were used to analyse the proton aurora H-α spectrum and magnetometer data. A 'field guide' to show the method of identification of proton aurora is shown in the appendix, Figure A1. EMIC waves are identified by an enhanced unstructured signal in the Pc1 band as measured by the 2-axis Search-Coil Magnetometer, examples shown in Figure 2. The two December 2021 events shown are used in the spectra comparison and periodicity methods described below. The first, subsection 3.1, is a comparison of the times and durations when Pc1 and proton aurora occur, to determine whether the occurrences are statistically linked. Subsection 3.2 is a comparison of the velocity spectrum of the incident protons during Pc1 events and during Pc1-quiet times to determine whether the Pc1 waves are linked to an increase in proton acceleration. The third method, subsection 3.3, is to search for periodic flickering in the proton aurora, as this has previously been identified as a signature of EMIC acceleration in electron aurora. All three methods fail to show any link between Pc1 and proton aurora.

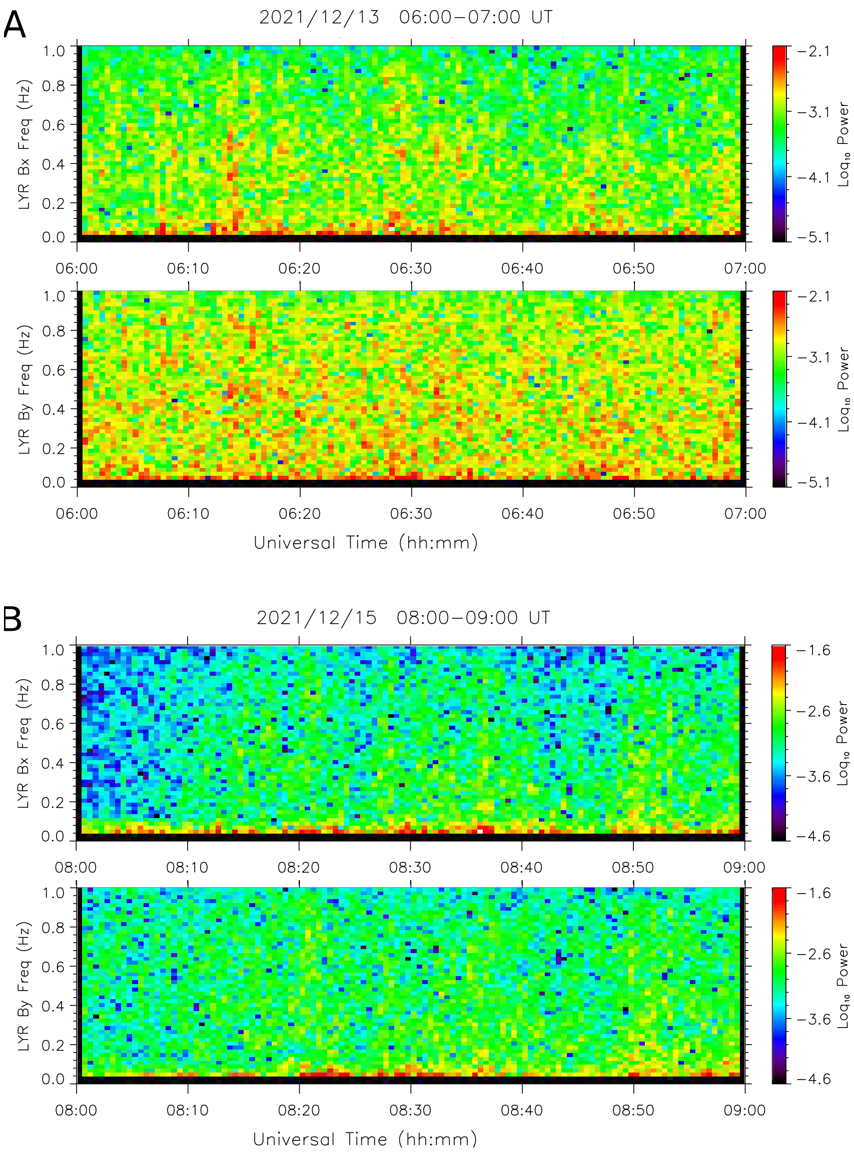

Figure 2: Magnetometer observations of Pc1 enhancements during 13 and 15 December 2021. Each panel shows from top to bottom the spectrogram of B_x and the spectrogram of B_y for each unstructured Pc1 wave observation, 13/12/2021 06-07 UT in Panel A and 15/12/2021 08-09 UT in Panel B.

3.1 Co-occurrence

We present a statistical study of the contingency of proton aurora and Pc1 pulsations, i.e. the likelihood that they are correlated based on how often they occur together vs. separately. Identifying proton aurora and Pc1 enhancements for the entire December/January period of the 2021/2022 observing season, we obtain occurrences for proton aurora and Pc1 pulsations. Note that all times where it is not possible to identify proton aurora, i.e. bright moonlit clouds or daylight, have been discounted from both data sets. The proton aurora and Pc1 enhancements were identified manually; see the identification process in the Field Guide, Appendices Figure A1. The occurrence relationship between the proton aurora and Pc1 is first tested with the odds ratio - this is a simple statistic which quantifies the strength of association between two events.

For some occurrence table of events A and B;

	B=1	B=0
A=1	p_{11}	p_{10}
A=0	p_{01}	p_{00}

The Odds ratio is;

$$OR = \frac{p_{11}p_{00}}{p_{10}p_{01}}$$

The proton aurora and Pc1 pulsation contingency table is found in Table 1. By comparing the number of 10 minute long time-intervals during the observing season where Pc1 and proton aurora are observed it is clear that while proton aurora is quite common, Pc1 observations are relatively rare. This already suggests that Pc1 pulsations are not likely to be the only acceleration mechanism since they are observed together in only 17 of the 10-minute intervals across a 2-month observing season.

The Odds ratio is calculated to examine whether proton aurora and Pc1 have any temporal relationship, as a statistic of the correlation in time. If Pc1 (EMIC) waves were the responsible acceleration mechanism for auroral protons, a positive time correlation would be expected between accelerated proton aurora and Pc1 pulsations. The odds ratio for this table is 1.249, with a p-value of 0.213 which is much greater than the standard threshold of 0.05. Therefore, the Odds ratio is not statistically significant and there is no evidence of time dependency between Pc1 enhancement and proton aurora.

	Pc1 present	No Pc1
Proton aurora present	17	1696
No proton aurora	54	6729

Table 1: Contingency table showing the number of 10-minute intervals of observation during the 21/22 Dec-Jan observing period with enhanced Pc1 power and proton aurora (times when proton aurora is not visible due to daylight or bright clouds have been discounted). Odds ratio = 1.249, p-value = 0.213, therefore not statistically significant.

3.2 Spectrum comparison

The second piece of evidence we present is a comparison of the average proton aurora spectrum during Pc1 pulsations, and when there are no Pc1 pulsations. 80 minutes of proton aurora observations during Pc1 and 350 minutes of proton aurora without Pc1 were averaged throughout the December 2021 observing season. The spectra were normalised for comparison. OH airglow contamination was removed by fitting and subtracting synthetic spectra, using a least-squares-fit algorithm (with temperature dependance). Synthetic spectra for temperatures 150 - 250 K were generated and fit to the H-α panel background, excluding the H-α emission from 6540 - 6570 Å. There is some H-α airglow visible in the no-Pc1 spectrum as it was integrated over a longer period, but it does not affect the results of this paper. Since the majority of emitting particles travel quasi-parallel to the magnetic field-line (Galperin, 1963) and we point to the magnetic zenith, the line-of-sight velocity determined from the Doppler shift of the proton spectrum can be used as an indication of the characteristic energy of the incident precipitation.

The average proton aurora spectra for Pc1 and no-Pc1 times are compared in Figure 3. The width and centre of the H-α spectrum is effectively identical during either Pc1 or no-Pc1 times, i.e. there is no significant change in the velocity distribution of the precipitating auroral protons. This shows no link between Pc1 pulsations and acceleration of auroral protons.

