

Novel radar and optical observations of black auroras in the upper atmosphere

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This thesis is dedicated to my parents, Nellis and Celeste, whose love and support made it possible for me to embark and complete this project.

Abstract

Black auroras show a significant reduction in optical brightness, i.e. reduced flux of particle precipitation, compared to the surrounding diffuse aurora. This phenomenon also exhibits lower mean energy than the surrounding brighter aurora it is embedded in. This shift in particle precipitation energy to a lower mean value is confirmed by using synchronised dual-wavelength optical and EISCAT incoherent scatter radar observations that ran in parallel. A newly observed type of aurora not yet reported in the literature, the anti-black aurora, is introduced. Anti-black auroras sometimes appear as brighter patches paired with the black aurora, always moving together. The underlying mechanisms that cause black auroras are not yet fully understood, although several theories have been proposed: a coupled ionospheric-magnetospheric generation mechanism, and a magnetospheric generation mechanism. No theories exist as to the formation of the anti-black aurora. A possible origin of the mechanism is investigated by mapping the observed motion of the black aurora as well as the anti-black aurora into the magnetosphere, to determine the probable energy of the source electron population, assuming gradient-curvature drift. This inferred particle energy in the equatorial plane in the magnetosphere is found to be higher than the source particle energy in the ionosphere, which leads to the hypothesis of an anomalous electric field in the auroral acceleration region in the upper ionosphere causing the loss of precipitating particle energy along the magnetic field line.

Keywords: black aurora, anti-black aurora
magnetosphere, incoherent scatter radar

Acronyms and Abbreviations

The acronyms and abbreviations used in the text are listed below. For the purposes of clarity, any such usages are written out in full when they first appear.

ASK: Auroral Structure and Kinetics

DN: Data Number

EISCAT: European Incoherent SCATter radar

ELSPEC: ELection SPECTrum estimation technique

FAC: Field aligned current

FOV: Field of View

GSE: Geocentric Solar Ecliptic

GSM: Geocentric Solar Magnetospheric

GUISDAP: Grand Unified Incoherent Scatter Design and Analysis Package

IMF: Interplanetary Magnetic Field

ISR: Incoherent Scatter Radar

LEP: Low Energy Particles experiment

PDLC: Partial Double Loss Cone

PMF: Planetary Magnetic Field

SAO: Smithsonian Astrophysical Observatory

SLC: Single Loss Cone

UB: Upper Band

UHF: Ultra High Frequency

UT: Universal Time

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Chapter 1

Introduction

Black aurora events are defined as dark structures embedded in brighter diffuse aurora. Although the origin and formation of brighter types of the aurora are by now well known, the underlying mechanisms causing black auroras are not. In this study, several events are studied using the EISCAT radar running in conjunction with optical instruments. Several examples of a new type of aurora, the anti-black aurora, are shown and analysed. Underlying mechanisms for both black aurora and anti-black aurora are proposed.

In Chapter 2 the events that lead up to auroral formation are discussed. The motion of particles in the presence of magnetic and electric fields relevant to this study is shown. The magnetosphere and substorms, and everything that leads to auroral formation are introduced. Different types of bright aurora are briefly discussed, and the morphology of the black aurora is discussed extensively. Current theories pertaining to the formation of the black aurora are presented, and related studies to the black aurora shown. The chapter ends with an introduction to a new kind of aurora, the anti-black aurora.

Several different instruments were used to gather data. These include the Auroral Structure and Kinetics instrument from the University of Southampton, the EISCAT UHF transmitter/receiver based in Tromsø, Norway, as well as optical instruments. These are summarised in Chapter 3, and also includes an introduction to the incoherent scatter radar theory.

Campaigns ran in 2006, 2009, and 2016 in which optical and radar data were collected for analysis. The author took part in the 2016 campaign. These campaigns, motivations behind events chosen for this study, and observations made during the campaigns, are discussed in Chapter 4.

The goal in Chapter 5 is to use calibrated data to eventually determine the host electron energies in the magnetosphere and make comparisons with the energies of the ionospheric precipitating particles inside the events, which could indicate the origin of the black aurora underlying mechanism. The first analysis using dual-wavelength methods of the anti-black aurora is shown. Methods used to extract precipitating particle energies are introduced, in particular, the optics-based Southampton ion chemistry model and the radar-based electron spectrum

estimation technique. This will be the first time comparisons are made between the aforementioned methods. A hypothesis as to the cause of the results is proposed.

The final chapter, Chapter 6, gives a summary of results and conclusions, with suggestions for future research.

Chapter 2

Background

2.1 Introduction

The formation of all auroras fundamentally starts with the interaction of plasma with electromagnetic fields in space [Kamide, 2007]. Thus the motion of particles in the presence of magnetic and electric fields is first discussed in Section 2.2. In Section 2.3 the magnetosphere and substorms, and everything that leads to auroral formation will be discussed. In Section 2.4 the bright aurora and its morphology in general are discussed. In Section 2.5 the black aurora phenomenon, which is the topic of this study, will be discussed in detail, in particular, its morphology and theories pertaining to its formation. Selected studies of black auroras are briefly discussed in Section 2.6.

2.2 Particle motion

Only particle motions relevant to this study will be discussed in this section, i.e., gyration, bounce, convection, gradient drift and curvature drift.

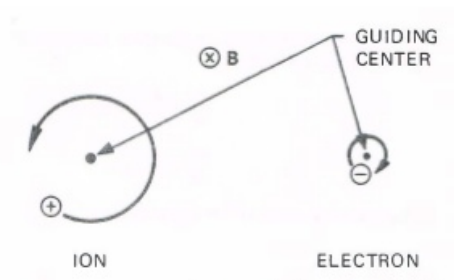


Figure 2.1: Larmor orbits and particle guiding centre in a magnetic field [Chen, 2010].

2.2.1 Gyration

The trajectory of a charged particle when a uniform magnetic field is present is the shape of a helix, with its axis parallel with the magnetic field. The point around which the particle orbits

(referred to as cyclotron motion [Kamide, 2007]) is called its guiding centre, shown in Figure 2.1. Here the Larmor orbit around the guiding centres for both an ion and an electron is shown in relation to the magnetic field B . The magnetic field is pointing into the page, and in relation to that the ion is orbiting counter-clockwise, and the electron clockwise. The cyclotron frequency of the particle is given by

$$\omega_g = \frac{qB}{m} \quad (2.1)$$

with q the charge, m the mass of the particle, B the magnetic field strength, and the gyroradius around the guiding centre is given by

$$r_g = \frac{mv_{\perp}}{qB} \quad (2.2)$$

where $v_{\perp}$ is the component of the velocity perpendicular to the magnetic field.

2.2.2 Bounce

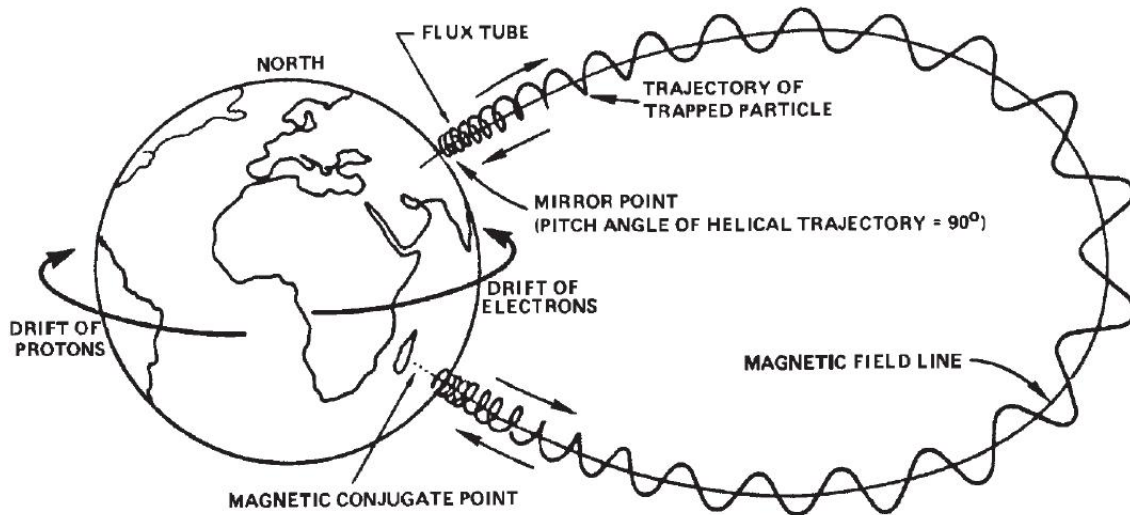


Figure 2.2: Particles trapped in Earth's magnetic field lines. Charged particles usually undergo three types of motion: Cyclotron motion, and total magnetic drift which consists of ∇B -drift and curvature drift [Gruntman, 1997].

The pitch angle between the particles velocity and the magnetic field that is present is given by

$$\alpha = \tan^{-1} \frac{v_{\perp}}{v_{\parallel}} \quad (2.3)$$

where $v_{\perp}$ and $v_{\parallel}$ are its velocity components transverse and along the magnetic field line. Pitch angle is the angle between the particle's velocity vector and the local magnetic field, so

if a particles pitch angle is 0° then its motion is purely parallel to the magnetic field, if it is 90° then its motion is purely perpendicular to the magnetic field. Related to this is the loss cone of a particle, which is a set of angles close to 0° with respect to the magnetic field line, where the particle will escape the magnetosphere and hit the atmosphere. Particles with pitch angles outside the loss cone will continue to be trapped, which then leads to the magnetic mirror effect. Earth's non-uniform magnetic field gives rise to the magnetic mirror effect, and particles drift along the magnetic field line and bounce from pole to pole (see Figure 2.2). The trajectory of the trapped particle can be seen along the dipole-like path of the magnetic field line. The magnetic conjugate point seen in the figure refers to two points that are on opposite ends on the surface of the same magnetic field line. The magnetic flux tube mentioned in the figure is defined as a magnetic field embedded in a field-free environment and entirely confined in a compact region [Cattaneo *et al.*, 2006]. It typically has a cylindrical shape.

Pitch angle determines the altitude of the mirror point. If the particles have a small enough pitch angle (i.e., through collision) they are not magnetic mirror-confined anymore, the bounce point reaching down to the ionosphere [Kamide, 2007; Chen, 2010].

2.2.3 Convection

If an electric field is present with a uniform magnetic field, a drift of the particle's guiding centre (see Figure 2.1) will occur [Chen, 2010]. The general formula for this electric field drift is

$$\mathbf{v}_{\perp gc} = \frac{\mathbf{E} \times \mathbf{B}}{B^2} \quad (2.4)$$

where $\mathbf{v}_{\perp gc}$ is the electric field drift of the guiding centre, $\mathbf{E}$ is the electric field, and $\mathbf{B}$ is the magnetic field strength. This drift is perpendicular to both the electric and magnetic fields present. This drift is referred to as electric drift or $\mathbf{E} \times \mathbf{B}$ drift and leads to ionospheric convection in the polar region. Note that the drift velocity is independent of charge.

2.2.4 Gradient drift

Where magnetic lines of force are present that are straight, but magnetic field strength increases in a direction perpendicular to the direction of the magnetic field, then the drift velocity is given by

$$\mathbf{v}_{\nabla B} = \pm \frac{1}{2} v_{\perp} r_L \frac{\mathbf{B} \times \nabla B}{B^2} \quad (2.5)$$

where $v_{\perp}$ is the particle's velocity component perpendicular to the magnetic field, r_L is the Larmor radius around the particles guiding centre (see Figure 2.1), and ∇B is the magnetic field gradient. This is called ∇B -drift and this drift is in a direction perpendicular to the magnetic field and is due to the changing gyroradius as the particle gyrates [Chen, 2010]. The

drift velocity is independent of charge, but electrons and protons drift eastward and westward respectively because their gyration is in opposite directions (see Figure 2.2).

2.2.5 Curvature drift

If a particle is moving along a line of force with velocity $v_{\parallel}$, curvature drift [Chen, 2010] arises and is defined as

$$\mathbf{v}_R = \frac{mv_{\parallel}^2}{qB^2} \frac{\mathbf{R}_c \times \mathbf{B}}{R_c^2} \quad (2.6)$$

where $\mathbf{R}_c$ is the local radius of curvature. This arises in the magnetosphere because the near-Earth's magnetic field is dipole-like. The dipole model for Earth's magnetic field is more accurate at lower L-shell values, i.e., less than $3 R_E$.

The electrons and protons in Earth's curved magnetic field drift in an eastward and westward direction respectively which is due to curvature drift and because they have opposite charge, causing the formation of the ring current (See Figure 2.5) [Kivelson and Russell, 1995].

Gradient B drift and curvature drift can be combined to give the total magnetic drift,

$$\mathbf{v}_B = \left(v_{\parallel}^2 + \frac{1}{2} v_{\perp}^2 \right) \frac{\mathbf{B} \times \nabla B}{\omega_g B^2} \quad (2.7)$$

where $v_{\parallel}$ and $v_{\perp}$ represent the parallel and perpendicular velocity components of the particle to the magnetic field at a given point [Baumjohann and Treumann, 2004].

2.3 The magnetosphere and substorms

Geomagnetic activity is mainly controlled by the north-south component of the Interplanetary Magnetic Field (IMF). Interplanetary and Planetary Magnetic Fields (PMF) become linked on the dayside, and magnetic flux is transported from the dayside of the magnetosphere to the nightside under pressure of the solar wind, as shown in Figure 2.3. The figure shows a cross-section of the magnetosphere, where the Sun is in the positive X-direction of the coordinate system and North is in the positive Z-direction. The trailing magnetotail, the nightside magnetosphere, is on the right-hand side of the figure in the negative X-direction. The aforementioned linking occurs on both the dayside and nightside magnetosphere, indicated in the figure by red arrows on the X-line.

This linking is referred to as magnetic reconnection [Cowley, 2000]. The solar wind presence drives the reconnected field lines to the night side, which become field lines in the tail lobe. Magnetic flux starts to accumulate, and at around $100 - 200 R_E$ the northern and southern field lines start to reconnect again in the tail [Koskinen, 2011]. In the ionosphere, the other end of

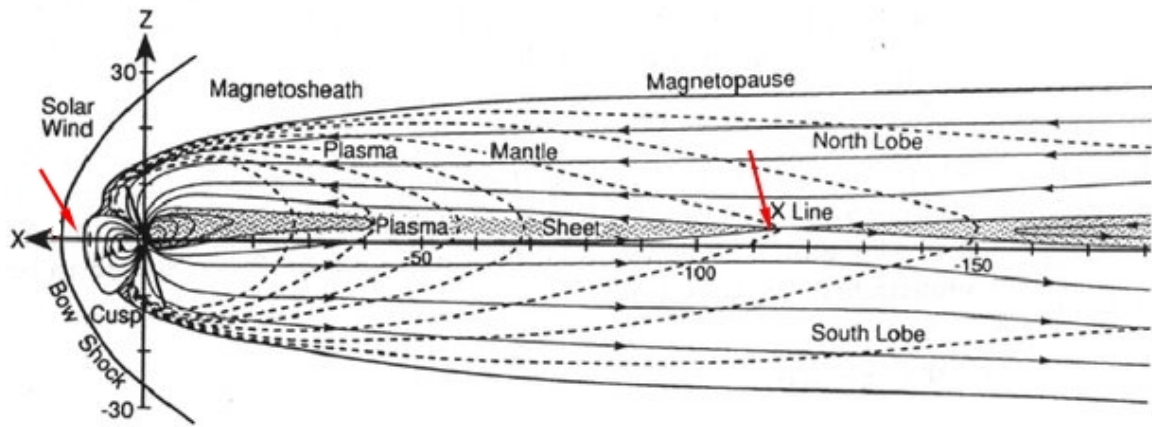


Figure 2.3: Cross section of the magnetosphere [Kivelson and Russell, 1995], with the distance given in Earth radii. The X-coordinate line is pointing towards the Sun, and the Z-coordinate is perpendicular to the X-line. Magnetic reconnection with the solar wind interplanetary magnetic field occurs at the x-line on the dayside and nightside magnetosphere, indicated by the red arrows.

these magnetic field lines have now reached the nightside. The newly reconnected lines start to flow earthward in the magnetosphere, and the ionospheric end of these field lines starts to move towards the dayside. This is shown in Figure 2.4. Figure 2.4 illustrates the flow of plasma over the poles, referred to as ionospheric convection. On the left-hand side, dayside reconnection is seen for the B_z component of the IMF indicated at (1). The magnetic flux then flows over the poles towards the night side of the magnetosphere, indicated by numbers (2)-(5). Nightside magnetic reconnection then occurs (6), followed by the shift of field lines towards the dayside again. This occurs at on the dawn and dusk sectors lower latitudes, shown by numbers (7)-(9).