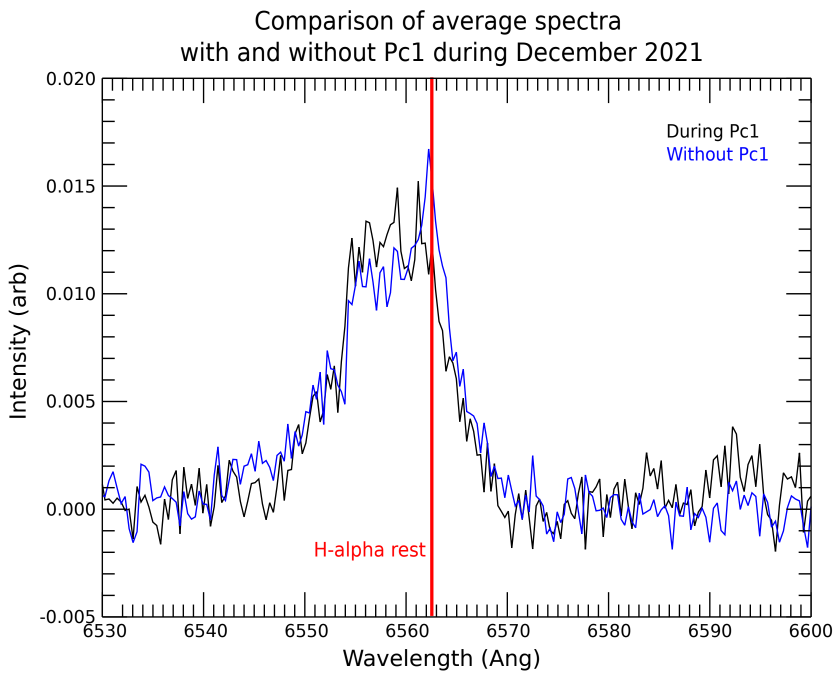

Figure 3: Comparison of 80 minutes of proton aurora during Pc1 event in black, and 350 minutes of proton aurora when the Pc1 band is quiet in blue, The rest wavelength of H-α, 656.3 nm is marked with a red vertical line, and OH spectral lines are marked with arrows. The plot shows no change in acceleration of the proton aurora when Pc1 is present or not present.

3.3 Periodicity

The integrated intensity and mean blueshift are calculated for the spectra at each time step during selected proton events, generating two time series each 60 s long. The timeseries backgrounds were removed by subtracting a linear fit, effectively a high-pass filter on the intensity variation (as we are looking for 1-10 s periodic signals). A range of different days during the December 2021 period were chosen, specifically those where Pc1 pulsations were also measured and where the proton spectrum was quite bright. The timeseries were analysed using autocorrelation and Fourier transform methods to identify any periodic oscillations that might show flickering aurora such as the flickering electron aurora observed by Whiter et al. (2010) or the flickering observed by Ozaki et al. (2018). The significance of the autocorrelation results was tested using a bootstrapping method.

Example autocorrelation and Fourier transforms performed on the proton aurora photon flux time series during 13th and 15th December 2021 do not show any periodic signal over the entire day of data. Pc1 band magnetometer plots during these times are shown in Figure 2. Figure 4 shows the results of performing an autocorrelation of the proton aurora intensity timeseries of each minute of data in a 50 minute period on 13/12/2021 and a 30 minute period on 15/12/2021 during which Pc1 enhancement and accelerated proton aurora were observed together. The red horizontal lines in these figures represent missing data when the HiTIES shutter is closed. In Figure 4b there are many times, e.g. at 7 minutes and 22 minutes, where the autocorrelation function falls off slowly to strongly negative values at 40s. This is the result of a time series with a slow variation (much too slow to be related to Pc1 pulsations) during the 60s interval, which is not removed by the time series background subtraction described in Section 3. Bootstrapping of the timeseries by recording the maximum autocorrelation value for each lag over 10, 100, 1000, and 10000 random permutations of the aurora intensity timeseries gives a minimum statistically significant amplitude of around 0.2. Neither of the autocorrelation plots shows structures that exceed this threshold, so we can conclude that there are no significant periodic signals.

4 Discussion

To relate the results of this study which concern Pc1 and proton aurora to EMIC waves, we must assume that EMIC waves nearly always cause Pc1, and Pc1 are nearly always caused by EMIC waves. While the two have been closely related, (Varlamov et al., 2021; Francia et al., 2020; Yahnin & Yahnina, 2007; Yahnina et al., 2000), there is a possibility that cusp EMIC waves do not always propagate down to cause Pc1 pulsations. Therefore it is possible that EMIC waves do accelerate auroral protons in the cusp, but do not cause Pc1 pulsations. However, this scenario seems unlikely since EMIC and Pc1 waves have been linked so closely by many studies. Note that this study is based on cusp proton aurora, therefore conclusions cannot be drawn about the role of EMIC waves in the closed-field regime.

In this study we show evidence that disproves the role of EMIC waves as the primary acceleration mechanism for aurora protons in the cusp. It is difficult to 'disprove' any process. From our results it seems clear that although it is possible that EMIC waves are capable of accelerating cusp protons, it cannot be the primary acceleration mechanism as we did not measure any change in the proton acceleration during Pc1 pulsations. Pc1 are also too infrequent to be causally linked to accelerated proton aurora (we would expect the magnetometer to detect Pc1 over a much larger area than HiTIES' small field-of-view, so could even expect Pc1 to be more frequent than proton aurora if they were linked).

We evidence this conclusion with the HITIES instrument which has high time resolution, throughput, and wavelength resolution. However, there are some limitations. The signal-to-noise ratio is low for very short integration periods which may affect the periodicity study. The Nyquist frequency for the time resolution of the instrument is 1 Hz which should be sufficient to observe in the Pc1 band (0.1 - 1 Hz) but the autocorrelation method may be less reliable close to the Nyquist limit.

As in any optical study, cloud cover and bright moon/day-light hours reduce the useful data within the season. Cloud cover and 'too-bright' times were removed from both the Pc1 and aurora datasets so these would not time-bias the occurrence statistics. However, there is also time-dependence of whether observations are made in the cusp or not. Unstructured Pc1 and proton aurora occur primarily in the cusp at this latitude so we might expect a slight time-dependence which would artificially inflate the Odd's ratio. However, we find that the Odd's ratio is still well under the threshold for statistical significance so we can ignore this effect.

We expected some temporal link between Pc1 and proton aurora as it has been reported to be a precipitating mechanism by Xiao et al. (2013). One explanation why we do not observe this is that EMIC waves are trapped in the same magnetic bottle region as the cusp proton population. This could result in EMIC waves causing auroral protons to precipitate but not propagating down the field-line to be observed as Pc1 pulsations.

The measured H-α spectra do contain contamination from airglow, which must be considered. The contribution is vanishingly small for short time-integrations but when we start to integrate longer times of around 20 minutes or more the airglow contribution appears. For our long time-integrated spectra the airglow is subtracted using temperature-dependent least-squares fitting. There is also some faint H-α airglow which we have ignored as it is a fairly narrow peak around the rest wavelength so does not affect the results of this study.

Our results indicate a need for an alternative explanation for acceleration of protons in the cusp. Since the proton aurora spectrum is accelerated almost all of the time, transient and infrequent events are unlikely candidates. The most obvious alternative mechanism is other forms of ion-acoustic wave, however they suffer the same transience as EMIC waves. Magnetic reconnection is known to accelerate protons (e.g. Phan et al. 2000; Gosling et al. 2005). Reconnection occurs in the high-latitude nightside cusp, but since this geometry requires northward IMF it is not frequent enough to be a good candidate for cusp proton aurora. Turbulent reconnection is also capable of accelerating ions and is an ever-present feature of the bow-shock (Gingell et al., 2020), however the amount of turbulence varies with different IMF regimes (quasi-parallel vs. quasi-perpendicular shock; Plank & Gingell 2023) so we would expect variation with IMF conditions. There are several possibilities for cusp proton acceleration to explore in future work, and we do not currently have a favoured alternative explanation.

5 Conclusions

We present three different analyses of spectrograph observations of proton aurora and co-located magnetometer ground-based observations, in order to investigate whether EMIC waves are the accelerating mechanism of proton aurora. Our analyses show no link, implying that EMIC waves are not the acceleration mechanism responsible for auroral protons in the cusp.

The first analysis is a study of the co-occurrence of Pc1 pulsations with accelerated proton aurora. Throughout the December and January of the 2021/2022 observing season, there was no temporal link between Pc1 pulsations and accelerated proton aurora. Although accelerated proton aurora is common, Pc1 pulsations were only present during proton aurora in 17 10-minute intervals during the two months. The second analysis is a comparison of the average proton aurora spectrum with and without the presence of Pc1. It shows that there is no significant difference in acceleration during Pc1 pulsations than at quiet times. The final piece of evidence is that accelerated proton aurora in the cusp shows no flickering (intensity modulation) during any of our Pc1 events, or at other non-Pc1 times (not shown).

Three separate methods have failed to find a link between auroral proton acceleration and Pc1 pulsations, contrary to the prevailing assumptions. This implies that another mechanism is responsible for the acceleration of auroral protons in the cusp.

In future work it would be interesting to compare the proton acceleration under various solar wind, IMF, and magnetospheric conditions.

Acknowledgments

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Availability

The HiTIES data used for measurements of proton aurora in the study are publicly available at Pure via https://www.soton.ac.uk/~dkw1f08/EMICProtonStudyData.zip[1], no access requirements, with GNU General Public License v3.0, and the SIF keograms used in the contingency study are available at sif.unis.no with no access requirements, with license . The 2-Axis Search-Coil magnetometer data used to identify Pc1 pulsation events in the study are publicly available at the University of New Hampshire - Magnetosphere Ionosphere Research Lab website at http://mirl.sr.unh.edu/projects_ulf.html. The data analysis was carried out in Interactive Data Language (IDL), provided by NV5 Geospatial.

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Appendix A Field-Guide to Proton Aurora

The proton aurora observations used in this study are explained in the following 'field-guide' in Figure A1, including a set of six keograms i.e. stack plots of intensity along the wavelength axis, in time where each plot shows 20 minutes of observations. Each keograms gives an example of different typical observations from the SIF instrument and is included here to demonstrate how proton aurora was identified.

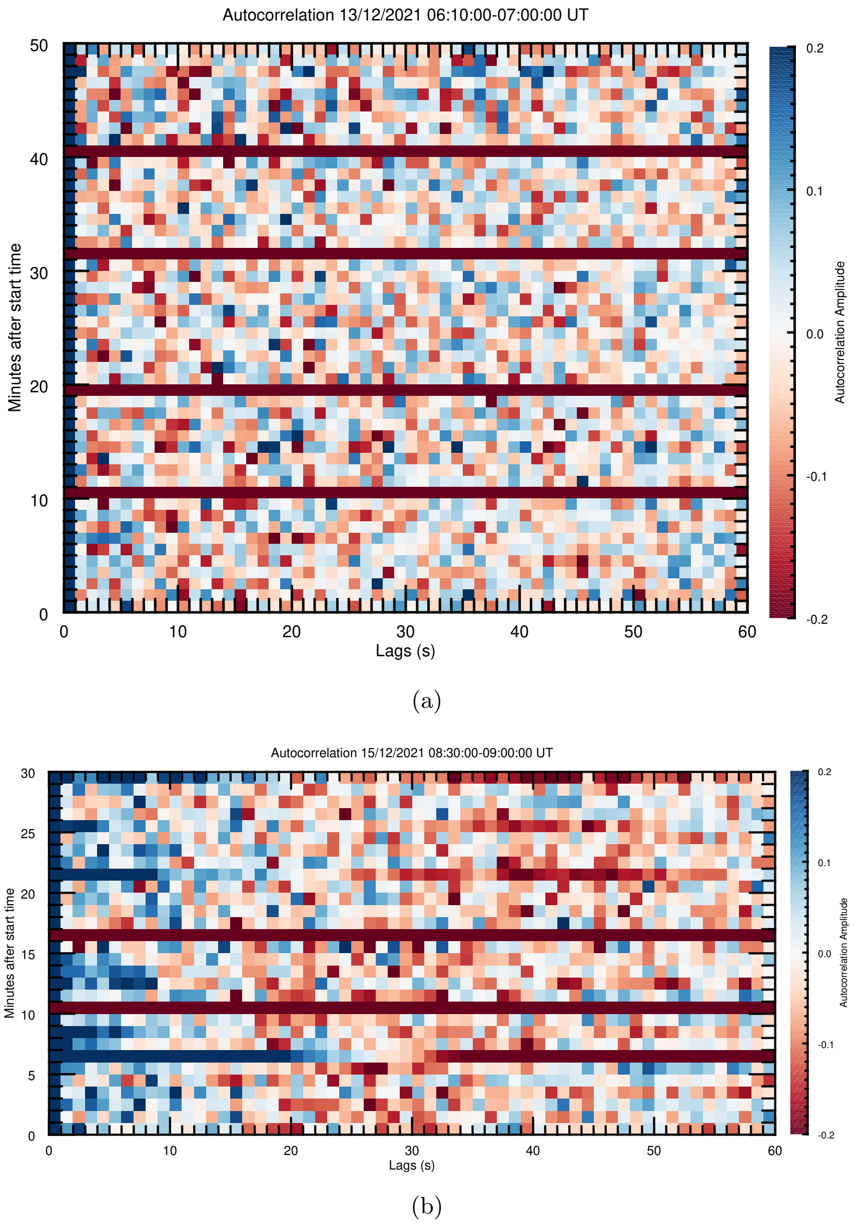

Figure 4: Autocorrelations on the proton aurora H-α total intensity during Pc1 activity shown in Figure 2. The x-axis is the autocorrelation test lags up to 60 seconds, and the y-axis is the minutes after the start time. Each row moving upwards is an intensity autocorrelation on a minute of data, with the amplitude shown by colour, red is negative and blue positive. Periodic signals would show up as vertical repeating structures in these ACF plots of red and blue lines. No such signals appear. The dark red horizontal bands represent missing data, this often occurs when HiTIES closes the shutter to take dark field calibration images. Note the colourbar is set so that the maximum range is equal to the minimum significant value, so no structure within these colourbars is significant.