Figure 2.5 shows another perspective of the geomagnetic field, here showing the current systems in more detail. The solar wind is seen propagating from the Sun on the left-hand side of the figure. The magnetopause is the outer boundary of the magnetosphere and separates the geomagnetic field (and plasma) from solar-wind plasma. The geomagnetic field is confined by sheet currents running through the magnetopause, referred to the magnetopause currents, and shown in the figure. Due to curvature drift discussed in Section 2.2.5 and electrons and protons having opposite charge, they drift in an eastward and westward direction respectively, causing the formation of the ring current. The field-aligned current sheets shown in the figure is also known as the Birkeland currents. These upward and downward moving currents are driven by the solar wind and IMF and connect the magnetosphere to the ionosphere and are strongest during geomagnetic storms and substorms. The plasmasphere is home to a dense cold-plasma population that exists out to $3-5 R_E$, terminated by the boundary called the plasmapause.

A region worth noting that can be seen in both Figures 2.3 and 2.5 is the plasma sheet. This region is situated between the North and South magnetic tail lobes of the nightside magnetosphere and lies for the most part on closed field lines. It consists of a dense, hot, plasma

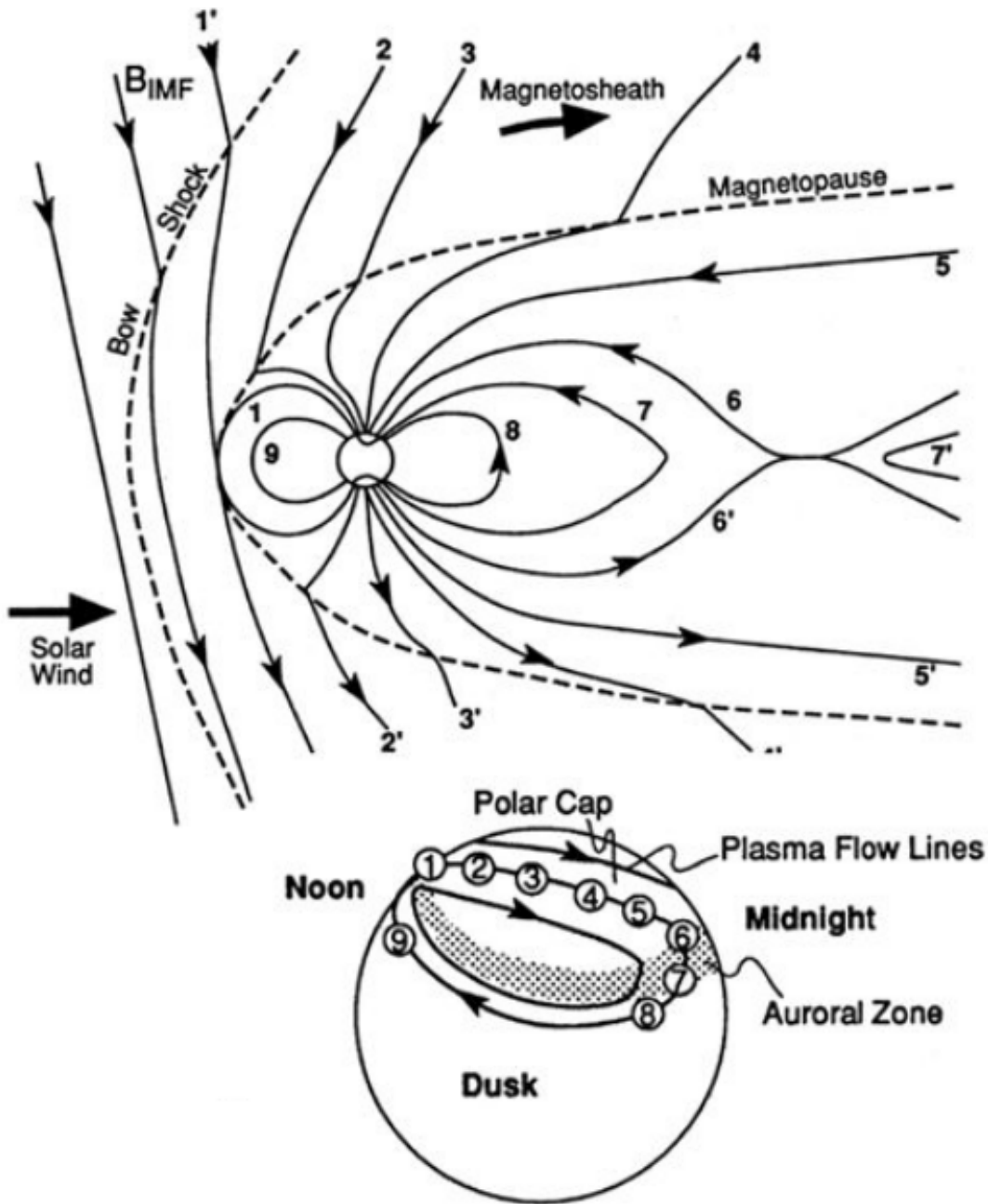


Figure 2.4: The figure illustrates ionospheric convection, the flow of plasma over the poles due to magnetic reconnection [Kivelson and Russell, 1995]. (1) shows the strong dayside reconnection, for the B_z component of the IMF, (2)-(5) shows the flow of field lines to the night side, (6) shows where negative magnetic reconnection on the nightside occurs, and where the field lines move back towards the dayside at lower latitudes (7)-(9) via the dusk or dawn sectors.

population, compared to the almost empty tail lobes.

The magnetospheric flows due to magnetic reconnection drive plasma convection that can be seen in the auroral ionosphere are shown in Figure 2.4. Plasma convection is due to $\mathbf{E} \times \mathbf{B}$ drift induced by the open magnetic field lines crossing the polar region, as shown in Figure

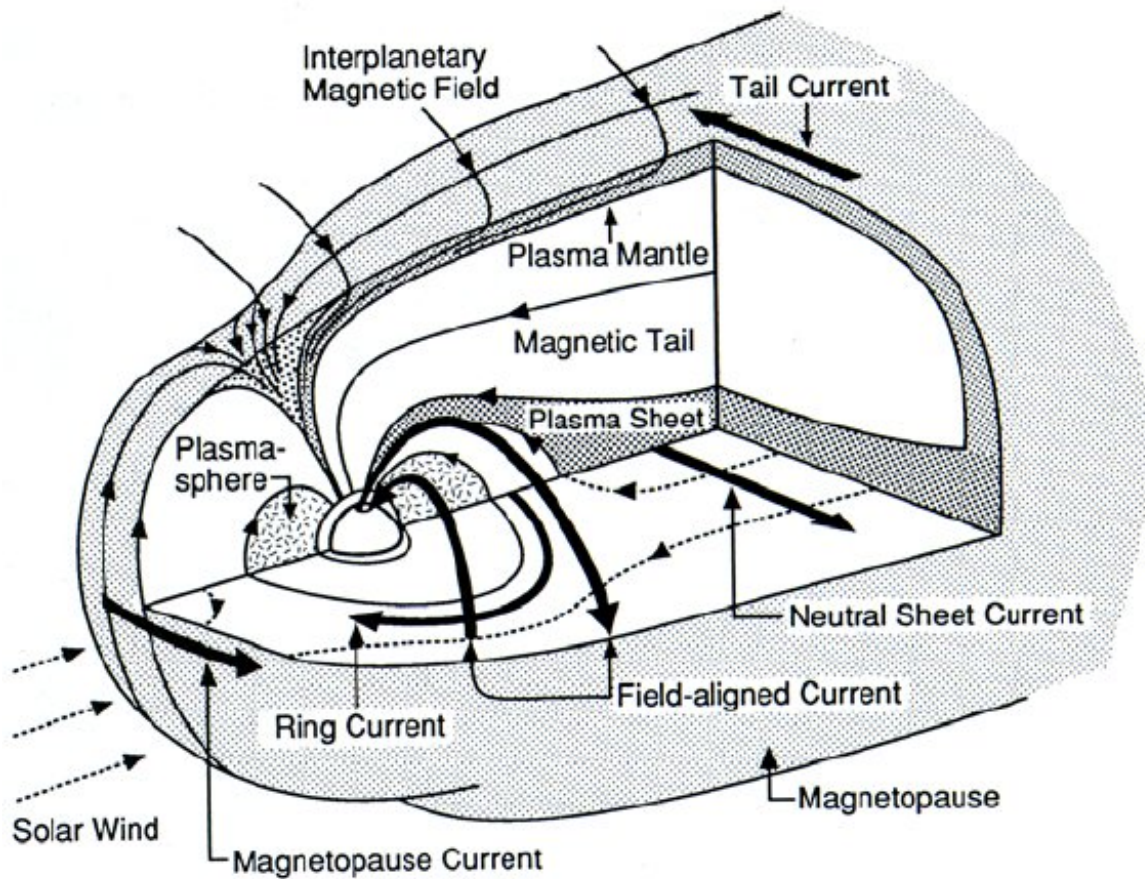


Figure 2.5: Earth's magnetosphere and large-scale current systems [Kivelson and Russell, 1995].

2.6 [Ondoh and Marubashi, 2001] and can be seen in the polar ionosphere as convection cells. Plasma flows from the dayside to the nightside across the polar cap and returns to the dayside through the morning and evening sectors, thus convection is always continuing. This erosion of the dayside magnetosphere and corresponding activity in the magnetotail leads to a process called a substorm.

A substorm has two phases, an expansive phase and a recovery phase [Akasofu, 1964]. It always originates around the midnight meridian where quiet auroral arcs can be located. Figure 2.7 shows the first phase in panel A (expansive phase) that consists of a rapid increase in brightness and development of a ray structure of the aforementioned arcs, as well as drifting towards the geomagnetic equator. Substorm onset (panel B and C) is signalled by a sudden brightening of the equatorward side and rapid poleward motion of the arcs. This bulge drifting polewards forms folds that rapidly move westwards in the dusk sector due to its expansion, and is referred to as a westward travelling surge (panel C).

After a short while (10 - 30 minutes) these drifting arcs reach their most poleward point (as high as 80° latitude) and gradually start to move equatorward again. At this point, the westward surges tend to show a decrease in speed, and may even disappear along with the field-aligned

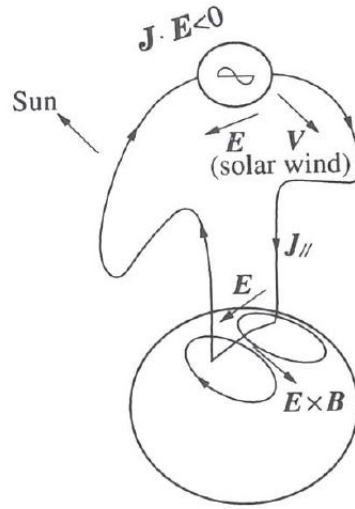


Figure 2.6: Ionospheric convection in the polar region is illustrated here. A magnetic field line is shown in both the polar region and magnetosphere, the electric field perpendicular to it, and the plasma convection due to $\mathbf{E} \times \mathbf{B}$ drift [Ondoh and Marubashi, 2001].

ray structures. Usually, at this point, these structures are replaced by quiet, homogenous arcs and pulsating patches in the morning sector which drift eastward, as well as diffuse aurora (which will be discussed in the next section) travelling eastward and showing a decrease in brightness. This is referred to as the substorm recovery phase in panel F [Akasofu, 1964]. Substorms may occur repeatedly in one night, together making up a geomagnetic storm.

The Earth's magnetosphere is a very dynamic system, and early empirical modelling attempts have had to take into account internal and external factors such as the orientation of the incoming solar wind flow with Earth's magnetic axis, and the orientation and strength of the IMF. More recently the near and inner magnetosphere ($X \leq -15 R_E$) have been modelled by using a set of space magnetometer data [Tsyganenko, 2002]. The Tsyganenko model is a semi-empirical, best-fit magnetospheric magnetic field model using solar wind and IMF data as input [Tsyganenko and Sitnov, 2005].

2.4 The aurora

The bright aurora, which is an optical manifestation of the interaction between solar particles and Earth's atmosphere, can usually be seen over high latitude regions (60° - 80°). It is caused by a large-scale electrical discharge process powered by the solar wind-magnetosphere interaction [Akasofu, 1978]. It has long been established to be caused by precipitating particles, electrons and protons, originating from the plasma sheet [Ondoh and Marubashi, 2001] accelerated by magnetic reconnection, colliding with atoms and molecules in the upper atmosphere, which then leads to their excitation and auroral optical emission. These emissions occur between altitudes of 100 km - 1000 km and can usually be seen in a region called the auroral oval which

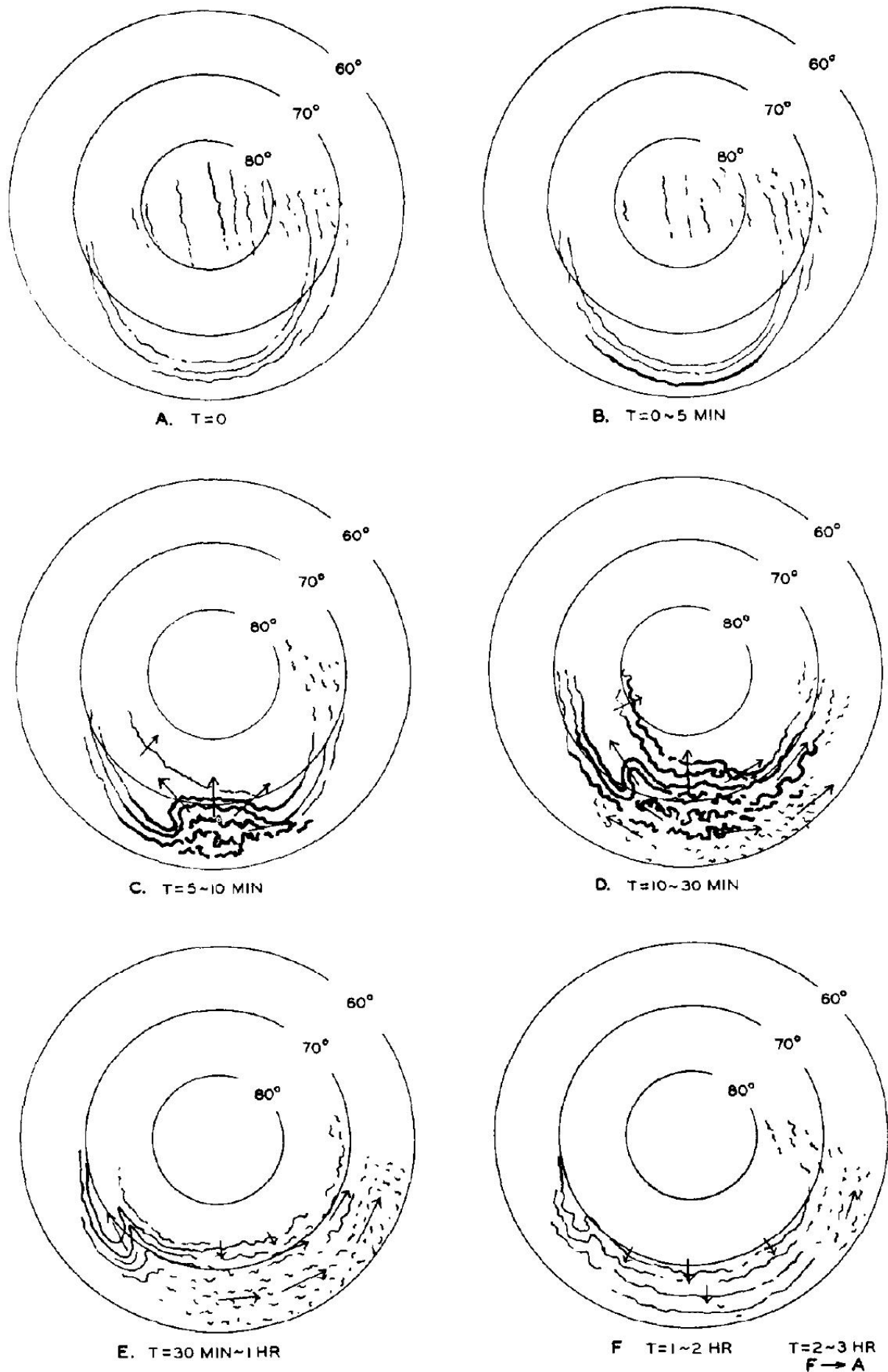


Figure 2.7: Development of the auroral substorm [Akasofu, 1964]. The dayside, nightside, dawn and dusk are located towards the top, bottom, right, and left respectively.

maps magnetically to the plasma sheet on the nightside, see Figure 2.5 [Kivelson and Russell, 1995].

2.4.1 The auroral oval

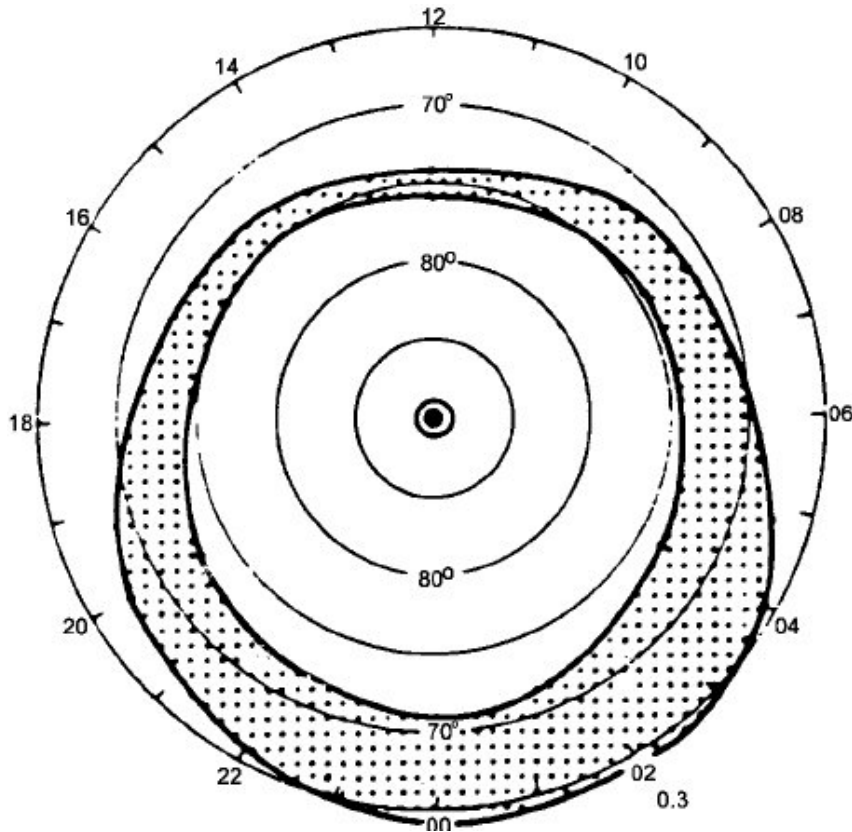


Figure 2.8: Schematic of the auroral oval [Tsurutani *et al.*, 2001]. The centre of the auroral oval is shifted toward the midnight meridian, indicated by 00, ranging from roughly 65° to 70° in latitude. The noon side of the auroral oval extends roughly between 74° and 76° latitude.

Auroral ovals are two oval-shaped bands centred about the north and south magnetic poles in which bright active aurora can usually be seen between magnetic latitudes of 60° - 80° [Kivelson and Russell, 1995], and can be seen in Figure 2.8. Here the centre of the auroral oval is displaced by about 5 degrees along the midnight (00 in the figure) meridian. The auroral oval is fixed with respect to the Sun, and the Earth rotates under it [Zmuda, 1966].

Several types of auroras can be seen in this region, of which some will be discussed in sections 2.4.3 and 2.5. The magnetic field lines in the auroral oval region are connected to the geomagnetic tail in the plasma sheet at night. In the auroral ovals, the strong magnetic disturbances during geomagnetic storms and substorms can be seen, which was discussed in the previous section.

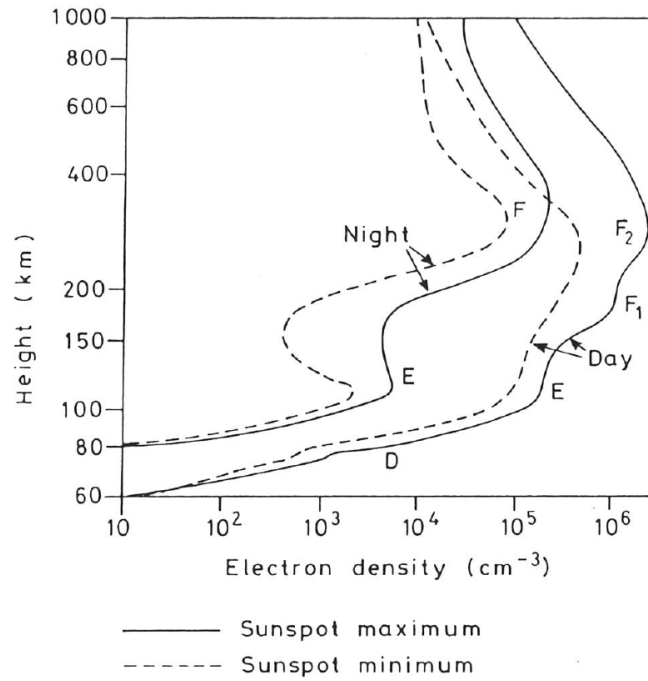


Figure 2.9: Typical temporal (i.e. day and night) and altitude variation of electron density in the mid-latitude ionosphere at different levels of solar activity. [Hargreaves, 1979]. The density height profile is shown ranging from 60 km to 1000 km in altitude. The E layer lies between 90 km and 150 km. Below it is the D layer that ranges between 60 km and 90 km. Above the E layer is the F layer, ranging from 150 km to above 800 km. Four density altitude profiles are shown. The solid lines represent the typical day and night density variation during sunspot maximum. The dotted lines represent the day and night density altitude profiles during sunspot minimum.

2.4.2 The auroral ionosphere

The ionosphere is a charged region in the upper atmosphere, and roughly lies between 60 - 2000 km [Kamide, 2007]. It consists of an abundance of charged particles formed through ionization of atmospheric neutral gaseous compounds, mainly by solar UV and X-ray emissions, and in this region radio waves are scattered and reflected [Kamide, 2007]. Within the ionosphere, there is an ionized, electrically conductive layer in the upper atmosphere at an altitude range of 90 - 150 km which is ionized mostly by precipitating electrons [Koskinen, 2011]. It is referred to as the E layer and primary ionized species in this region are O_2^+ , N_2^+ , and O^+ . This layer is shown in Figure 2.9, along with the D layer below it. The F layer above it reaches up to about 800 km. In this Figure, the density height profiles during sunspot maximum are depicted with solid lines, for day and night times respectively. The profile shifts towards higher electron density values from night time to day time, and this is true for the D, E, and F layers. During sunspot minimum the same is true, the profile shifts towards higher electron densities at all altitudes during day time, but the electron density versus altitude profile overall shifts towards lower electron density values compared to sunspot maximum.

The types of auroral emission are determined by the energy of precipitating particles as well

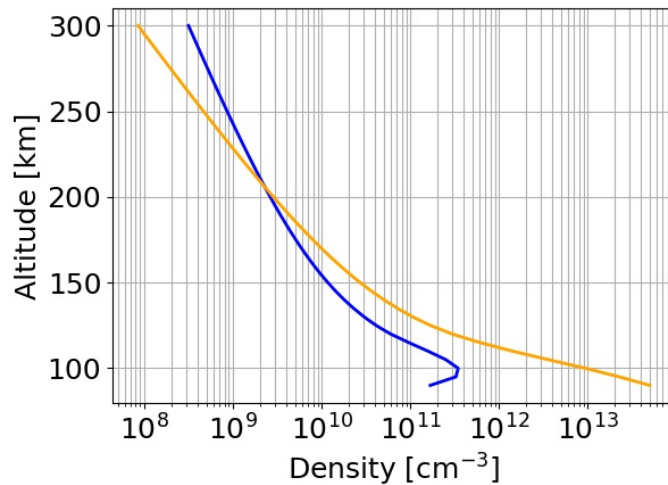


Figure 2.10: NRLMSISE-00 model atmosphere for 2016-03-12 at 22:00:00 UT. The graph shows the density altitude profile for atomic oxygen (blue) and nitrogen (orange). The density altitude profile for atomic oxygen is dominant in the higher altitude range, shown here to be roughly between 200 km and 300 km. At the lower altitudes, roughly between 100 km and 200 km, nitrogen dominates [<https://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php>].

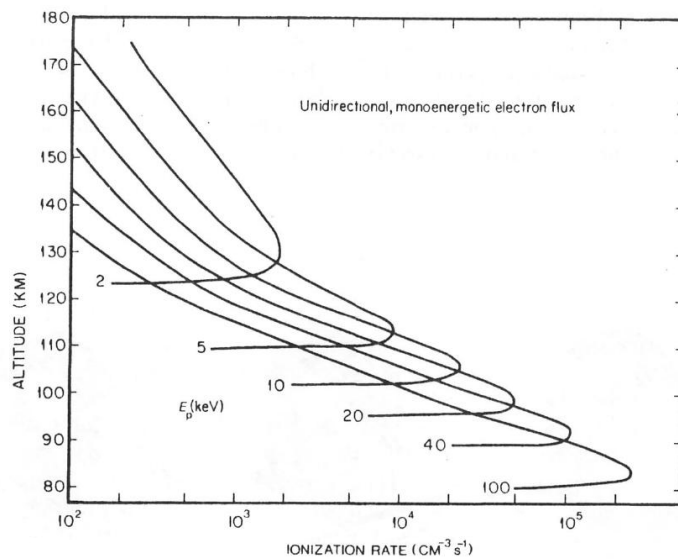


Figure 2.11: Altitude profile of the ionization rate due to a flux of 10^8 electrons $\text{cm}^{-2}\text{s}^{-1}$ at several initial values of energy E_p precipitating into the atmosphere along magnetic field lines [Rees, 1989]. The altitude range here is from 80 km to 180 km, thus shows mainly the ionization rate in the E layer, shown in Figure 2.9. The initial energy levels of the precipitating electrons range from 2 keV to 100 keV, where the lower energy electrons are deposited at higher altitudes and the higher energy precipitating particles penetrate to lower altitudes [Rees, 1963].

as the density of ionospheric constituents (i.e., mainly O and N₂ and O₂) [Kivelson and Russell, 1995; Ondoh and Marubashi, 2001]. The kinetic energy of precipitating particles are transferred, through collisions, to the translational, vibrational, and rotational energies of the atmospheric

Emission	Source	$4\pi B$
<i>OI</i> 557.7 nm	Night airglow, zenith E	250 R
<i>OI</i> 557.7 nm	Aurora	1 - 1000 kR
<i>NaI</i> 589.3 nm	Night airglow, zenith	70 R (summer), 300 R (winter)
<i>NaI</i> 589.3 nm	Twilight airglow, zenith	820 R (summer), 4300 R (winter)

Table 2.1: Typical values of $4\pi B$, measured in Rayleigh. The table shows measurements taken using two emission lines, *OI* 557.7 nm and *NaI* 589.3 nm. Brightness variations for the different auroral classifications are shown for the 557.7 nm emission line, as well as the brightness of the night airglow as a comparison. The seasonal variations for the night and twilight airglow during summer and winter in the 589.3 nm emission line is also shown.

constituents. This excitation could in some instances lead to ionisation and optical emissions in the auroral spectrum. The optical emissions of ionospheric constituents vary with altitude. Figure 2.10 shows the density of N_2 and O as a function of altitude. Both gradually increase as altitude decreases. For the altitude range 300 km to around 200 km atomic oxygen still dominates. From 200 km and below, nitrogen dominates the composition density. At around 100 km atomic oxygen shows a sharp decrease, and nitrogen is still showing an increase in density. The spectral lines and bands of the auroral spectrum have a wide range from ultraviolet, visible, to infrared. The spectrum is made up of the atomic lines and molecular bands of the atmospheric particles. This is mainly due to the temporal and altitude variation of densities of aforementioned constituents, as well as due to precipitating particles with higher energies that can penetrate and reach lower altitudes compared to particles with lower energies. An example of the altitude variation of electron density is shown in Figure 2.9. The altitude to where the particle can penetrate and precipitate to is dependent on its energy, and the level of penetration is illustrated in Figure 2.11.

Forbidden atomic emission lines identified in auroral spectra which appear most regularly are those of 557.7 nm and 630.0 nm transitions in atomic oxygen (OI). These two forbidden emission lines are strong and easy to measure [Omholt, 1971]. Permitted emissions in the auroral spectra which have prompt transitions, and are of importance for this study, are the 777.4 nm and 844.6 nm atomic emission lines in OI, the 427.8 nm molecular band in nitrogen (N_2^+), and 673.0 nm in nitrogen (N_2) [Chamberlain, 1961; Archer, 2009]. Nitrogen dominates lower altitudes and thus interact with the higher energy precipitating particles, and the 427.8 and 673.0 nm prompt emissions are used to pick these up, as seen in Figure 2.10. Atomic oxygen dominates at higher altitudes, and here the 844.6 and 777.4 nm atomic emission lines are used.

The emission intensity is usually measured in Rayleigh. It was suggested that the angular surface brightness, B in the literature and not to be confused with a magnetic field component (eg. B_r), of aurora and airglow sources should be measured as $4\pi B$ and referred to as Rayleigh [Hunten *et al.*, 1956]. Typical values for night/twilight aurora and airglow measured using photoelectric photometry in the atomic oxygen 557.7 nm and 589.3 nm emission lines are shown in Table 2.1. Night airglow has a lower intensity than auroras, by a factor of 4 for class I auroras, which are auroras classified as those with the lowest intensity. Auroras have a wide range of brightness values, ranging from 1 kR to up to 1000 kR. Using the results measured in the 589.3

nm emission line, it is also clear that there is a variation in airglow brightness during different seasons. Night airglow, pointing towards the zenith, has an average of 70 R brightness during summer, and 300 R brightness during winter. Twilight airglow, pointing towards the zenith, measures an 820 R average brightness during summer, and a 4300 R average brightness during winter. Note that ideally airglow should be measured in Rayleigh, and auroras in kilo-Rayleigh [Hunten *et al.*, 1956]. These emission lines fall in the human eye detection threshold. This threshold is between 400 and 700 nanometres, with 555 nanometres the peak sensitivity which is in the green region of the visible light spectrum. The human eye can detect 557.7 nm from about 1 kR.

Rayleigh is now the standard unit for apparent photon radiance, $1 \text{ R} = 1/4\pi \times 10^{10} \text{ photons} \cdot \text{s}^{-1} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$ [Doran and Pendleton, 1976].

Several types of bright aurora have been identified, what will be discussed next is only discrete, diffuse, and pulsating auroras.

2.4.3 Aurora types

Two different types of auroral imagery led to the present day understanding of the morphology of bright aurora. Television techniques from ground- and aircraft based instruments, as well as from very-large-scale satellite images, have formed the terminology used around describing both discrete and diffuse auroras [Davis, 1978]. These will be discussed, as well as pulsating and diffuse auroras, which can usually be seen in the morning sector.

The discrete aurora is a bright, sharply defined, curtain-like structure consisting of either a single arc or separated arcs [Akasofu, 1974] seen on the nightside auroral oval. It is the brightest of the different types of aurora [Davis, 1978]. It can extend from tens to hundreds of kilometres in length in an east-west direction, and its width ranges from 50 m to 10 km. Its vertical extent is up to several hundreds of kilometres. Low-intensity arcs tend to have uniform intensities and curvature, but brighter arcs often develop vortex streets.

The diffuse aurora is a broad band of uniform auroral glow with a vertical extent of several tens of kilometres [Akasofu, 1974], depending on substorm activity [Sergienko *et al.*, 2008]. It is caused by electron precipitation due to strong pitch angle diffusion of near-Earth plasma sheet electrons [Frank and Ackerson, 1972; Sergienko *et al.*, 2008], and has a relatively constant energy spectrum [Akasofu, 1974]. It is seen most clearly moving equatorward on the edge of the nightside auroral oval due to westward travelling surges. It shows a significant brightening when discrete auroras in the auroral oval become active [Anger and Lui, 1973]. During quiet times it is likely to be under 1 kR and well above that during auroral substorms. The duration of diffuse auroras can last from half an hour (during weak westward travelling surges) to more than an hour (during strong surges).

Pulsating aurora is defined as a low-intensity aurora whose luminosity rapidly increases and

decreases [Royrvik and Davis, 1977]. These variations are repetitive and periodic, and its periodicity ranges from one to several tens of seconds. Pulsating auroras have no specific morphological classification, and varies greatly in shape and size.

2.5 The black aurora

It was in diffuse auroras that typically appear after magnetic midnight, that the black aurora structure was first observed. It was defined as gaps within diffuse auroras (and sometimes between pulsating auroras [Trondsen and Cogger, 1997]) that lack optical emissions [Blixt and Kosch, 2004]. It is known now that although they seem black in appearance, optical emissions are present but are dimmed relative to the surrounding diffuse aurora [Gustavsson *et al.*, 2008]. Black auroras are usually seen during the late substorm recovery phase (during the midnight sector) [Trondsen and Cogger, 1996a], usually post magnetic midnight.

2.5.1 Morphology of the black aurora

Several distinct forms of the black aurora have been observed, such as black patches, black arc segments, thin black arcs, and black vortex streets [Trondsen and Cogger, 1996b].

Figure 2.12 shows a black patch that is embedded in the midnight sector diffuse aurora. These are usually seen post magnetic midnight drifting eastwards embedded in homogeneous diffuse auroral surface.

Arc segments were seen along with black patches during the Trondsen and Cogger [1997] observations, and show many features in common with each other and also tend to morph from one type to the other. Both tend to have sharply defined boundaries, and an average drift speed in the range of 0.6 - 1.5 km/s usually eastward (as do pulsating auroras). Object width was typically around 0.5 - 4 km, and an average length of about 2.5 - 5 (up to 20) km. Examples of black arc segments are also shown in 2.12. There are two arc segments drifting above and below the black patch, and with two more possible arc segments coming into view on the right-hand side of the image.

Figure 2.13 shows a black arc, which is seen to be east-west aligned, embedded within the midnight sector diffuse aurora [Trondsen and Cogger, 1997]. The average width is around 615 m. Spacing between arcs is around 0.5 - 1.2 km. There may be a slow southward drift of a few hundred meters per second.