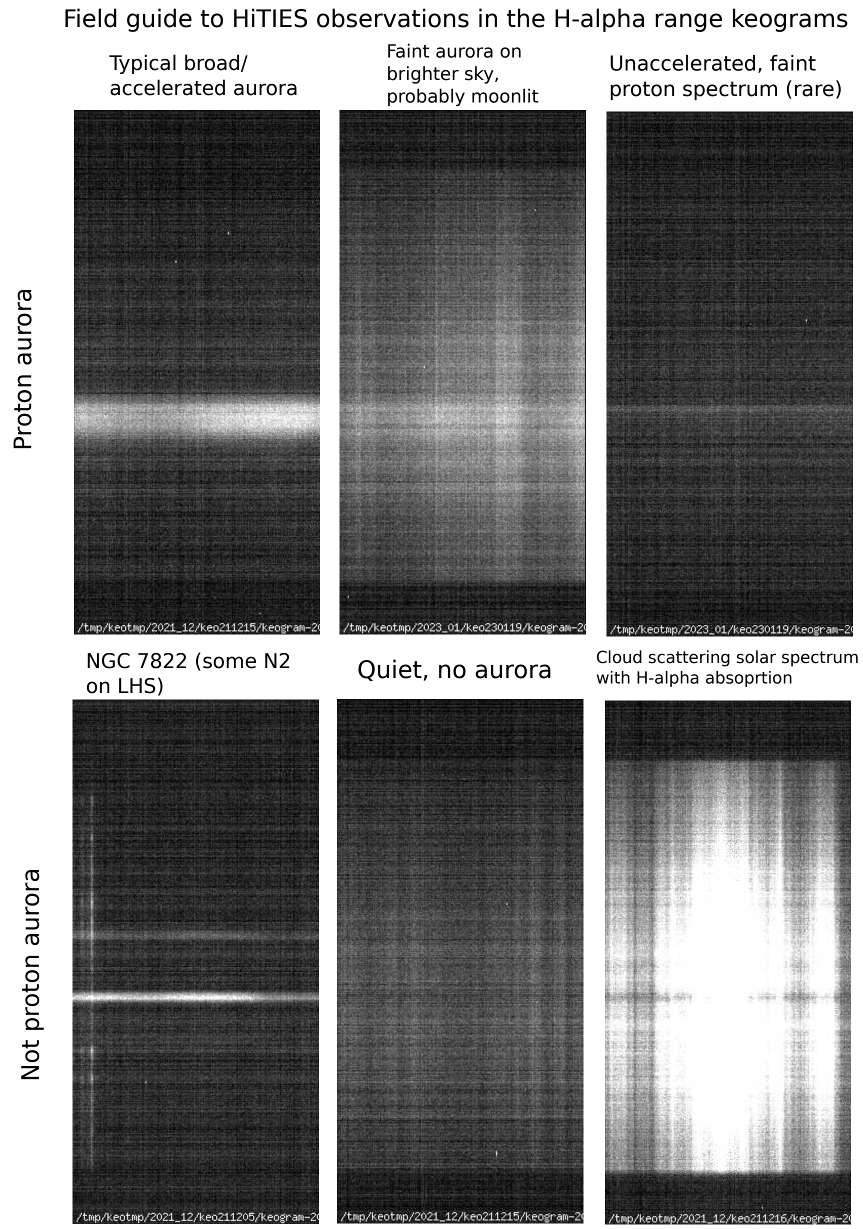

Figure A1: This 'field-guide' shows some common observations from the HiTIES instrument in the H-α panel in keogram form i.e. a row of pixels from each frame of the spectrograph stacked horizontally, with time on the horizontal and wavelength on the vertical axis. The top row shows three examples of proton H-α emission, the most clear and bright on the left and the fainter example in the middle are both auroral proton emission. The top right proton spectrum could be from unaccelerated auroral protons or from H-α airglow or geocorona. The bottom row shows typical non-proton aurora keograms. From left to right, the first is a spectrum from the nebula NGC 7822, which is rich in hydrogen and passes through the HiTIES FOV each day for about 30 minutes. It can be easily identified by the emission line above the bright H-α line which we identify as the N II 658.34 nm line. The second is an quiet panel with no auroral emission, and the third is an example of sun or moonlit sky/cloud signal (the H-α absorption line comes from the solar spectrum).

Pc1 measurements of EMIC waves are not significantly linked to the acceleration of auroral protons in the cusp.

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Key Points:

- We present evidence that EMIC waves are not the mechanism responsible for the acceleration of auroral protons in the cusp.
- Three separate methods using ground observations from Svalbard failed to show a link between proton acceleration and Pc1 pulsations.
- While EMIC waves are known to cause protons to precipitate, another mechanism is likely responsible for their acceleration.

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Abstract

We present three pieces of observational evidence to conclude that EMIC waves are not the mechanism responsible for the acceleration of auroral protons in the polar cusp. It is widely believed that ElectroMagnetic Ion Cyclotron (EMIC) plasma waves are the mechanism responsible for the acceleration of auroral protons - however, measurements of auroral proton precipitation and Pc1 pulsations from Svalbard under the cusp region indicate that there is no significant link between the two phenomena. Spectrograph measurements of proton aurora over Svalbard are studied alongside co-located magnetometer measurements of Pc1 pulsations. No evidence of a link between proton aurora and Pc1 waves was found by three different methods. Firstly, accelerated protons and Pc1 pulsations have no coincident occurrence. Secondly, the proton energy spectrum does not change between Pc1 activity and quiet times. Finally, no imprint of the EMIC wave is found in periodicity of the intensity and blue-shift of the proton H-α line, unlike in flickering electron aurora where intensity fluctuations are caused by EMIC waves. It may be possible that EMIC waves are causing acceleration but not propagating down to cause Pc1 pulsations, however we deem this unlikely. Therefore we conclude that EMIC waves are not the mechanism responsible for accelerating auroral protons in the cusp.

Plain Language Summary

Is it widely thought that a type of plasma wave called an EMIC (Electromagnetic Ion Cyclotron) wave is responsible for the observed acceleration of protons which enter the Earth's atmosphere from space at high-latitudes, in a region of the Earth's magnetic field called the cusp. When these protons reach the atmosphere they cause aurora invisible to the naked eye. This proton aurora can be observed using the Spectrographic Imaging Facility (SIF), which is situated on the Arctic archipelago of Svalbard. The EMIC plasma waves can also be measured by the low frequency pulsations they cause in the magnetic field, measured from the same location in Svalbard. In this study we compare the proton aurora's characteristics with magnetic measurements of the plasma waves by three different methods. Finding no significant evidence of a link between the two phenomena, we conclude that EMIC plasma waves are not responsible for accelerating auroral protons in the high-latitude cusp region. This means that some other acceleration mechanism must be responsible, however, there is a lack of suitable candidates which could indicate the true mechanism is something new or unexpected.

1 Introduction

Proton aurora is a natural atmospheric light, invisible to the human eye, caused by the precipitation of energetic protons into the atmosphere from space. When observed in the high Arctic under the polar cusp, proton aurora originating directly from the solar wind can be observed. The cusp proton aurora is typically observed with a blue-shifted spectrum with super-solar wind velocities (430 - 1400 $\mathrm{km\,s^{-1}}$; Lummerzheim & Galand 2001; Galand et al. 2001; compared to around 400 $\mathrm{km\,s^{-1}}$ in the slow solar wind; Hundhausen 1970), indicating that some acceleration process occurs within the polar cusp (Galperin, 1963). This acceleration process is typically assumed to be by Landau damping of ElectroMagnetic Ion Cyclotron (EMIC) waves (Engebretson et al., 2013; Xiao et al., 2013; Khazanov et al., 2015; Ozaki et al., 2018). However, observational evidence that EMIC waves are the acceleration mechanism of proton aurora has never been shown definitively, and there are no observational studies of proton acceleration in the cusp. This paper presents observations of accelerated proton aurora and Pc1 pulsations from Svalbard and shows that there is no discernible link between the two phenomena, contrary to expectations.

EMIC plasma waves are left-circularly polarised electromagnetic waves which propagate quasi-parallel along magnetic field lines, oscillating transverse to the magnetic field. The wave-particle interactions of EMIC waves are one of the main precipitation mechanisms for protons trapped in the magnetosphere, resulting in proton aurora equatorward of the auroral oval. EMIC waves are typically generated at equatorial latitudes as a result of a fundamental plasma instability (e.g. due to the mixing of hot and cold plasmas) and propagate along field-lines to their foot-points at higher latitudes, where they manifest as structured geomagnetic Pc1 (period of 0.2-1 Hz; Glaßmeier (2007)) pulsations at the ground (Varlamov et al., 2021; Yahnin & Yahnina, 2007; Yahnina et al., 2000; Francia et al., 2020). However, high-latitude and cusp EMIC waves are generally observed as unstructured Pc1 pulsations, suggesting that their origin lies in the outer magnetosphere (Menk et al., 1993; Mursula et al., 1994; Regi et al., 2017).

EMIC waves have been observed to precipitate protons in several studies (e.g. Xiao et al., 2013; Ozaki et al., 2018; Liang et al., 2022; Tian et al., 2023). The polar cusp contains a minimum magnetic potential, around which protons with high field-perpendicular velocities can become trapped. EMIC waves have been shown by Xiao et al. (2013) to be capable of violating the invariance of the magnetic moment and scattering protons into the atmosphere, leading to cusp proton aurora.