In Figure 2.14 black vortex streets are spaced quasi-periodically along a black arc. Note the lack of curls or vortices, an indication of a lack of shear motion in the first three frames of the top panel. By the fourth frame in the top panel black arcs can be seen to start forming. By the third panel these curls can clearly be seen, thus an indication of the presence of shear mo-

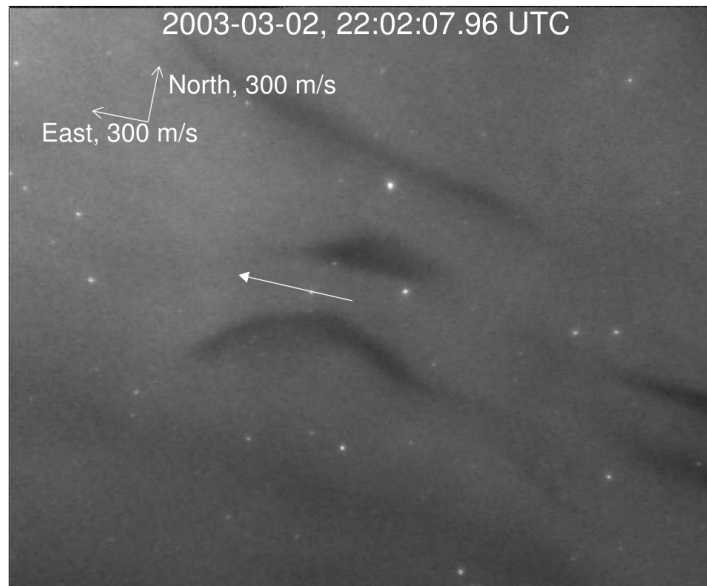


Figure 2.12: Example of black arc segments and black patches. It was observed during a 2003 EISCAT campaign on 3 March. These specific events were recorded at 22:02:07.96 UT. The arrow at the centre of the image represents the plasma convection velocity measured from the EISCAT radar. In the centre of the image, above the white arrow, an example of a black patch can be seen. Just above and below this black patch, are examples of black arc segments, also moving in the same drift direction. On the right-hand side of the image, partial black aurora structures can be seen moving into view. The Field of View (FOV) is $14.3^\circ \times 10.9^\circ$ [Blixt *et al.*, 2005].

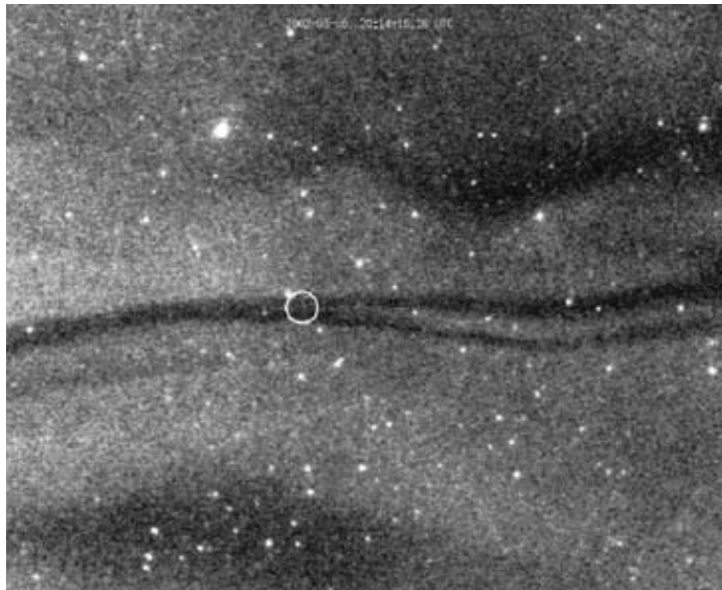


Figure 2.13: Example of a black arc. The white circle shows the position of the European Incoherent SCATter radar (EISCAT) radar beam located in Tromsø, Norway. The FOV was $14.3^\circ \times 10.9^\circ$, and was observed 2002-03-05, 20:04:11 - 20:04:30 UT [Blixt and Kosch, 2004]. Here embedded in a brighter diffuse aurora lies a black arc, stretching across the FOV from East to West. On the left-hand side, it is a single arc stretching out, and to its right-hand side it splits into two separate arcs.

tion. These curls (or vortices) are attributed to the Kelvin-Helmholtz instability of the plasma current acting on a sheet of positive space charge [Trondsen and Cogger, 1997].

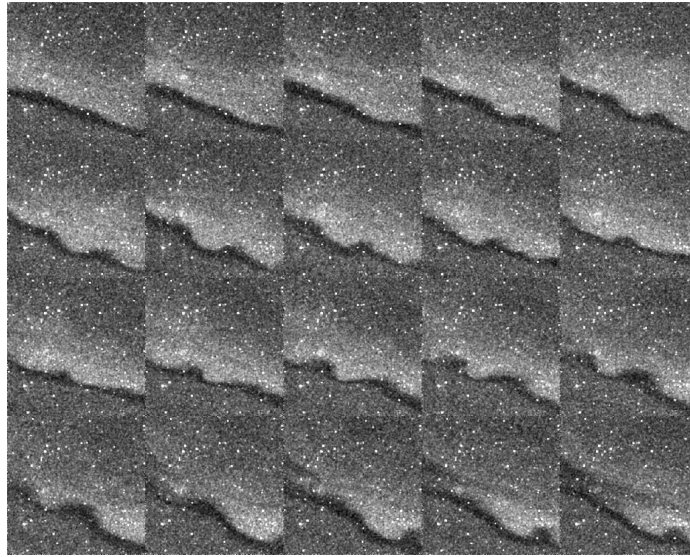


Figure 2.14: Example of the time evolution of black vortex streets due to shear instabilities, where the FOV is $3.1^\circ \times 3.1^\circ$, and it was observed on 22 October 2006, at 20:50:56 UT [Archer, 2009]. Time runs from left to right, and top to bottom. Time increment between frames is $\Delta t = 0.469$ s. The black aurora structure is embedded in a brighter diffuse aurora. This diffuse aurora appears brighter on the top (North) side of the black aurora than at the bottom (South) side. In the first three frames in the top panel the structure appears as a black arc, and by the fourth frame in the top panel black vortex streets starts to evolve along it. The fourth frame in the third panel shows these curls very clearly, two curls can be seen in the top section of the arc.

2.5.2 Black aurora underlying mechanism theories

The underlying generation mechanism behind the structures mentioned above are as of yet unknown, but two major mechanisms have been proposed. One theory is that of a downward field-aligned current carried by cold electrons flowing out of the E-region [Marklund *et al.*, 2001]. This is referred to as the coupled ionospheric-magnetospheric generation mechanism. It acts in the ionosphere and has been associated with black vortex streets [Blixt and Kosch, 2004]. There is also a magnetospheric generation mechanism that has been proposed, which locally impedes the strong pitch angle scattering into the loss cone, and thus causes a depletion of precipitating electrons [Peticolas *et al.*, 2002]. Both will be discussed in more detail next.

A coupled ionospheric-magnetospheric generation mechanism

The Freja satellite [Marklund *et al.*, 1994] was launched on October 6, 1992. It was in a 63° inclination orbit. Its low inclination orbit provides the ability to take measurements of east-west variations of auroral parameters, which is not possible with polar orbiting satellites, thus

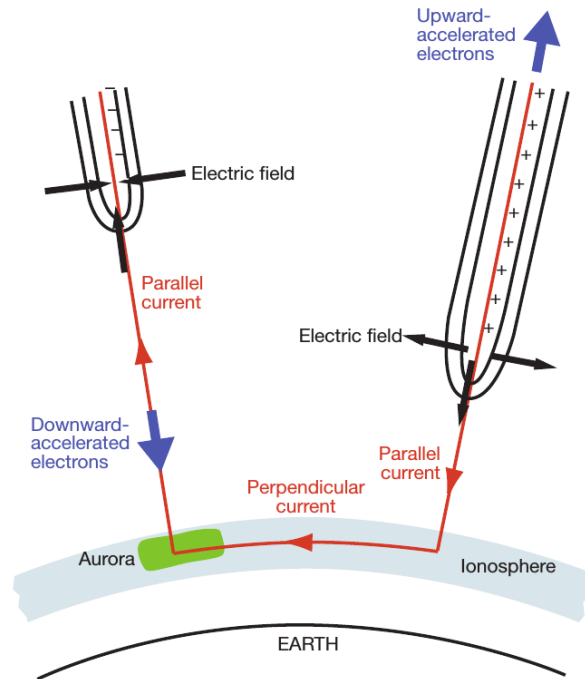


Figure 2.15: Acceleration structures within the auroral current circuit typical of auroral arcs. The red line and arrows represent a downward and upward parallel to the magnetic field line current, connected by a perpendicular to the magnetic field line current located in the auroral zone. Downward accelerated electrons move along the upward parallel current, and upward accelerated electrons move along the downward parallel current. On the left is a negatively charged potential structure representative of the aurora. On the right is a downward positively charged potential structure, and these two structures are connected via a perpendicular current shown in the middle [Marklund *et al.*, 2001].

making it unique [Marklund *et al.*, 1997]. This mission studied the fine-scale auroral features using high-resolution plasma and electric and magnetic field measurements.

During its orbit very intense (1 V/m) and small-scale (1 km) electric fields occurred at an altitude range of 800 - 1700 km, which is right below the auroral acceleration region. Some of the events showed two narrow electric field structures of 1 V/m having radially diverging electric fields and associated with dropouts of precipitating electrons, depletions of thermal plasma, and downward field-aligned currents. They suggested that these observations, combined with their scale size of 1 km as well as the 5 km spacing between them, were consistent with the presence of east-west aligned vortex street structures of the black aurora, but there was no optical proof for this. Figure 2.15 shows the upward field-aligned current, which is connected to this positive potential structure via a perpendicular current and is in turn responsible for the brighter diffuse aurora alongside the black vortex street structures, which can be seen in Figure 2.14. The generally accepted theory for black vortex streets is that they occur in these positive potential structures due to Kelvin-Helmholtz instabilities [Blixt *et al.*, 2005].

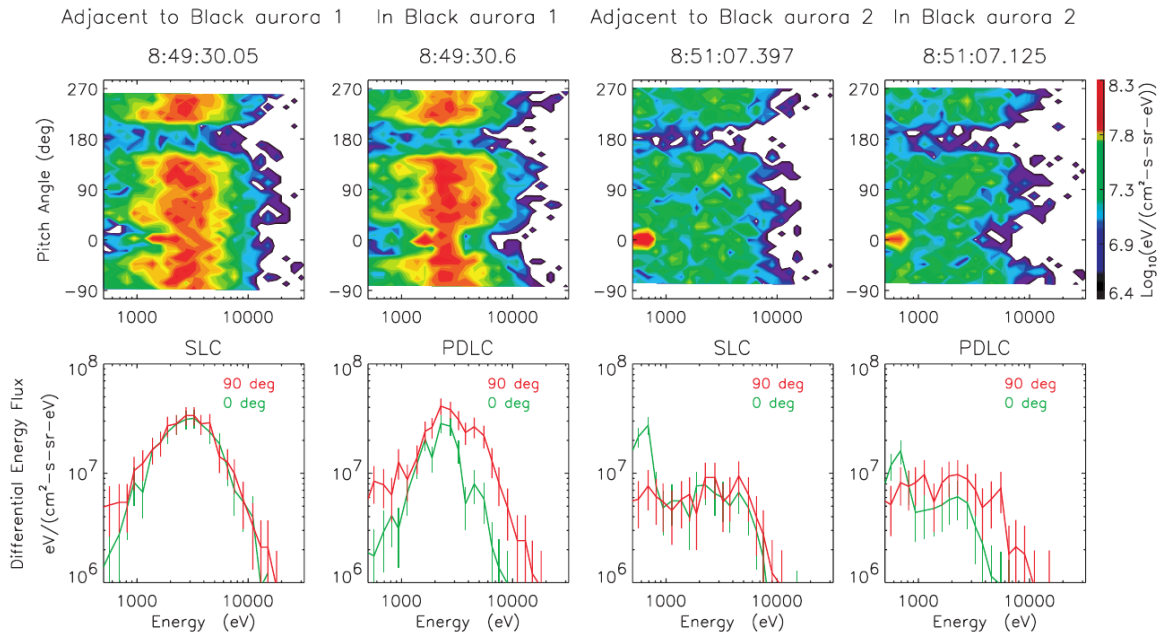


Figure 2.16: In the top panel the electron differential energy flux as a function of pitch angle and energy is shown for two different time periods. The bottom panel shows the differential energy flux as a function of energy at pitch angles $0^\circ \pm 22^\circ$ (green) and $90^\circ \pm 22^\circ$ (red) for the corresponding times [Peticolas *et al.*, 2002].

Magnetospheric generation mechanism

Peticolas *et al.* [2002] made black aurora observations using aircraft-based optical instruments as well as plasma measurements using the FAST satellite on 30 January 1998. The FAST satellite was designed specifically to take high-resolution data samples of auroral zones, thus follows a high apogee, near-polar orbit [Pfaff *et al.*, 2001].

The electron differential energy fluxes were sampled at 48 energies between 4 eV and 32 keV. While FAST spun, analyzers on board measured 32 pitch angles between 0° and 360° . The satellite also had a magnetometer on board, thus the angle measurements for the pitch angles were taken in relation to the magnetic field alignment over very short timescales.

They noticed that as the FAST satellite passed over the black aurora, the differential energy flux measurements showed large decreases in the precipitating electrons at energies above ~ 2 keV, but only at $0^\circ \pm 22^\circ$ pitch angle. This gives rise to a partial double loss cone (PDLC) distribution shown in Figure 2.16. In this figure, the negative and positive pitch angles relate to the plane in which the electrons were detected by the FAST analyzers. The 0° angle refers to the direction parallel to the magnetic field line, in the downward (towards the ionosphere) direction. The angle 180° is in the upwards direction, parallel to the magnetic field line. Here the -90° angle is the same as the 270° angle. As the satellite moved over the area adjacent to the black aurora, the downward differential energy flux at pitch angles 0° and 90° is isotropic at all energies, forming a single loss cone (SLC) distribution, which can be seen in the first and third graph of

the bottom panel in Figure 2.16.

The PDLC distributions in the black auroral region suggest that there are narrow plasma sheet regions where there is a reduction in pitch angle diffusion at higher energies and thus a loss cone that was partially empty. These depleted regions were also surrounded by broad spatial regions of pitch angle diffusion at all measured energies, producing SLC distributions [Peticolas *et al.*, 2002].

This is in good agreement with Kimball and Hallinan [1998a], who showed that when a pulsating aurora overlaps with black aurora regions, it adds more to the intensity than to the surrounding diffuse aurora. This suggests that the loss cone in the black aurora regions was not filled to capacity, but was then filled by the pulsations.

These authors further propose that SLCs are caused by upper band (UB) whistler mode chorus waves and that PDLCs are due to a suppression of scattering by UB chorus waves in narrow regions in the plasma sheet. The backscattered electron fluxes measured by FAST did not match the precipitating fluxes below 2 keV, so they suggest that there could be another mechanism responsible for the low-energy precipitating electrons.

2.6 Further studies

Blixt and Kosch [2004] performed the first coordinated optical and incoherent scatter radar campaign for observations of black aurora. Two observations of unsheared black arcs were made that drifted through the radar beam (see Figure 2.13). During the time that the arcs drifted through the beam, they found no evidence of electron density decreases and concluded that there is no association between any strong downward field-aligned currents and unsheared black arcs to within the detection limit.

Several events, mostly black patches, were studied in Blixt *et al.* [2005] to determine whether they were drifting with a velocity consistent with the ∇B -curvature velocity of the hot source plasma in the magnetosphere (See Figure 2.12). This is important because if the blocking mechanism suggested in Section 2.5.2 is drifting with the source electron population in the magnetosphere, then its velocity would be energy dependent [Archer, 2009]. They observed eastward drifting patches moving several km/s faster than the surrounding $\mathbf{E} \times \mathbf{B}$ ionospheric plasma flow. Blixt *et al.* [2005] concluded that black aurora drift is precipitating particle energy-dependent and unrelated to ionospheric plasma convection (See Figure 2.4), thus reinforcing the magnetospheric mechanism theory.