Outwith the cusp region, Kim et al. (2017) showed travelling convection vortices to generate EMIC waves coincident with proton auroral precipitation. In the night-side auroral oval, proton aurora is understood to be caused by precipitation from the plasma sheet. EMIC wave scattering is also associated with detached proton auroral arcs, i.e. low-latitude bands of proton aurora detached from the main auroral oval. Magnetic Pc1 pulsations consistent with EMIC waves have been detected near detached subauroral proton arc events (Immel et al., 2005; Sakaguchi et al., 2007) and isolated proton aurora (IPA) (Sakaguchi et al., 2015; Nomura et al., 2016; Kim et al., 2021; Liang et al., 2022; Nakamura et al., 2021; Ozaki et al., 2022). EMIC waves have been shown to produce detached proton aurora arcs by pitch-angle scattering of protons from the ring current into the upper atmosphere (Spasojevi et al., 2013). Geomagnetic Pc1 pulsations associated with a substorm have been observed occurring during a proton arc and Strong Thermal Emission Velocity Enhancement (STEVE) event (Varlamov et al., 2021). EMIC/Pc1 waves have also been linked to proton precipitation on the dayside on Svalbard by Engebretson et al. (2013), on closed field lines.

Weak evidence of periodic flickering of a wide-band assumed to be isolated proton aurora (IPA) was reported as evidence of EMIC acceleration by Ozaki et al. (2018) (akin to flickering electron aurora (Whiter et al., 2010)). They present a 1 Hz periodic modulation in photometer measurements correlated with Pc1 observations; however, they show no method of separating IPA from contamination by electron precipitation. In addition, their conclusions do not necessarily apply to the cusp region.

This study compares observations of the proton H-α auroral emission with observations of Pc1 pulsations in the cusp. We do not observe any temporal link between proton aurora and Pc1 waves or any effect from Pc1 waves on the velocity spectrum of the protons. We do not observe any periodic flickering in the H-α auroral emission line.

2 Instrumentation and Observations

The proton aurora H-α spectrum was observed using the High-Throughput Imaging Echelle Spectrograph (HiTIES, Chakrabarti et al. 2001). HiTIES is part of the Spectrographic Imaging Facility (SIF), located at the Kjell Henriksen Observatory (KHO) at Longyearbyen on the Arctic archipelago, Svalbard at geographic latitude 78° 8' 52.8" N, and longitude 16° 2' 34.8" E . The instrument includes an echelle spectrograph grating, an EMCCD (Electron-Multiplying Charged Coupled Device) detector, and a mosaic filter, which is used to select multiple overlapping spectral orders, enabling observation of multiple non-contiguous wavelength bands at high resolution. HiTIES is directed at magnetic zenith with a 8° by 0.05° field-of-view. The imaging cadence is 2 Hz giving a temporal Nyquist frequency of 1 Hz. This study uses the H-α filter panel, which selects the band 649 - 663 nm, and has been installed from December 2015 to the present. An example observation of the proton aurora spectrum with HiTIES is shown in Figure 1.

This work uses observations taken during the 2021-2022 observing season, from 4th December 2021 - 31 January 2022. Periodicity studies were carried out on proton aurora events with concurrent Pc1 observations on 13 December 2021 and 15 December 2021. Observations during February and March were not used since daylight limits and time-biases the observations.

The H-α spectrum is extracted from the EMCCD image of the H-α panel in the mosaic filter by integrating the pixel intensity in the spatial direction (along the slit). The spectrum is then calibrated using flat-field images taken on 4 December 2021, and dark-field images taken every 20 minutes. The wavelength of the spectrum is calibrated using the OH airglow spectrum and the solar spectrum.

A 2-axis search-coil magnetometer (Engebretson et al., 2009), co-located with HiTIES at the KHO, Svalbard was used to observe Pc1 pulsations. It consists of two sensors aligned with magnetic N-S and E-W. The Pc1 geomagnetic pulsations are observed in the 0.1 - 1 Hz range, and are used as a proxy for EMIC waves (Paulson et al., 2017; Francia et al., 2020).

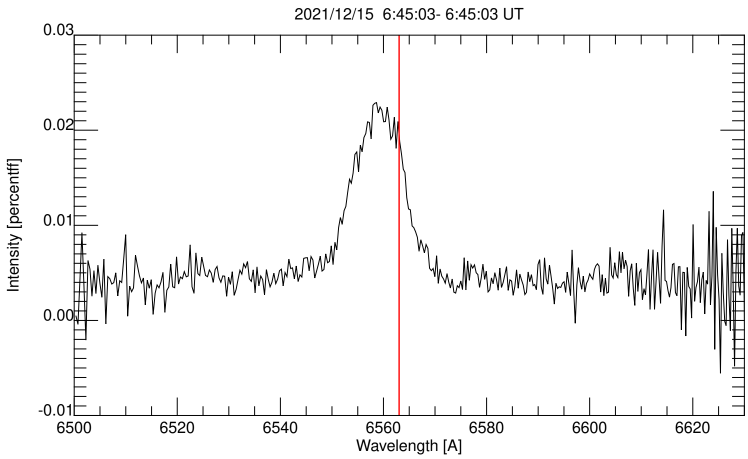

Figure 1: An example H-α spectrum as measured by the HiTIES instrument, where the vertical red line signifies the stationary H-α wavelength at 656.3 nm. The broad H-α line is clearly visible above the background showing its usual blueshifted peak. The median velocity from the blueshift of this spectrum is around 300 km s^{-1}, with the top end around 600 km s^{-1}.

3 Methods and Results

Three methods were used to analyse the proton aurora H-α spectrum and magnetometer data. A 'field guide' to show the method of identification of proton aurora is shown in the appendix, Figure A1. EMIC waves are identified by an enhanced unstructured signal in the Pc1 band as measured by the 2-axis Search-Coil Magnetometer, examples shown in Figure 2. The two December 2021 events shown are used in the spectra comparison and periodicity methods described below. The first, subsection 3.1, is a comparison of the times and durations when Pc1 and proton aurora occur, to determine whether the occurrences are statistically linked. Subsection 3.2 is a comparison of the velocity spectrum of the incident protons during Pc1 events and during Pc1-quiet times to determine whether the Pc1 waves are linked to an increase in proton acceleration. The third method, subsection 3.3, is to search for periodic flickering in the proton aurora, as this has previously been identified as a signature of EMIC acceleration in electron aurora. All three methods fail to show any link between Pc1 and proton aurora.