Observations using the first combined multi-monochromatic optical imaging at 427.8 nm and 844.6 nm, bi-static white-light TV recordings with incoherent scatter radar observations showed that it's unlikely that non-sheared black auroras are caused by downward directed electrical fields as suggested in Section 2.5.2 [Gustavsson *et al.*, 2008] (i.e., not consistent intensity reduction for both wavelengths). Figure 2.17 shows white light images showing the presence of

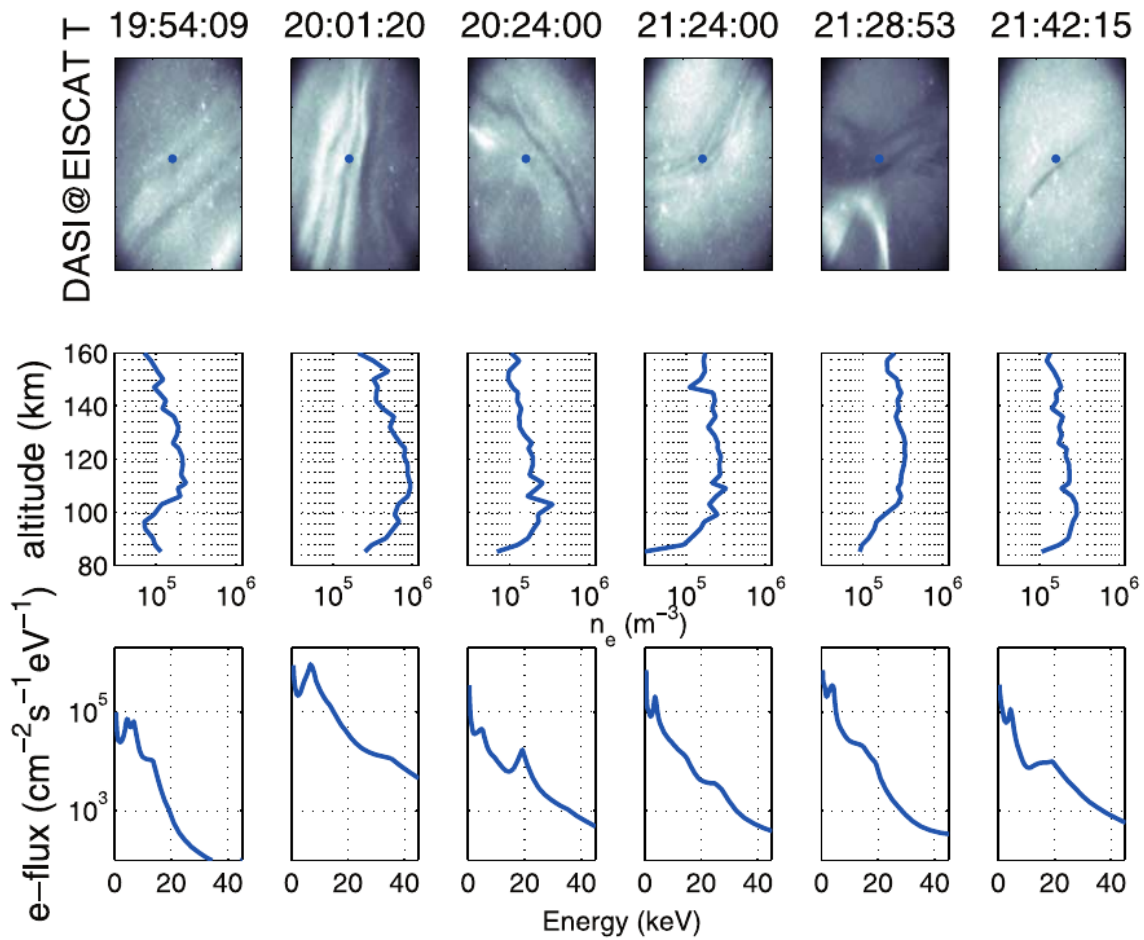


Figure 2.17: Data from a 2005 campaign [Gustavsson *et al.*, 2008]. The top panel shows white light images indicating the presence of black auroras, with the blue dot showing the position of the EISCAT UHF radar pointing direction. The middle panel shows the electron density profile from the EISCAT data, and the bottom panel shows the precipitating particle energy spectrum.

black auroras, and the respective electron density profiles and precipitating particle energy spectra. They also concluded that these events are more likely due to a magnetospheric mechanism rather than ionospheric.

The Reimei satellite was launched in August 2005 into a Sun-synchronous polar orbit at an altitude of around 640 km and an orbital period of 98 min. This satellite was used to obtain a set of black auroral events, 13 in total, between November 2005 and October 2006 [Obuchi *et al.*, 2011]. This was done using simultaneous ground-based imaging and particle data from the Reimei satellite. A depletion of precipitating electron flux at energies greater than 2 keV was observed. They suggest that the decay of electron flux with energies greater than 2-7 keV was not due to a dropout of precipitating particles in a divergent electric field, but due to pitch angle scattering by upper band whistler mode waves being suppressed in black aurora source regions. These conclusions are in agreement with Peticolas *et al.* [2002] as discussed in Section 2.5.2.

A more recent theory has been proposed by *Sakaguchi et al.* [2011], using ground-based all-sky cameras in conjunction with the THEMIS satellites. The THEMIS satellites were placed in highly elliptical orbits where they line up at the orbital point furthest from Earth (apogee) every four days. As the apogee slowly precesses around Earth this then gives the ability to cover the dayside, dawnside, nightside, and duskside of the magnetosphere. Three of the satellites were close to being magnetically conjugate in the plasma sheet (see Figure 2.3), and along with ground-based proton auroral observations they noticed a dipolarisation front, and associated dawnward ion eastward flow, just poleward of the black patches. A dipolarisation front occurs in the magnetotail and is characterised by a sharp, large amplitude increase in the Z-component (*Fu et al.* [2012]) of the magnetic field. It is defined as a tangential discontinuity (*Nosé et al.* [2016]) evolving as it approaches near-Earth. They suggest from their observations that the periodic black patches were generated in the plasma sheet associated with a dipolarisation front passage during a substorm.

During January 2007 ground-based observations were made of black auroras, and how they relate to pulsating auroras [*Fritz et al.*, 2015]. This was done using optical instruments (intensified CCD video camera with a bandpass of between 700 and 850 nm) along with a meridian scanning photometer (MSP) used to measure intensities of both diffuse, pulsating, and black auroras. They measured a total of 26 black aurora events, noting the times that black auroras were observed, their drift motion, and relation to the brighter auroras in the surrounding area. They concluded that their observations support the widely held notion that black auroras are observed during the substorm recovery phase, as mentioned in Section 2.5. These authors also suggest that an ionospheric mechanism, like the theory proposed by *Marklund et al.* [1994], might be playing a more active role than previous studies suggest. Although they do not dismiss the role of a magnetospheric driver, such as *Peticolas et al.* [2002], from the orientation and morphology of their observations it seems likely that there exists an ionospheric feedback system. They conclude that there might be new possible ways in which black auroras might occur, in addition to magnetospheric mechanisms.

2.7 Anti-black auroras

Recently a wholly new type of Aurora has been discovered (*Kosch, M.J. Private communication, 2016*) which can be seen in Figure 2.18. In the first frame, several black patches are seen moving into view from the left-hand side. There are also at least two black patches visible to the right of the middle of the frame. One of these black patches (or possible arc segment) drifting into view from the left-hand side appears to have a bright patch, significantly brighter than the surrounding diffuse aurora, attached adjacent to it. By the second frame this bright patch jumps from the top side of the black patch it is drifting alongside, to the bottom side. Note in all the frames how this bright patch clearly travels together with the black patch and seems to be linked together. Because the white patch seems to be linked to the black aurora, this brighter

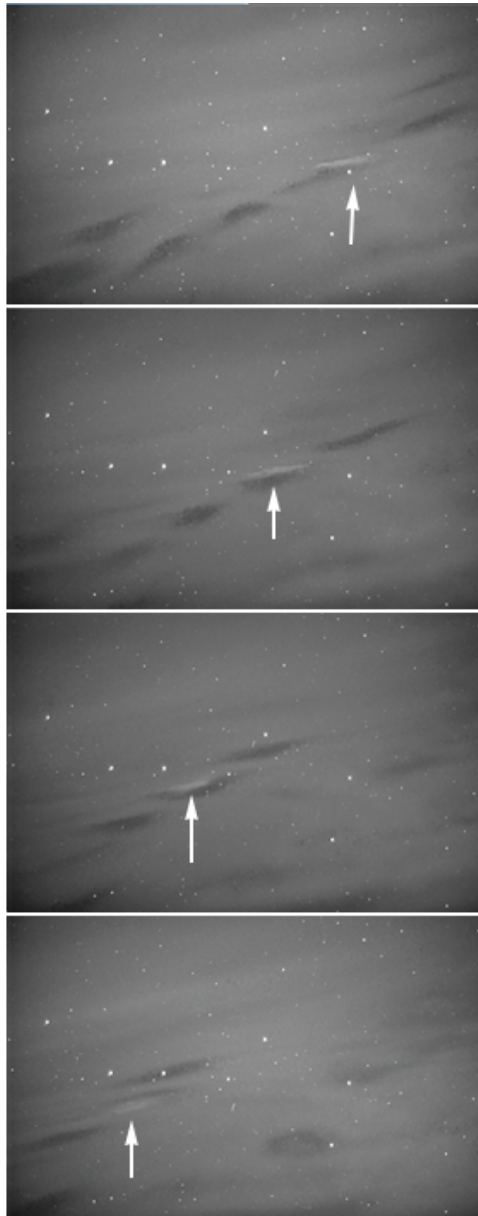


Figure 2.18: White light images of an anti-black aurora that could be seen moving in parallel with a cluster of black aurora patches in an eastward direction. The frames were taken with a 50° FOV in steps of 1 second on 2007-03-16 in Tromsø (Kosch, M.J. *Private communication*, 2016).

patch will be referred to as an anti-black aurora in this study.

These observations were imaged in white light, and no spectral information of this phenomenon is available. The author is not aware of any dual-wavelength optical, or radar observations, made of this type of event to date.

2.8 Summary

Particle motion in the magnetosphere experiences total magnetic field drift, which is dependent on the curvature of the magnetic field, as well as the magnetic field gradient as a function of radius. Particles with pitch angles outside the loss cone remain trapped in the magnetosphere due to the magnetic mirror effect, bouncing from pole to pole. The particles can escape the magnetosphere and precipitate into the ionosphere if particles have a pitch angle inside the loss cone.

IMF and PMF linking driven by the solar wind lead to magnetic reconnection. This process drives plasma convection and can be seen in the auroral ionosphere. This process could lead to a substorm. A substorm has two phases, an expansive phase and a recovery phase. During the expansive phase, an increase in brightness and the development of a ray structure are seen in auroral arcs. During the recovery phase, these dynamic auroras are replaced by quiet, homogeneous arcs and diffuse aurora. Substorms can occur repeatedly in one night. The Tsyganenko magnetic field model is used to model the magnetic field, using the solar wind and IMF data as input.

Auroral emissions usually occur between altitudes of 100 km - 1000 km in the ionosphere, seen in the auroral oval which maps magnetically to the plasma sheet. The auroral oval is centred around the pole (for both the north and south poles) between latitudes 60° - 80° . The ionosphere itself lies between altitudes of 60 km - 2000 km. Within the ionosphere is the E-layer, which is a weakly ionized, electrically conductive layer in the upper atmosphere that is mainly ionized by precipitating electrons. The type of auroral optical emissions depends on the energy of the precipitating particles and the ionospheric composition. The excitation of atmospheric constituents due to precipitation leads to optical emissions in the auroral spectrum. Emission lines relevant in this study are the two atomic oxygen emission lines, 777.4 nm and 844.6 nm, as well as the nitrogen emissions 427.8 nm and 673.0 nm. Molecular nitrogen is more prevalent in the lower altitudes, and atomic oxygen more prevalent at higher altitudes. The emission intensity is measured in Rayleigh, a brightness unit. Aurora brightness in the oxygen 557.7 nm emission line varies in the range of 1 kR to 1000 kR.

There are several types of bright aurora. The discrete aurora is a bright, sharply defined structure seen on the nightside auroral oval. Pulsating aurora has a varying luminosity, and vary greatly in shape and size. The diffuse aurora is a broad band of uniform glow with a relatively constant energy spectrum. Embedded within this type of bright aurora, the black aurora can sometimes be observed. Optical emissions are present in this type of aurora, but at a lower luminosity than the surrounding diffuse aurora, thus appearing black. Black auroras are usually seen during the late substorm recovery phase and can present as an arc, arc segment, vortex streets or patch.

Although the underlying mechanisms for the brighter types of aurora have been established, the underlying mechanism causing black auroras has not been established. Two popular the-

ories exist. One is the coupled ionospheric-magnetospheric generation mechanism that proposes that a downward field-aligned current is carried by cold electrons flowing out of the E-region within the black aurora and thus occurs in the ionosphere. The other one is the magnetospheric generation mechanism which hinders scattering of high energy electrons into the loss cone within the black aurora.

Studies have shown that there is no association between strong FAC's and unsheared black arcs [Blixt and Kosch, 2004]. Black aurora drift is also now considered to be precipitating particle energy dependent and unrelated to ionospheric plasma convection [Blixt *et al.*, 2005]. This reinforces the magnetospheric mechanism theory. A study in 2008 came to the conclusion that it's unlikely that non-sheared black auroras are caused by downward directed electric currents, thus coming to the conclusion that the underlying mechanism for black auroras is most likely due to a magnetospheric mechanism rather than ionospheric [Gustavsson *et al.*, 2008]. Using the Reimei satellite, it was concluded in a 2011 study that the decay of electron flux with energies greater than 2-7 keV is due to pitch angle scattering by upper band whistler mode waves being suppressed in black aurora source regions, thus reinforcing the magnetospheric mechanism theory.

Anti-black auroras are a new type of aurora, first observed in white-light images in 2007. It presents as a white patch that travels alongside a black aurora at the same velocity. No spectral information of this phenomenon is available. In this thesis is presented the first quantitative study, using optical and radar data, of the anti-black aurora.

Chapter 3

Instrumentation

3.1 Introduction

Several different instruments were used to gather data in the 2006, 2009, and 2016 campaigns, of which the author partook in the 2016 campaign. It includes the Auroral Structure and Kinetics instrument from the University of Southampton, electron multiplying charge-coupled device (EMCCDs) and charged-couple device (CCDs), as well as the EISCAT Ultra High Frequency (UHF) transmitter/receiver. These are discussed in more detail in the following sections.

3.2 ASK instrumentation of the 2006 campaign

The Auroral Structure and Kinetics (ASK) instrument is a multi-spectral imager run by the University of Southampton. The instrument consists of three Andor iXon back-illuminated EMCCD detectors with a 512×512 pixel chip, each equipped with a Kowa 75 mm F/1 lens. It provides simultaneous 256×256 pixel resolution images of ionospheric events in three different spectral bands, in a FOV of $3.1^\circ \times 3.1^\circ$ (5×5 km at an altitude of 100 km) [Ashrafi, 2007; Dahlgren *et al.*, 2008]. It has a temporal resolution of 32 Hz.

For the 2006 campaign, cameras ASK1 and ASK3 were used, each fitted with a narrow pass-band filter. The ASK1 camera has a filter at 673.0 nm (N_2 emission line) with a full width at half maximum (FWHM) of 14 nm and is used to measure higher energy electron precipitation. The ASK3 camera isolates a line of atomic oxygen emission at 777.4 nm, has a FWHM of 1.5 nm, and is used to measure lower energy electron precipitation [Dahlgren *et al.*, 2008; Archer, 2009].

For this campaign the ASK cameras were set up at the EISCAT Ramfjordmoen radar site ($69^\circ 35' 11''$ N $19^\circ 13' 38''$ E) outside Tromsø, Norway, pointing towards the magnetic zenith.

3.3 Optical instruments of the 2009/2016 campaigns



Figure 3.1: Camera setup for the 2016 campaign. On the left-hand side is an iXon-888 EMCCD pointing into the magnetic zenith, fitted with a 427.8 nm filter. The camera in the middle is an ALTA-U47 back-illuminated full frame megapixel CCD pointing into the local zenith, fitted with a 844.6 nm filter. On the right-hand side is a TV imager camera pointing into the local zenith. Image was taken by the author during the 2016 campaign.

During the 2009 campaign, two iXon-888 back-illuminated EMCCD detectors ran in parallel, mounted next to each other. EMCCD's has eliminated the problem of read-out noise and makes low-light imaging with high frame rates possible [Lanchester *et al.*, 2009]. Each produced images with 256×256 pixel resolution in a 30° FOV. They had a maximum temporal resolution of 10 Hz. There were two filters available for this campaign. For the one camera an Andover 840FS10-25 filter at 844.6 nm with 50% transmission was fitted. The 844.6 nm emission results from the $(2p^33p)^3P \rightarrow (2p^33s)^3S$ transition. The excitation threshold energy for 844.6 nm is around 11 eV. This state requires a higher excitation energy than the upper states of auroral green and red lines [Waldrop *et al.*, 2018]. The other camera had an Andover 430HC10 filter at 427.8 nm (N_2^+ emission) with a minimum transmission of 90% fitted, and has an excitation threshold of around 18.6 eV. Both filters have a FWHM of 10 nm.

For the 2016 campaign one of the iXon-888 EMCCD's was used again, this time in parallel with an ALTA-U47 back-illuminated full frame megapixel CCD (DASI), mounted next to each other, shown in Figure 3.1. The EMCCD was attached with an Andover 430HC10 filter and the DASI with an Andover 844.6 nm filter with an 85% transmission and 10 nm FWHM, which were available for this campaign. Images produced by the EMCCD had 256×256 pixel resolution in a 30° FOV. The DASI produced the same resolution images in a FOV of 50° , with a maximum temporal resolution of 1 Hz. The author was responsible for recording using optical instruments for all evenings of observation, as well as monitoring the radar instruments. For both the 2009 and 2016 campaigns, the filters were chosen to be within the operating range of

the camera.

3.4 ISR and EISCAT

It was first suggested by Fabry in 1928 that the scattering of electromagnetic waves by electrons could be used to probe the ionosphere, and later *Gordon* [1958] suggested that radio waves could be used to this effect. Incoherent scatter radars work on the basis that free electrons in an ionised medium scatter radio waves. It is assumed that electrons are independent, thus the scattered signal strength is proportional to electron density. An overview of incoherent scatter radars (ISR) will be discussed briefly next [*Rishbeth and Williams*, 1985].

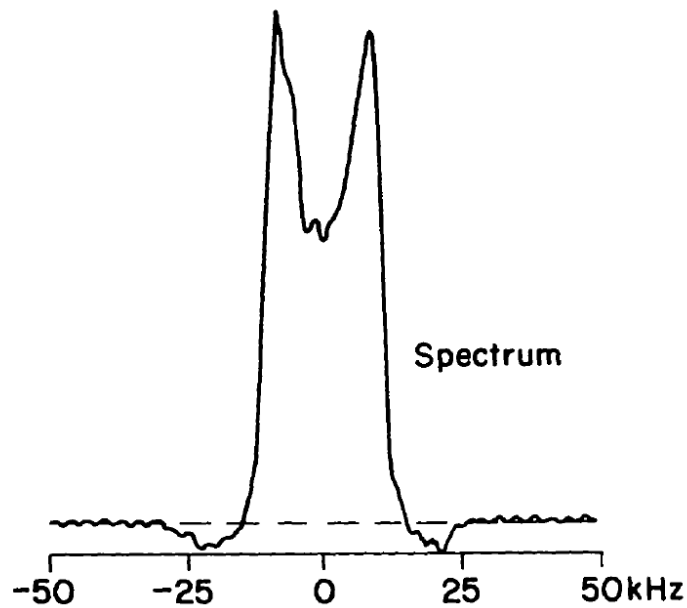


Figure 3.2: UHF signal transmitted from the EISCAT site in Tromsø and received at the Kiruna site. Taken at 08:47 UT, 1984-09-22 [*Rishbeth and Williams*, 1985].

Incoherent scattering is weak, but it is possible to detect using powerful enough radars [*Gordon*, 1958]. Incoherent scattering refers to the Thomson scattering process where the energy of the incident wave is scattered in all directions, and at various frequencies. These scattered waves differing in frequency are due to the Doppler shift caused by the moving free electrons in the ionised medium. This Doppler shift is illustrated in Figure 3.2, which shows a UHF signal transmitted from the EISCAT site in Tromsø and received at the EISCAT Kiruna site. The double peak of the received UHF signal can clearly be seen here. The double peak has a width of about 50 kHz, and the trough is located at 0 kHz. These shifts are due to the thermal motion of the electrons, so by measuring the width of the spectrum of backscatter frequencies the ion temperature can be deduced. Studies have shown that the width of this spectrum corresponds to the thermal velocities of ions, which is approximately $4\Delta f_i$, where f_i is the ion-Doppler frequency given by

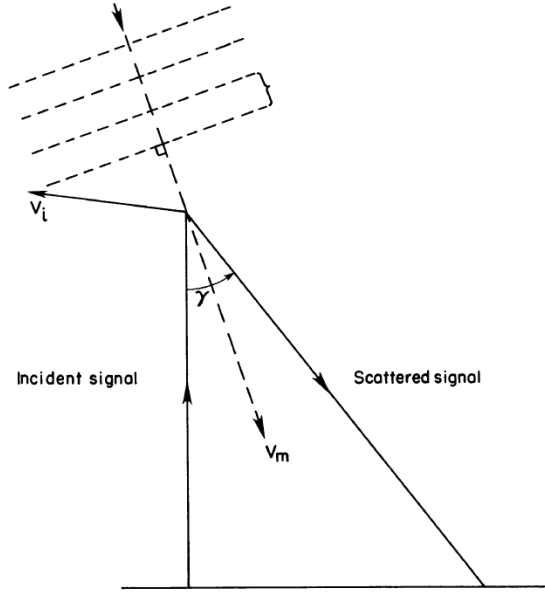


Figure 3.3: Scattering geometry for bistatic antennas. The angle γ is the angle between the incident and scattered signal. The velocity V_m is the line-of-sight velocity component of ions [Rishbeth and Williams, 1985].

$$\Delta f_i = \frac{\sqrt{8kT_i/m_i}}{\lambda} \cos\left(\frac{1}{2}\gamma\right) \quad (3.1)$$

where k is the Boltzmann constant, T_i is the ion temperature, m_i the ion mass, λ the radar wavelength, and γ the angle between the transmitted and scattered beam. This angle is shown in Figure 3.3, which would be $\gamma = 0^\circ$ for the monostatic radar in this study. The incident signal is shown on the left-hand side of the figure pointing upward, where it scatters in the ionosphere and the reflected signal moves downwards, shown on the right-hand side of the figure.

The spectrum width specifically for EISCAT for the UHF radar is

$$4\Delta f_i = 3 \cdot 24 \sqrt{T_i/m_i} \cos(1/2\gamma) \text{ kHz} \quad (3.2)$$

The centre frequency shown in Figure 3.2 is determined by

$$\delta f_i = 2(V_m/\lambda) \cos(1/2\gamma) \quad (3.3)$$

where δf_i is the Doppler shift, i.e., the offset from the transmitted radar frequency f , and V_m is the mirror velocity of the ions, the ion velocity component that is in the line of sight of the radar. This is the basic theory of a single-ion plasma system where the ion-neutral collision frequency is small.

The ratio of the peaks to the trough in the spectrum in Figure 3.2 is a sensitive function of T_e/T_i which is the temperature of electrons and ions respectively. From the area under the spectrum N_e , the electron density, can be deduced. From the width and shape of the spectrum T_i/m_i can be determined, where m_i is the ion mass. The F-layer atmosphere is dominated by atomic oxygen.

This double peak is narrowed and becomes single peaked in the lower ionosphere (i.e., the D-layer). This is due to an increase in ion neutral collisions. When the mean free path of the ions become shorter than the wavelength of the incident signal of the radar then the ion acoustic waves can no longer propagate.

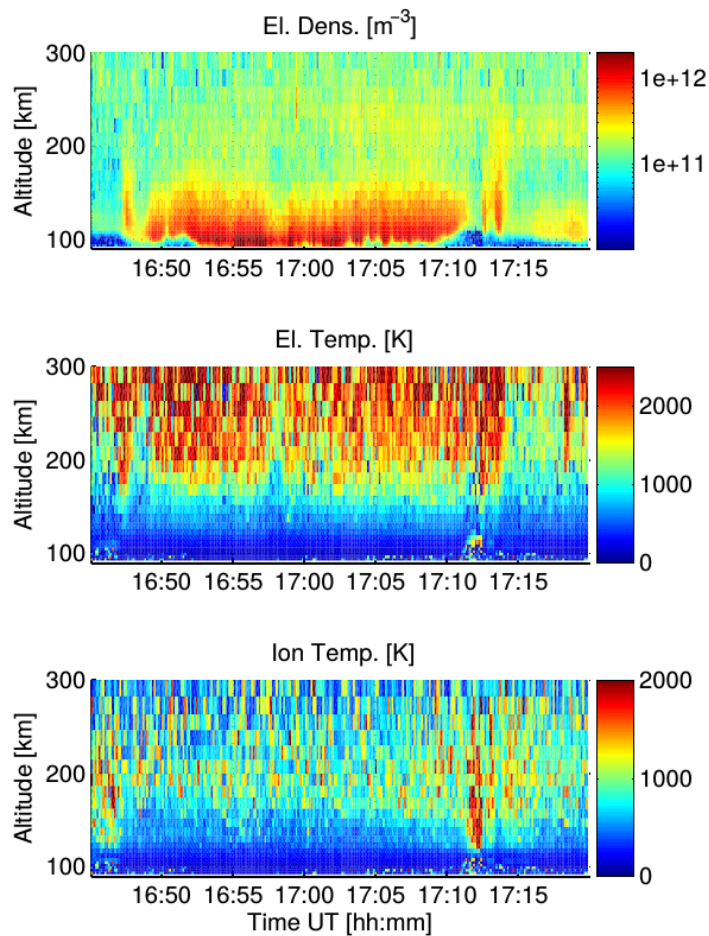


Figure 3.4: From top to bottom panel: examples of electron density, electron temperature, and ion temperature of a high-energy auroral electron precipitation event on 2006-12-12 [Schlatter *et al.*, 2013].

An example of typical high-energy auroral electron precipitation measurements using the UHF EISCAT radar is shown in Figure 3.4.

The EISCAT (European Incoherent SCATter Scientific Association) has been running since 1981 and several instruments are based in various locations: A transmitter/receiver at the Ramfjordmoen (Norway) site, and two receivers in Kiruna (Sweden) and Sodankyla (Finland) [Rishbeth and Williams, 1985; Blixt *et al.*, 2005]. The benefit of the incoherent scatter technique is the abil-



Figure 3.5: The Ramfjordmoen EISCAT facility outside Trømsø, Norway. In the front is the radar control room, and in the back the UHF radar used in this study. (Photo courtesy of <https://www.eiscat.se/>)

ity to study the upper atmosphere as a whole, but the downside is its considerable scattering volume. This can be up to 100 km^3 in the F_2 layer [Rishbeth and Williams, 1985]. This of course means that powerful transmitters need to be supplemented by sensitive receivers.

For this study, only the monostatic UHF radar at Ramfjordmoen was used, which is shown in Figure 3.5. The UHF radar has an 32 m antenna that is a mechanically fully steerable parabolic dish used for transmission and reception. It has a transmitter peak power of 2.0 MW and operates in the 930 MHz band (radio spectrum) [Haggstrom, 2018, Accessed 30 March 2018]. The beam itself has a full opening of 0.6° .

3.5 Summary

The ASK instrument is a multi-spectral imager that consists of three Andor iXon back-illuminated EMCCD detectors. It was used for the 2006 campaign. For this campaign, the ASK1 camera was fitted with a molecular nitrogen emission line (673.0 nm) filter, and the ASK3 camera was fitted with an atomic oxygen emission line (777.4 nm) filter. The imager was set up at the EISCAT Ramfjordmoen radar site. It ran in parallel with the EISCAT UHF radar.

Two iXon-888 back-illuminated EMCCD detectors were set up at the EISCAT Ramfjordmoen radar site during the 2009 campaign. The detectors were mounted with an atomic oxygen emission line (844.6 nm) filter and a molecular nitrogen emission line (427.8 nm) filter respectively. The detectors ran in parallel with the EISCAT UHF radar.

During the 2016 campaign, an iXon-888 back-illuminated EMCCD detector and an ALTA-U47 back-illuminated full frame megapixel CCD were set up at the EISCAT Ramfjordmoen radar

site. On the EMCCD a molecular nitrogen emission line (427.8 nm) filter was mounted and on the CCD an atomic oxygen emission line (844.6 nm) filter. These detectors ran in parallel

The EISCAT UHF radar is a transmitter/receiver at the EISCAT Ramfjordmoen site. It is an antenna with a fully steerable parabolic dish with a beam opening of 0.6° . Radio waves emitted by the radar are used to probe the ionosphere by using incoherent scattering techniques.

Chapter 4

Observations

4.1 Introduction

Black aurora events, as discussed in Section 2.5, are defined as dark structures embedded in the brighter diffuse aurora [Trondsen and Cogger, 1997]. In the following datasets, any dark structure that satisfies that definition, regardless of its intensity, is considered a black aurora. Dark structures that are embedded in discrete or pulsating aurora are not considered black auroras.

This chapter is divided into three sections: Observations made during the 2006 ASK campaign (Section 4.2), observations made during the 2009 campaign (Section 4.3), and observations made during the 2016 campaign (Section 4.4). The 2006 ASK campaign was recorded by the Southampton group and the 2009 campaign was recorded by M.J. Kosch and B. Gustavsson. The raw optical and radar data for both these campaigns was acquired by the author for calibration, analysis, and interpretation purposes. The optical data was scanned by eye to identify potential events for this study. The 2016 campaign ran from 28 February to 13 March 2016, where the raw optical and radar data was recorded by the author on the EISCAT site, which will be discussed in more detail in the following sections. Identification of potential events, and calibration of this data was done by the author during and after the campaign. Each section will discuss in detail the types of observations made, where it was recorded, the camera setup, how the events were identified, as well as the intensities measured for each event. Only the relevant events are shown in this chapter, and any additional events observed during the campaigns are shown in the Appendix.

All times refer to universal time (UT), and all camera and radar pointing directions are given in horizon coordinates (azimuth, elevation). Magnetic midnight local times for the three sets were 21:40:00 UT, 21:45:00 UT, and 21:54:00 UT respectively. This puts all events shown in this chapter in the post-magnetic midnight sector.

All frames were rotated for geographic North to point upward, as shown in Figure 4.1. The ground-based optical instruments point up towards the sky, thus in each frame, East is towards the left. The horizontal coordinate system is used in this study to indicate the pointing



Figure 4.1: Compass directions. All frames in this study were rotated for geographic North to point upward and East to the left.

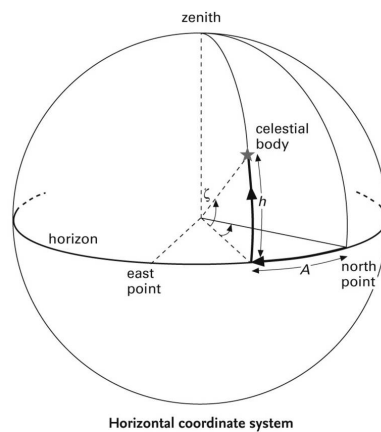


Figure 4.2: The horizontal coordinate system. It is used to indicate the location of a celestial object in relation to the observers plane on Earth. The angle measured from the horizon Northward towards the object is the altitude h , and the angle measured horizontally from true North to the vertical intersection with the objects is the azimuth, A .

(Source <https://encyclopedia2.thefreedictionary.com/horizontal+coordinate+system>)

Event	Date	UT	Width	Length	Drift velocity
1A	20061022	20:50:22 - 20:51:47	1.00 ± 0.1 km	–	–
1B	20061022	20:51:57 - 20:53:07	0.70 ± 0.1 km	–	–
1C	20061022	20:54:03 - 20:54:13	1.80 ± 0.1 km	–	–
2A	20090125	22:58:12 - 23:01:28	1.47 ± 0.4 km	–	–
2B	20090125	23:42:59 - 23:43:38	3.15 ± 0.4 km	–	–
3A	20160307	23:48:11 - 23:52:50	1.89 ± 0.4 km	–	–
4A	20160310	22:44:17 - 22:46:59	2.10 ± 0.4 km	–	–
4C	20160311	00:07:05 - 00:07:47	3.99 ± 0.4 km	–	–
4D	20160311	00:11:17 - 00:17:24	2.31 ± 0.4 km	7.35 ± 0.4 km	0.32 km.s^{-1} E 0.25 km.s^{-1} N
4E	20160311	00:16:53 - 00:17:41	1.05 ± 0.4 km (w) 1 ± 0.4 km (b)	13.86 ± 0.4 km	0.22 km.s^{-1} E 0.11 km.s^{-1} N
5A	20160312	21:45:28 - 21:47:37	11.13 ± 0.4 km	–	–
5B	20160312	21:54:22 - 22:11:13	2.73 ± 0.4 km (w) 2.52 ± 0.4 km (b)	16.40 ± 0.4 km	0.87 km.s^{-1} E
5C	20160312	22:11:14 - 22:13:58	4.62 ± 0.4 km	–	–
5D	20160312	22:32:07 - 22:32:37	5.46 ± 0.4 km (w) 3.57 ± 0.4 km (b)	4.00 ± 0.4 km	2.00 km.s^{-1} E
5E	20160312	22:51:34 - 22:55:37	2.17 ± 0.4 km	16.19 ± 0.4 km	0.65 km.s^{-1} E
5F	20160312	22:55:46 - 23:00:22	1.79 ± 0.4 km	14.49 ± 0.4 km	0.95 km.s^{-1} E
5G	20160312	23:00:23 - 23:04:04	0.82 ± 0.4 km	–	–
5H	20160312	23:05:43 - 23:06:19	0.93 ± 0.4 km (w) 0.92 ± 0.4 km (b)	17.70 ± 0.4 km	2.26 km.s^{-1} E
5I	20160312	23:06:20 - 23:15:52	1.18 ± 0.4 km (w) $1.22 \text{ km} \pm 0.4$ (b)	–	–
5J-1	20160312	23:15:53 - 23:26:01	4.71 ± 0.4 km	–	–
5J-2	20160312	23:15:53 - 23:26:01	1.24 ± 0.4 km (w) $1.49 \text{ km} \pm 0.4$ (b)	13.53 ± 0.4 km	–

Table 4.1: Observed events from 2006, 2009, and 2016 campaigns. Column 1 gives the event name. Column 2 shows the date of event recording. Column 3 shows time range when the event was visible in FOV. Columns 4 and 5 show width and length determined from ASK1 frames (Events 1A-C), and from the EMCCD camera mounted with the 427.8 nm filter (Events 2A-5J), along with their errors. Anti-black aurora is denoted by (w), and black aurora by (b). The last column shows the drift velocity of structures.

direction of the instruments. It is shown in Figure 4.2, and is in reference to the observer's local plane on the Earth's surface in relation to the location of celestial objects. The altitude h is the angular distance measuring from the horizon upwards, and the azimuth A is the angular distance around the horizon, measured from true North to the intersection of the objects vertical circle. The azimuth and altitude in this study are given in degrees and shown in brackets, (A, h) .