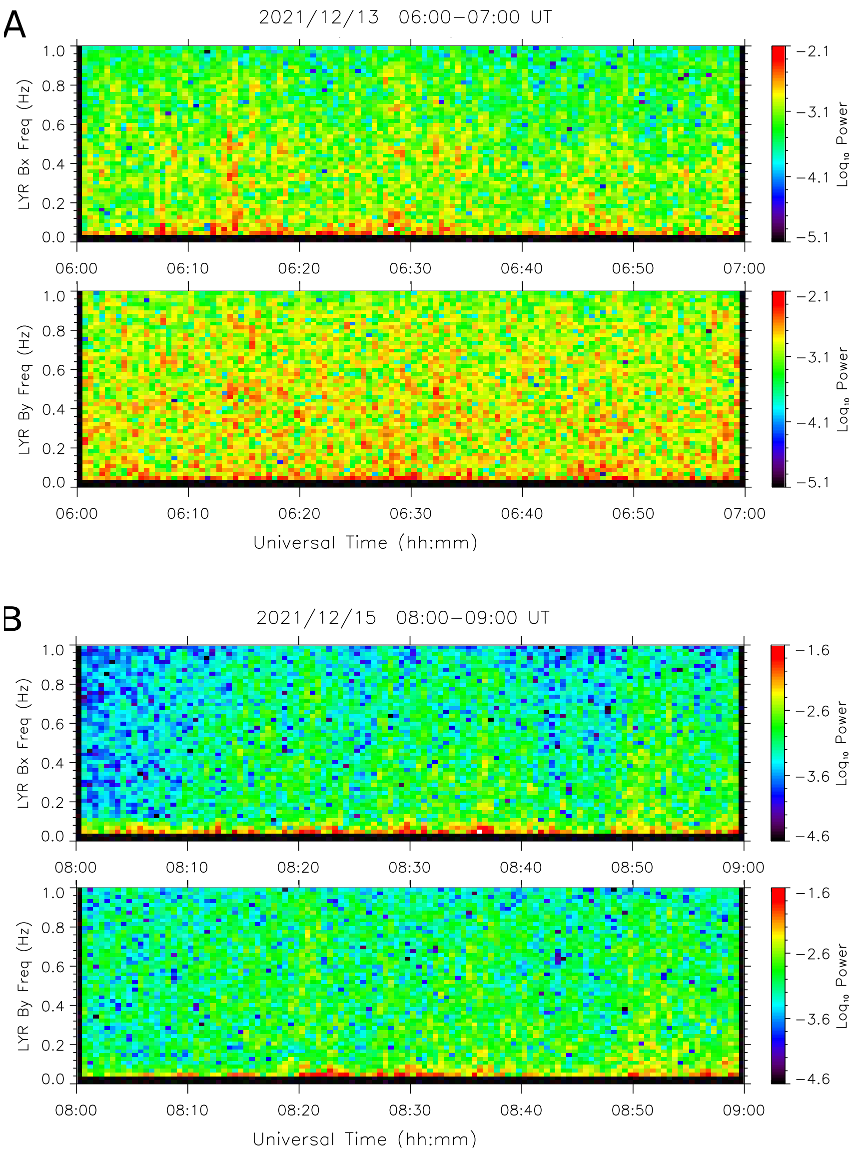

Figure 2: Magnetometer observations of Pc1 enhancements during 13 and 15 December 2021. Each panel shows from top to bottom the spectrogram of B_x and the spectrogram of B_y for each unstructured Pc1 wave observation, 13/12/2021 06-07 UT in Panel A and 15/12/2021 08-09 UT in Panel B.

3.1 Co-occurrence

We present a statistical study of the contingency of proton aurora and Pc1 pulsations, i.e. the likelihood that they are correlated based on how often they occur together vs. separately. Identifying proton aurora and Pc1 enhancements for the entire December/January period of the 2021/2022 observing season, we obtain occurrences for proton aurora and Pc1 pulsations. Note that all times where it is not possible to identify proton aurora, i.e. bright moonlit clouds or daylight, have been discounted from both data sets. The proton aurora and Pc1 enhancements were identified manually; see the identification process in the Field Guide, Appendices Figure A1. The occurrence relationship between the proton aurora and Pc1 is first tested with the odds ratio - this is a simple statistic which quantifies the strength of association between two events.

For some occurrence table of events A and B;

	B=1	B=0
A=1	p_{11}	p_{10}
A=0	p_{01}	p_{00}

The Odds ratio is;

$$OR = \frac{p_{11}p_{00}}{p_{10}p_{01}}$$

The proton aurora and Pc1 pulsation contingency table is found in Table 1. By comparing the number of 10 minute long time-intervals during the observing season where Pc1 and proton aurora are observed it is clear that while proton aurora is quite common, Pc1 observations are relatively rare. This already suggests that Pc1 pulsations are not likely to be the only acceleration mechanism since they are observed together in only 17 of the 10-minute intervals across a 2-month observing season.

The Odds ratio is calculated to examine whether proton aurora and Pc1 have any temporal relationship, as a statistic of the correlation in time. If Pc1 (EMIC) waves were the responsible acceleration mechanism for auroral protons, a positive time correlation would be expected between accelerated proton aurora and Pc1 pulsations. The odds ratio for this table is 1.249, with a p-value of 0.213 which is much greater than the standard threshold of 0.05. Therefore, the Odds ratio is not statistically significant and there is no evidence of time dependency between Pc1 enhancement and proton aurora.

	Pc1 present	No Pc1
Proton aurora present	17	1696
No proton aurora	54	6729

Table 1: Contingency table showing the number of 10-minute intervals of observation during the 21/22 Dec-Jan observing period with enhanced Pc1 power and proton aurora (times when proton aurora is not visible due to daylight or bright clouds have been discounted). Odds ratio = 1.249, p-value = 0.213, therefore not statistically significant.

3.2 Spectrum comparison

The second piece of evidence we present is a comparison of the average proton aurora spectrum during Pc1 pulsations, and when there are no Pc1 pulsations. 80 minutes of proton aurora observations during Pc1 and 350 minutes of proton aurora without Pc1 were averaged throughout the December 2021 observing season. The spectra were normalised for comparison. OH airglow contamination was removed by fitting and subtracting synthetic spectra, using a least-squares-fit algorithm (with temperature dependance). Synthetic spectra for temperatures 150 - 250 K were generated and fit to the H-α panel background, excluding the H-α emission from 6540 - 6570 Å. There is some H-α airglow visible in the no-Pc1 spectrum as it was integrated over a longer period, but it does not affect the results of this paper. Since the majority of emitting particles travel quasi-parallel to the magnetic field-line (Galperin, 1963) and we point to the magnetic zenith, the line-of-sight velocity determined from the Doppler shift of the proton spectrum can be used as an indication of the characteristic energy of the incident precipitation.

The average proton aurora spectra for Pc1 and no-Pc1 times are compared in Figure 3. The width and centre of the H-α spectrum is effectively identical during either Pc1 or no-Pc1 times, i.e. there is no significant change in the velocity distribution of the precipitating auroral protons. This shows no link between Pc1 pulsations and acceleration of auroral protons.

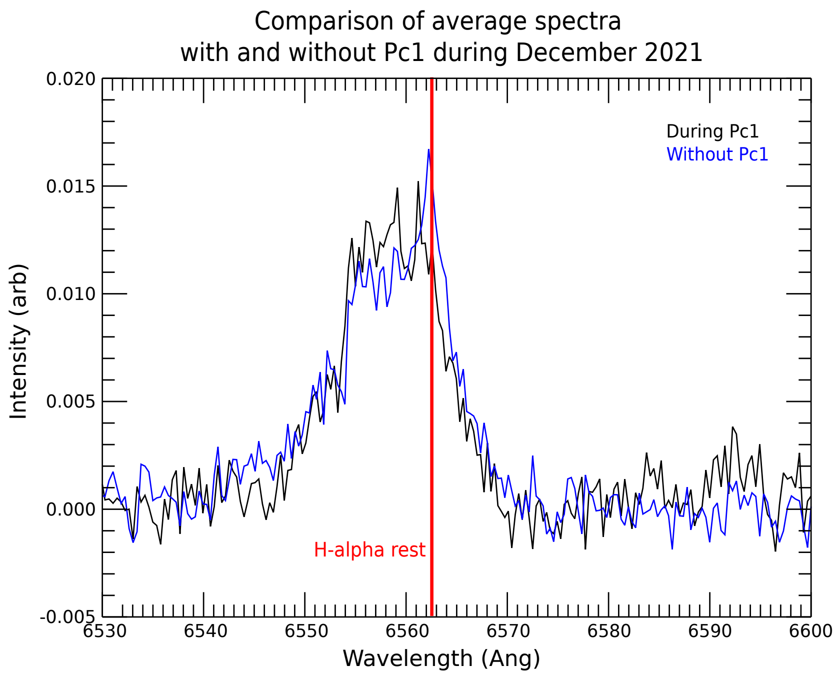

Figure 3: Comparison of 80 minutes of proton aurora during Pc1 event in black, and 350 minutes of proton aurora when the Pc1 band is quiet in blue, The rest wavelength of H-α, 656.3 nm is marked with a red vertical line, and OH spectral lines are marked with arrows. The plot shows no change in acceleration of the proton aurora when Pc1 is present or not present.

3.3 Periodicity

The integrated intensity and mean blueshift are calculated for the spectra at each time step during selected proton events, generating two time series each 60 s long. The timeseries backgrounds were removed by subtracting a linear fit, effectively a high-pass filter on the intensity variation (as we are looking for 1-10 s periodic signals). A range of different days during the December 2021 period were chosen, specifically those where Pc1 pulsations were also measured and where the proton spectrum was quite bright. The timeseries were analysed using autocorrelation and Fourier transform methods to identify any periodic oscillations that might show flickering aurora such as the flickering electron aurora observed by Whiter et al. (2010) or the flickering observed by Ozaki et al. (2018). The significance of the autocorrelation results was tested using a bootstrapping method.

Example autocorrelation and Fourier transforms performed on the proton aurora photon flux time series during 13th and 15th December 2021 do not show any periodic signal over the entire day of data. Pc1 band magnetometer plots during these times are shown in Figure 2. Figure 4 shows the results of performing an autocorrelation of the proton aurora intensity timeseries of each minute of data in a 50 minute period on 13/12/2021 and a 30 minute period on 15/12/2021 during which Pc1 enhancement and accelerated proton aurora were observed together. The red horizontal lines in these figures represent missing data when the HiTIES shutter is closed. In Figure 4b there are many times, e.g. at 7 minutes and 22 minutes, where the autocorrelation function falls off slowly to strongly negative values at 40s. This is the result of a time series with a slow variation (much too slow to be related to Pc1 pulsations) during the 60s interval, which is not removed by the time series background subtraction described in Section 3. Bootstrapping of the timeseries by recording the maximum autocorrelation value for each lag over 10, 100, 1000, and 10000 random permutations of the aurora intensity timeseries gives a minimum statistically significant amplitude of around 0.2. Neither of the autocorrelation plots shows structures that exceed this threshold, so we can conclude that there are no significant periodic signals.

4 Discussion

To relate the results of this study which concern Pc1 and proton aurora to EMIC waves, we must assume that EMIC waves nearly always cause Pc1, and Pc1 are nearly always caused by EMIC waves. While the two have been closely related, (Varlamov et al., 2021; Francia et al., 2020; Yahnin & Yahnina, 2007; Yahnina et al., 2000), there is a possibility that cusp EMIC waves do not always propagate down to cause Pc1 pulsations. Therefore it is possible that EMIC waves do accelerate auroral protons in the cusp, but do not cause Pc1 pulsations. However, this scenario seems unlikely since EMIC and Pc1 waves have been linked so closely by many studies. Note that this study is based on cusp proton aurora, therefore conclusions cannot be drawn about the role of EMIC waves in the closed-field regime.

In this study we show evidence that disproves the role of EMIC waves as the primary acceleration mechanism for aurora protons in the cusp. It is difficult to ‘disprove’ any process. From our results it seems clear that although it is possible that EMIC waves are capable of accelerating cusp protons, it cannot be the primary acceleration mechanism as we did not measure any change in the proton acceleration during Pc1 pulsations. Pc1 are also too infrequent to be causally linked to accelerated proton aurora (we would expect the magnetometer to detect Pc1 over a much larger area than HiTIES’ small field-of-view, so could even expect Pc1 to be more frequent than proton aurora if they were linked).

We evidence this conclusion with the HITIES instrument which has high time resolution, throughput, and wavelength resolution. However, there are some limitations. The signal-to-noise ratio is low for very short integration periods which may affect the periodicity study. The Nyquist frequency for the time resolution of the instrument is 1 Hz which should be sufficient to observe in the Pc1 band (0.1 - 1 Hz) but the autocorrelation method may be less reliable close to the Nyquist limit.

As in any optical study, cloud cover and bright moon/day-light hours reduce the useful data within the season. Cloud cover and ‘too-bright’ times were removed from both the Pc1 and aurora datasets so these would not time-bias the occurrence statistics. However, there is also time-dependence of whether observations are made in the cusp or not. Unstructured Pc1 and proton aurora occur primarily in the cusp at this latitude so we might expect a slight time-dependence which would artificially inflate the Odd’s ratio. However, we find that the Odd’s ratio is still well under the threshold for statistical significance so we can ignore this effect.

We expected some temporal link between Pc1 and proton aurora as it has been reported to be a precipitating mechanism by Xiao et al. (2013). One explanation why we do not observe this is that EMIC waves are trapped in the same magnetic bottle region as the cusp proton population. This could result in EMIC waves causing auroral protons to precipitate but not propagating down the field-line to be observed as Pc1 pulsations.

The measured H-α spectra do contain contamination from airglow, which must be considered. The contribution is vanishingly small for short time-integrations but when we start to integrate longer times of around 20 minutes or more the airglow contribution appears. For our long time-integrated spectra the airglow is subtracted using temperature-dependent least-squares fitting. There is also some faint H-α airglow which we have ignored as it is a fairly narrow peak around the rest wavelength so does not affect the results of this study.

Our results indicate a need for an alternative explanation for acceleration of protons in the cusp. Since the proton aurora spectrum is accelerated almost all of the time, transient and infrequent events are unlikely candidates. The most obvious alternative mechanism is other forms of ion-acoustic wave, however they suffer the same transience as EMIC waves. Magnetic reconnection is known to accelerate protons (e.g. Phan et al. 2000; Gosling et al. 2005). Reconnection occurs in the high-latitude nightside cusp, but since this geometry requires northward IMF it is not frequent enough to be a good candidate for cusp proton aurora. Turbulent reconnection is also capable of accelerating ions and is an ever-present feature of the bow-shock (Gingell et al., 2020), however the amount of turbulence varies with different IMF regimes (quasi-parallel vs. quasi-perpendicular shock; Plank & Gingell 2023) so we would expect variation with IMF conditions. There are several possibilities for cusp proton acceleration to explore in future work, and we do not currently have a favoured alternative explanation.

5 Conclusions

We present three different analyses of spectrograph observations of proton aurora and co-located magnetometer ground-based observations, in order to investigate whether EMIC waves are the accelerating mechanism of proton aurora. Our analyses show no link, implying that EMIC waves are not the acceleration mechanism responsible for auroral protons in the cusp.

The first analysis is a study of the co-occurrence of Pc1 pulsations with accelerated proton aurora. Throughout the December and January of the 2021/2022 observing season, there was no temporal link between Pc1 pulsations and accelerated proton aurora. Although accelerated proton aurora is common, Pc1 pulsations were only present during proton aurora in 17 10-minute intervals during the two months. The second analysis is a comparison of the average proton aurora spectrum with and without the presence of Pc1. It shows that there is no significant difference in acceleration during Pc1 pulsations than at quiet times. The final piece of evidence is that accelerated proton aurora in the cusp shows no flickering (intensity modulation) during any of our Pc1 events, or at other non-Pc1 times (not shown).

Three separate methods have failed to find a link between auroral proton acceleration and Pc1 pulsations, contrary to the prevailing assumptions. This implies that another mechanism is responsible for the acceleration of auroral protons in the cusp.

In future work it would be interesting to compare the proton acceleration under various solar wind, IMF, and magnetospheric conditions.

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Availability

The HiTIES data used for measurements of proton aurora in the study are publicly available at Pure via https://www.soton.ac.uk/~dkw1f08/EMICProtonStudyData.zip[1], no access requirements, with GNU General Public License v3.0, and the SIF keograms used in the contingency study are available at sif.unis.no with no access requirements, with license . The 2-Axis Search-Coil magnetometer data used to identify Pc1 pulsation events in the study are publicly available at the University of New Hampshire - Magnetosphere Ionosphere Research Lab website at http://mirl.sr.unh.edu/projects_ulf.html. The data analysis was carried out in Interactive Data Language (IDL), provided by NV5 Geospatial.