Where applicable, black structure widths, lengths, drift speeds (relative to the ground), and drift direction are shown in Table 4.1, with the times indicating when these events were clearly visible in the FOV. The widths, lengths, and drift speeds were determined by angular measurements for an altitude of 105 km. The FOV for each frame is known, thus by counting the number of pixels of each events width and length, the angles could be determined.

The altitude of the peak energy deposition adjacent to each black aurora was measured as 105 km, which is similar to the average height of homogenous arcs and bands measured in other studies [Currie, 1955; Gustavsson *et al.*, 2008]. This height has been well established in previous studies, but even if an over- or underestimation occurred it would not lead to any significant errors at that height. For example, if the height were over- or underestimated by ± 5 km, the resulting error for a black patch with a typical width would be 2 ± 0.1 km. When considering errors during width and length measurements only objects with sharply defined boundaries were estimated in Table 4.1. The boundaries are measured by eye, using the frames shown in Figures 4.3 - 4.15. An error of ± 4 pixels is estimated for the 2006 campaign set and an error of ± 2 pixels is estimated for the 2009 and 2016 set. For the 2006 campaign the frames had a 3.1° FOV, this leads to an error of ± 0.1 km. For the 2009 and 2016 campaign, where the EMCCD camera used for this estimation had a 30° FOV, the error was ± 0.4 km. This is shown in Table 4.1.

The centre of each event is defined as the point where the maximum length line and maximum width line cross. The pixel coordinates when each event drifts into the FOV is noted, and again when each event drifts out of FOV. Drifts speeds were estimated by noting the displacement of each event from frame to frame. Faster moving objects were taken over shorter time intervals (e.g. 3 seconds), and slower moving objects were taken over longer intervals (e.g. 10 seconds or more). As mentioned earlier, if an object could not be tracked over a long enough interval, the drift speed was not determined. From this the drift speed North and East components of events 4D, 4E, 5B, 5D, 5E, 5F, 5H, and 5J-2 are estimated and shown in Table 4.1. Note that some events are only drifting East, and have no North drift component.

In cases where a cluster of structures are classified as one event, the width of the structures shown in Figures 4.3 - 4.15 is given in Table 4.1. The frames on the left-hand side of each figure show the evolution of the structures over the sampled time range taken for each event. The dotted line in each frame is taken, where possible, roughly through the middle of the frame where the black-aurora structure can clearly be discerned from the surrounding diffuse aurora, i.e., where the boundaries between these two different types of auroras can clearly

be seen. Most of the structures, especially the black arcs (eg. Figure 4.3) drift too slowly to show any significant change over the times indicated, thus during the analysis of these events (i.e. determining average intensity of event), there is no possibility of mistaking one structure for another. Note that the intensity, indicated for each frame on the right-hand side, does vary from frame to frame, thus the intensities for each event used in calculations in this study is taken over an averaged time period. The lengths of structures, for both the black aurora and anti-black aurora, are only shown for events where there are clear boundaries between structures and the surrounding diffuse aurora. Drift velocity is only shown for events where the structure could be clearly tracked over several frames. Note that event 4B was discarded as it is highly likely to be gaps in the diffuse aurora, and not black arcs. It is therefore not included in Table 4.1, but is shown in Figure A.2 in the Appendix.

4.2 ASK events from 2006 EISCAT campaign

These observations commenced on 2006-10-26, between 20:51:00 and 20:55:00 UT at the EISCAT facility outside Tromsø, Norway and was run by the Southampton University group. ASK multi-spectral instruments were set up to point to $(185.8^\circ, 76.9^\circ)$, producing frames with a FOV of $3.1^\circ \times 3.1^\circ$. This translates to a FOV of $5.4 \text{ km} \times 5.4 \text{ km}$ at a 100 km altitude. The frame rate is 32 Hz, and the image size is 256×256 pixels. The EISCAT UHF radar was running in conjunction with the ASK instruments, in a fixed look direction of the azimuth 185.12° and elevation 77.5° .

Events 1A (Figure 4.3) and 1B (Figure 4.4) in this study were events identified by *Archer* [2009] (referred to in her dissertation as 2B and 2C respectively) using an ask.esr.eiscat.no keogram catalog. Event 1C (Figure 4.5) was added in this study due to the optimal position of the black aurora structure inside the radar beam, and the diffuse event (Figure 4.6) was added for comparison. Observations during this evening will be discussed in detail next, but only events chosen for analysis in this study are shown in Figures 4.3-4.5. Although auroral structures can be identified in both ASK1 and ASK3, structures in ASK1 are clearer and are shown in the figures for the sake of clarity. The data was recorded by the University of Southampton group during the 2006 campaign. All raw data acquired from this campaign was processed and analysed by the author.

At the beginning of evening observations (20:41:34 UT) it was mostly clear skies, with possible traces of cloud. Bright auroral bands with a uniform luminosity started to appear from the northerly direction, slowly moving equatorward at around 20:43:00 UT. By 20:45:00 UT possible thin (0.68 km) black arcs appeared from the north side, drifting equatorward. Up until 20:47:06 UT uniformly luminous bright aurora dominated, then gave way to 1.8 km bright auroral bands, with intermittent dark bands. These cannot be verified to be black aurora, due to the unclear structure, and questionable boundaries. By 20:50:28 UT a clear black arc appeared. Slight curls, indicating shear motion, was seen around 20:50:40 UT. By 20:51:30 UT the arc has

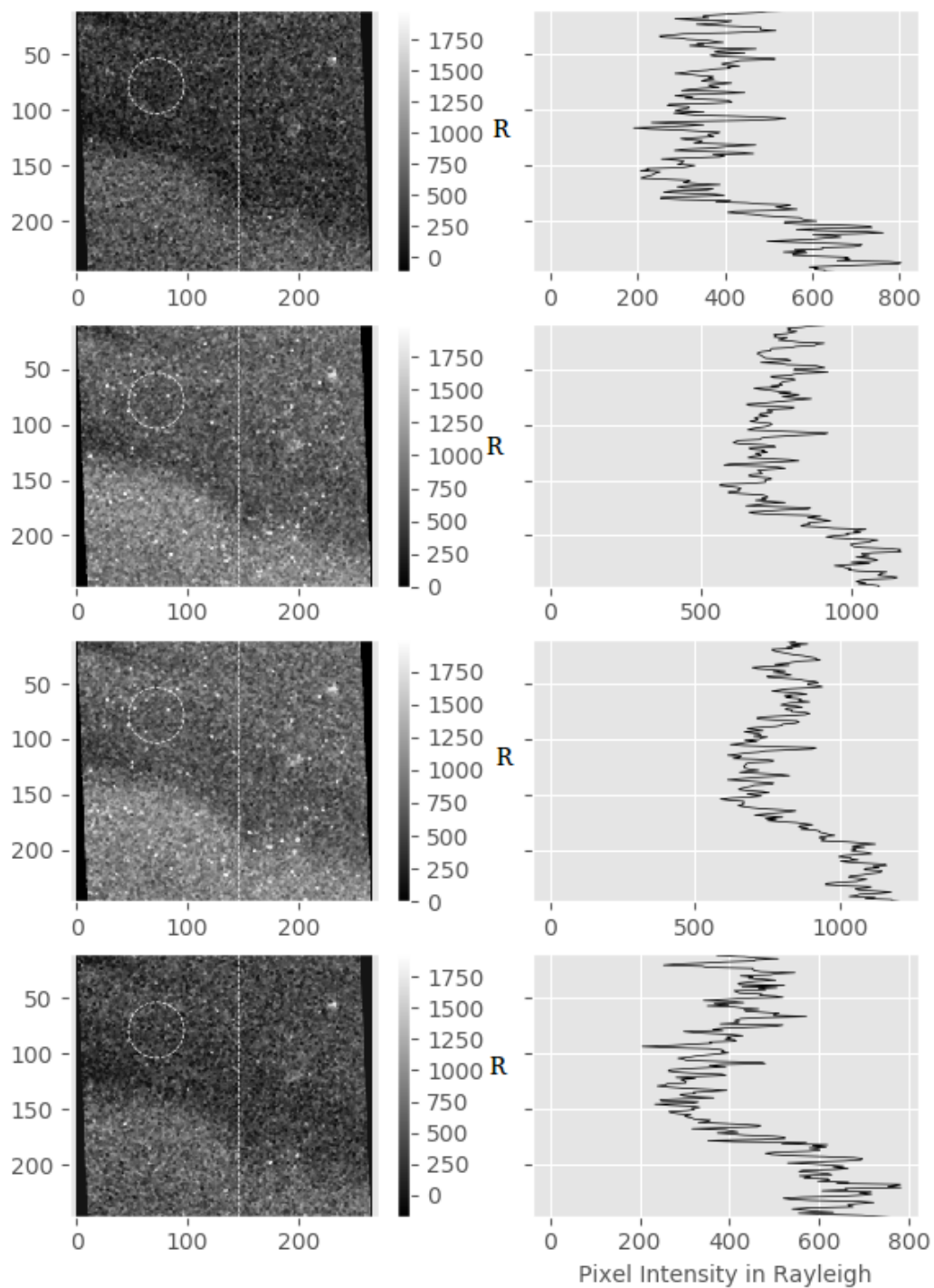


Figure 4.3: ASK1 (673.0 nm) frames from event 1A. Times were 20:51:30 , 20:51:31 , 20:51:32 , and 20:51:33 UT from top to bottom panel. The frames on the left-hand side are given in pixel coordinates. The dotted circle represents the EISCAT beam projected to 105 km, and each frame has a field of view of $3.1^\circ \times 3.1^\circ$. The dotted line represents the intensity sampling line shown in the right-hand column of panels.

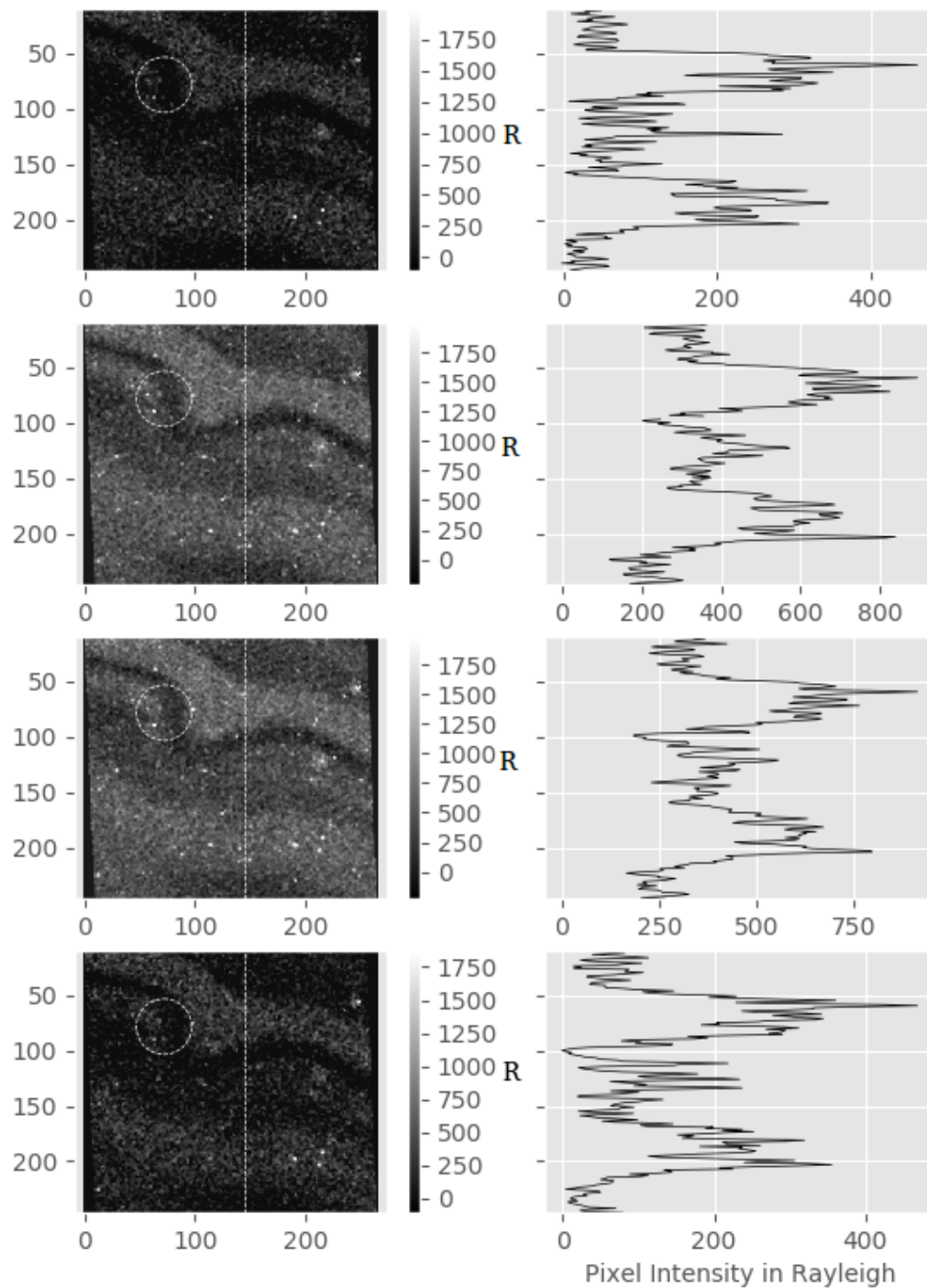


Figure 4.4: ASK1 frames from event 1B in the same format as Figure 4.3. Times were 20:53:00 , 20:53:01 , 20:53:02 , and 20:53:03 UT from top to bottom panel.

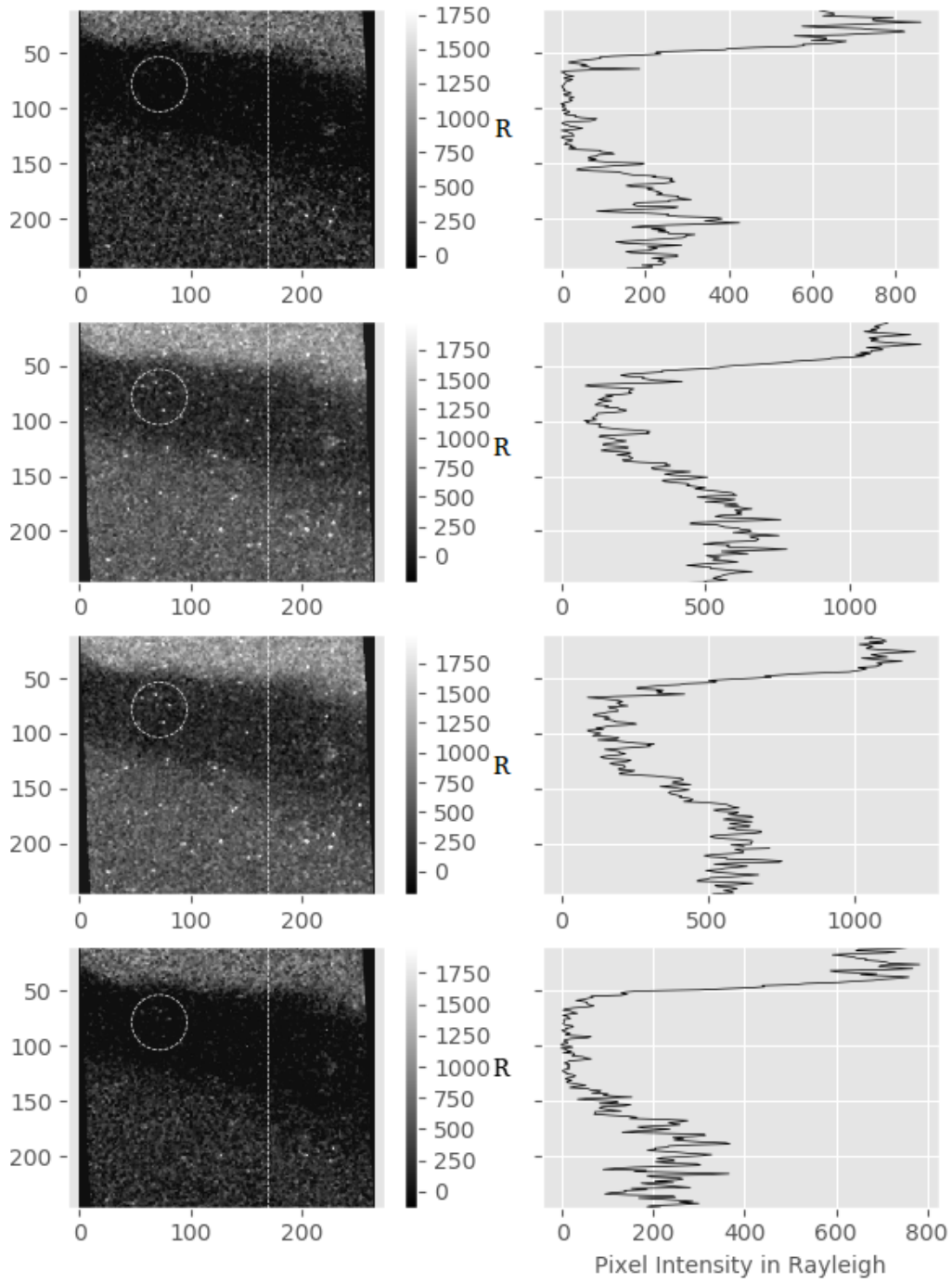


Figure 4.5: ASK1 frames from event 1C in the same format as Figure 4.3. Times were 20:54:03 , 20:54:06 , 20:54:09 , and 20:54:13 UT from top to bottom panel.