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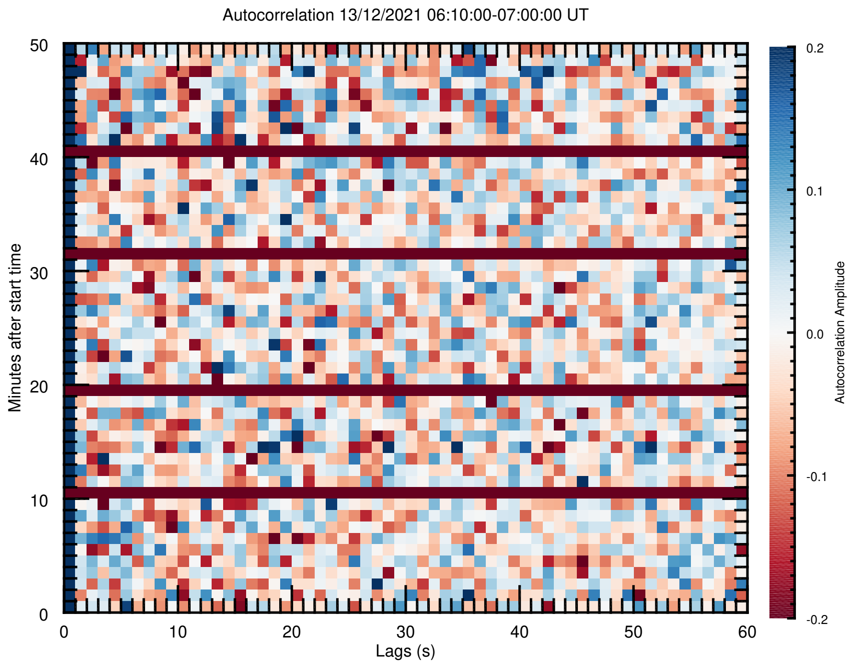
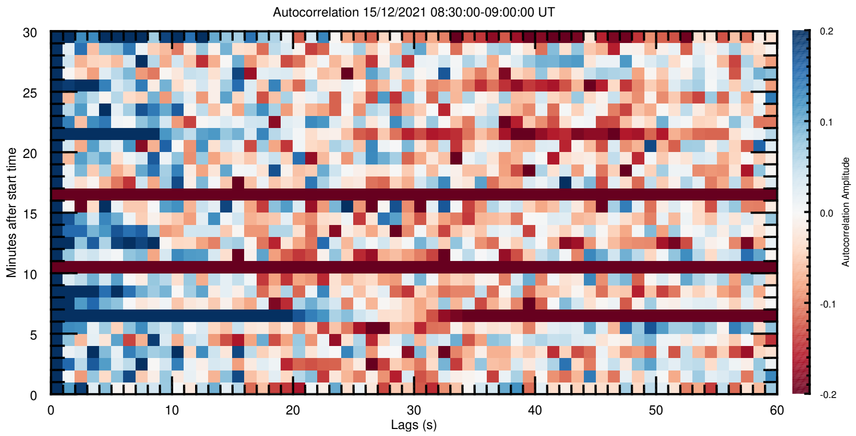
Appendix A Field-Guide to Proton Aurora

The proton aurora observations used in this study are explained in the following 'field-guide' in Figure A1, including a set of six keograms i.e. stack plots of intensity along the wavelength axis, in time where each plot shows 20 minutes of observations. Each keograms gives an example of different typical observations from the SIF instrument and is included here to demonstrate how proton aurora was identified.



(a)



(b)

Figure 4: Autocorrelations on the proton aurora H-α total intensity during Pc1 activity shown in Figure 2. The x-axis is the autocorrelation test lags up to 60 seconds, and the y-axis is the minutes after the start time. Each row moving upwards is an intensity autocorrelation on a minute of data, with the amplitude shown by colour, red is negative and blue positive. Periodic signals would show up as vertical repeating structures in these ACF plots of red and blue lines. No such signals appear. The dark red horizontal bands represent missing data, this often occurs when HiTIES closes the shutter to take dark field calibration images. Note the colourbar is set so that the maximum range is equal to the minimum significant value, so no structure within these colourbars is significant.

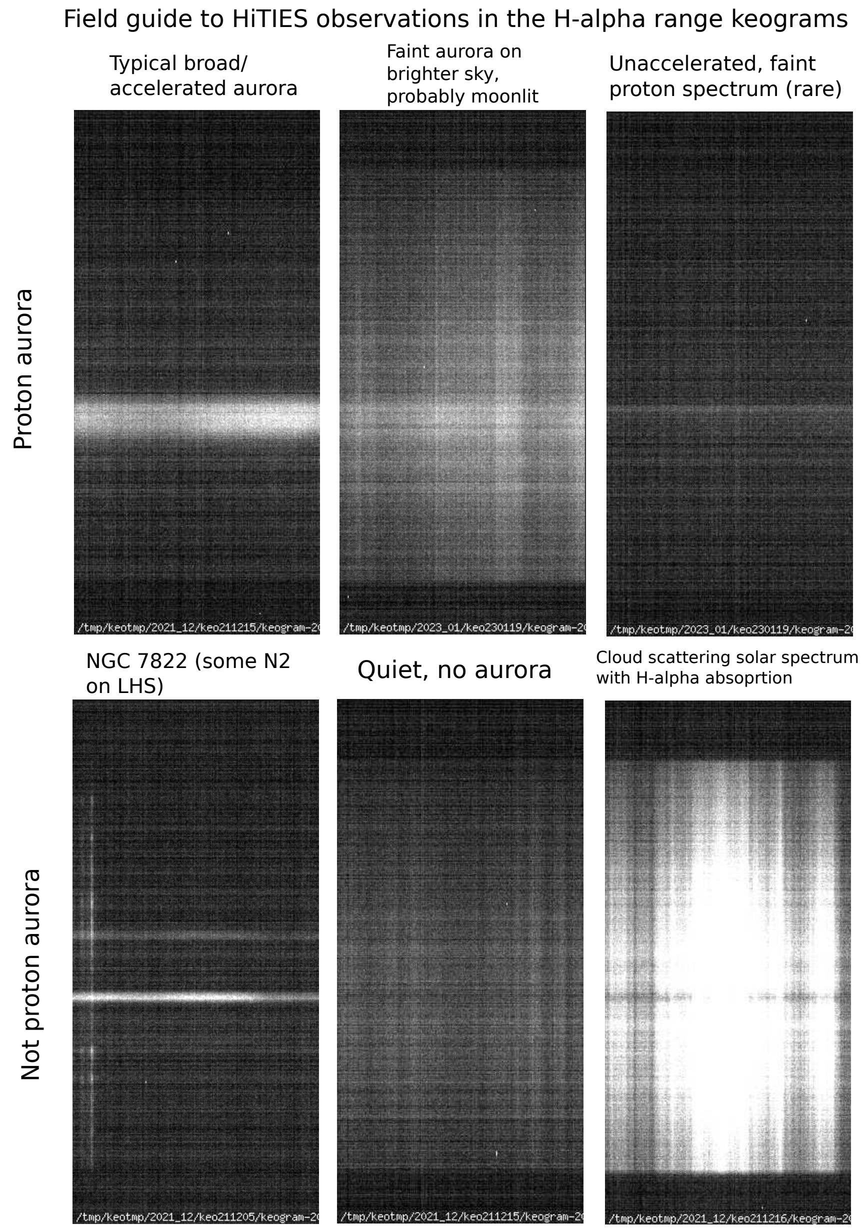


Figure A1: This 'field-guide' shows some common observations from the HiTIES instrument in the H-α panel in keogram form i.e. a row of pixels from each frame of the spectrograph stacked horizontally, with time on the horizontal and wavelength on the vertical axis. The top row shows three examples of proton H-α emission, the most clear and bright on the left and the fainter example in the middle are both auroral proton emission. The top right proton spectrum could be from unaccelerated auroral protons or from H-α airglow or geocorona. The bottom row shows typical non-proton aurora keograms. From left to right, the first is a spectrum from the nebula NGC 7822, which is rich in hydrogen and passes through the HiTIES FOV each day for about 30 minutes. It can be easily identified by the emission line above the bright H-α line which we identify as the N II 658.34 nm line. The second is an quiet panel with no auroral emission, and the third is an example of sun or moonlit sky/cloud signal (the H-α absorption line comes from the solar spectrum).