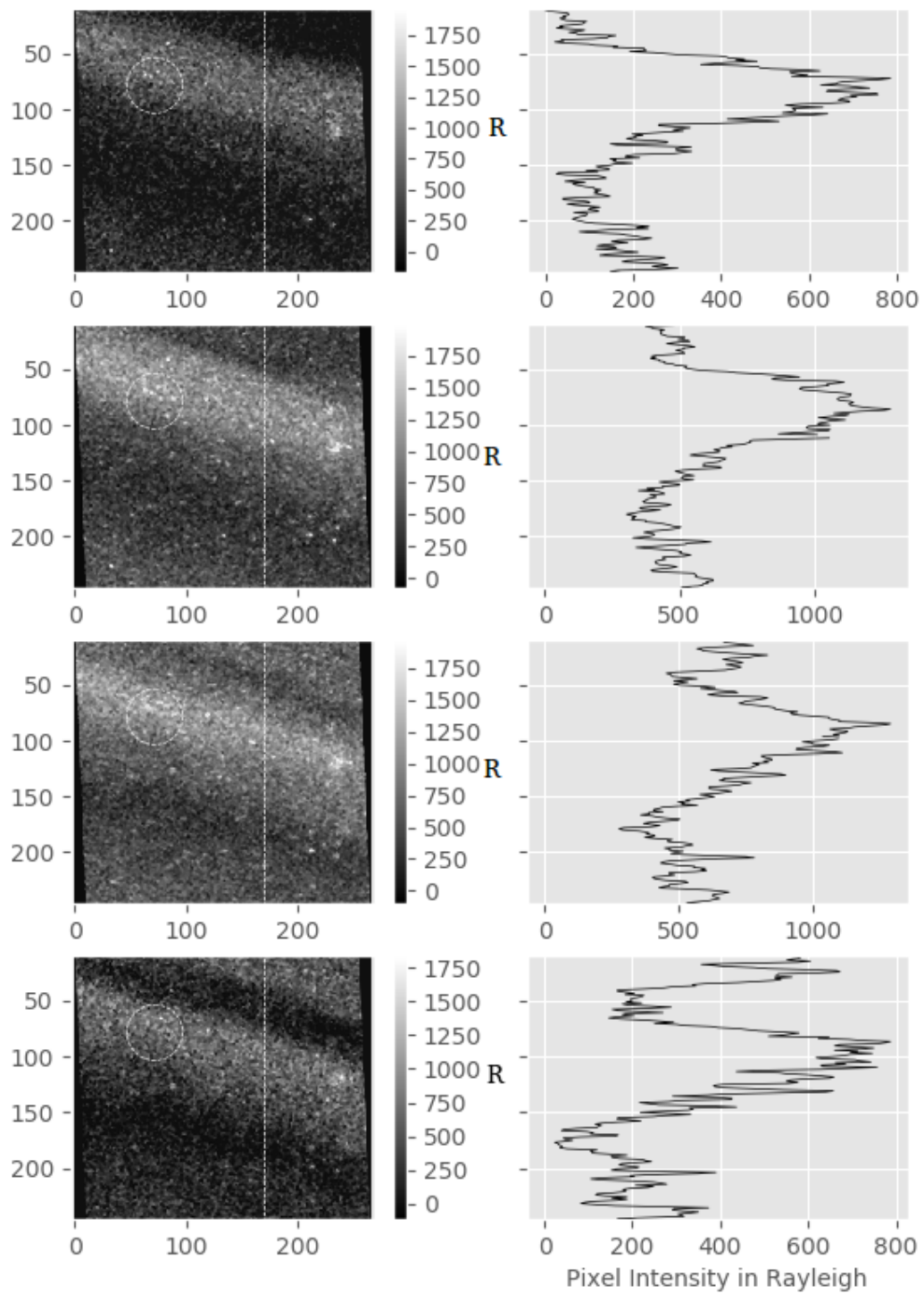


Figure 4.6: ASK1 frames for example of a diffuse aurora in the same format as Figure 4.3. This occurred after event 1C at times 20:54:40 , 20:54:43 , 20:54:51 , and 20:54:59 UT from top to bottom panel.

drifted to roughly the middle of the FOV and filled the radar beam, seen in Figure 4.3. This has been classified as a black arc (event 1A), due to its lower intensity. In these frames the surrounding diffuse aurora appears brighter below the black arc band than at the top. This is also clear by looking at the brightness profile on the right-hand side of the panels. For example in the bottom panel the diffuse aurora at the top of the black arc has an intensity of around 450 Rayleigh, and at the bottom around 600 Rayleigh. The top section of the diffuse is still brighter than the black arc, which is around 300 Rayleigh. Note that there is a significant temporal variation for the intensities. Comparing panel 3 with panel 4, the intensity of the bottom section of the diffuse aurora is over 1000 Rayleigh, and for the bottom panel the bottom section of the diffuse aurora is around 600 Rayleigh. Note that due to this variation the brightness intensity profiles for the 2006 are not on the same scale. There also appears to be curls or vortices present in the arc, seen here along the dotted line in the frames on the left-hand side.

By 20:52:07 UT the structure disappeared from view, and a group of about three curved black arcs appeared, moving relatively fast in an equatorward direction. The arcs reached the middle of the FOV by 20:53:00 UT and partially filled the radar beam, shown in Figure 4.4. This was the start of event 1B. In these frames a distinct, curving arc is seen in the top section of each frame. It is also this arc that partially fills the radar beam, indicated by a dotted circle. Above and below it wider arcs are seen, albeit dimmer than the aforementioned arc. In the brightness profile in panel 2, the black arcs have a brightness between 200 and 300 Rayleigh. The two peaks in this brightness profile are the surrounding diffuse aurora, which ranges between 600 - 700 Rayleigh. Also note that in this Figure the brightness profiles are not on the same scale.

Distinct arcs (event 1C) started to appear again around 20:53:43 UT, reaching roughly the middle of the FOV and filling the radar beam by 20:54:03 UT shown in Figure 4.5. Here too the intensity showed significant temporal variation. Comparing panels 1 and 2, the bottom section of the surrounding diffuse aurora is around 200 Rayleigh and 500 Rayleigh respectively. The diffuse aurora in the top section of the frames is much brighter. In panel 1 it is around 700 Rayleigh, and in panel 2 over 1000 Rayleigh. The dynamic aurora was brighter north of the black arc than south of it. A diffuse auroral band with a thin black arc (width of 0.9 km) embedded at 20:54:40 UT showed signs of vortices and curls due to shear motion. By 20:56:00 UT the field of view was almost completely filled by a homogeneous diffuse auroral surface.

The three selected events, 1A, 1B, and 1C, from this campaign are shown in Table 4.1. These were black arcs which cross the length of the FOV, thus no length or drift velocity could be measured.

4.3 Events from 2009 EISCAT campaign

On the evening of 2009-01-25, a pair iXon-888 back-illuminated EMCCD detectors ran in parallel, positioned at the EISCAT radar site. The produced images have a 256×256 pixel resolution, along with a 30° FOV. Each camera was fitted with a filter at different spectral bands:

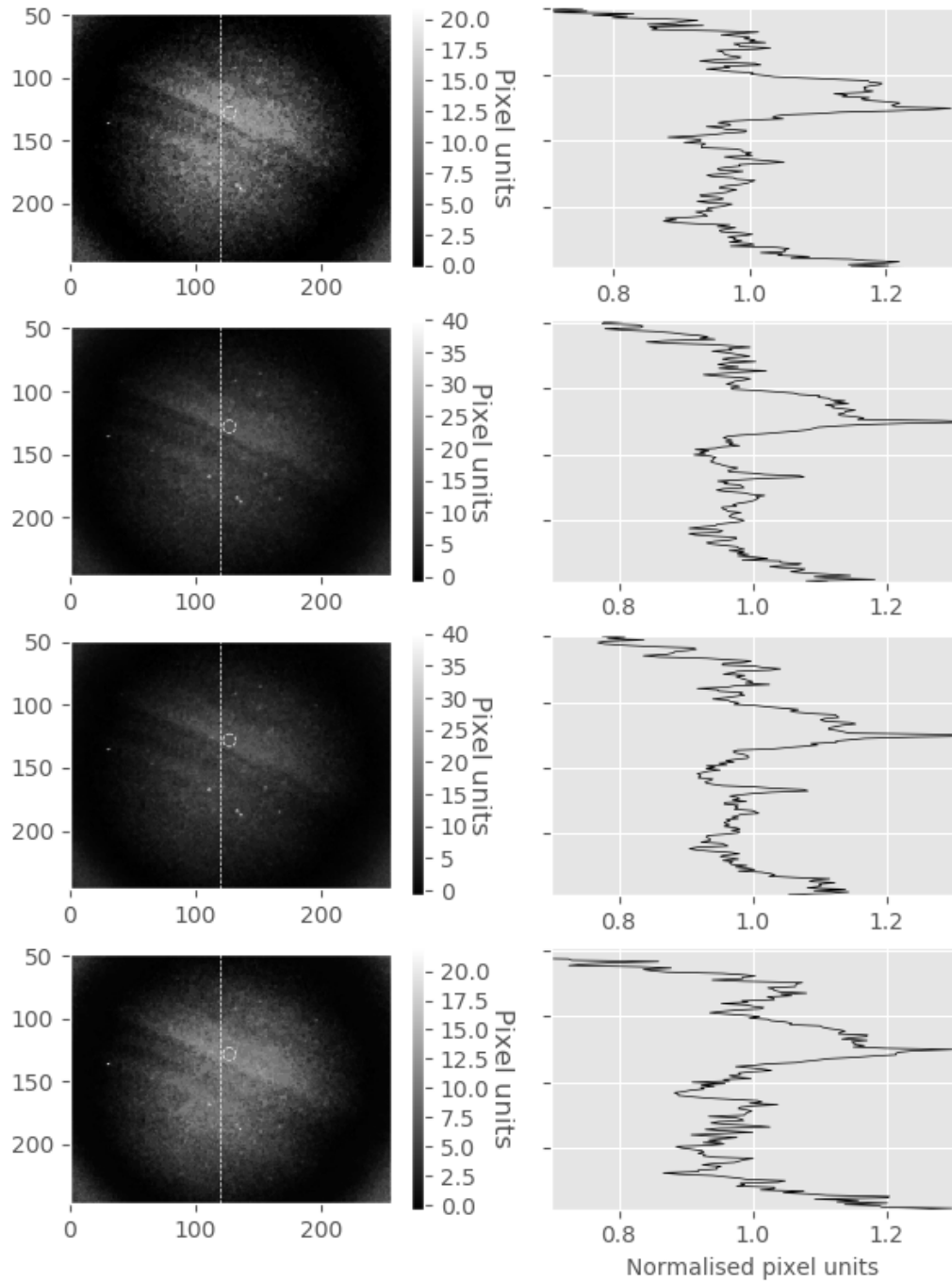


Figure 4.7: Select frames from 427.8 nm event 2A on 2009-01-25. The dotted circle represents the EISCAT beam projected to 105 km, and each frame has a field of view of $30^\circ \times 30^\circ$. The frames on the left-hand side are given in pixel coordinates. The dotted line represents the intensity sampling line shown in the right-hand column of panels. Times were 22:59:17 , 22:59:20 , 22:59:22 , and 22:59:25 UT from top to bottom panel. Note that the intensity scale is variable.

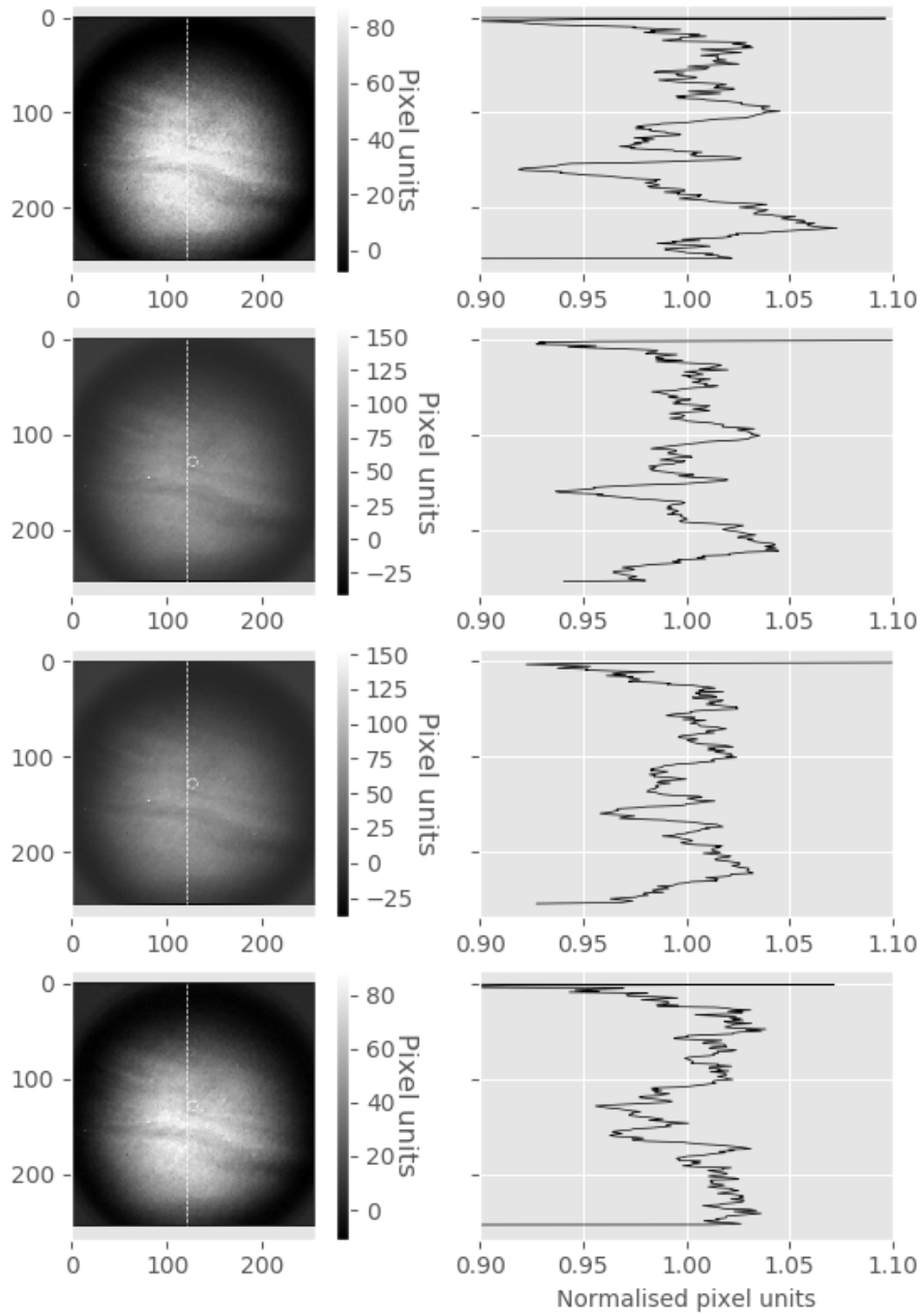


Figure 4.8: Select frames from 427.8 nm event 2B on 2009-01-25 in the same format as Figure 4.7. Times were 23:43:21 , 23:43:22 , 23:43:24 , and 23:43:28 UT from top to bottom panel.

844.6 nm and 427.8 nm respectively. The frame rate was 1 Hz.

The UHF radar was running in conjunction with the optical observations, and rotated between four different pointing directions in azimuth and elevation (180° , 90°), (193° , 64°), (226° , 61°), and (185° , 77°) in 1-minute intervals. The events for this campaign was chosen specifically when the radar was pointing into magnetic zenith (185° , 77°). The raw data for this campaign was processed and analysed by the author.

Events 2A and 2B (See Figures 4.7 and 4.8) were selected on a dataset that commenced from 2009-01-25 22:37:02 UT, until camera shut down 26 January 01:41:01 UT. Several possible black arcs and black arcs segments were identified, but only two events showed morphologies and features characteristic of black aurora structures. Brightness profiles are shown on the right-hand side for each corresponding frame. Each brightness profile was an average taken over 10 columns. To enhance the images to better observe and identify auroral events, contrast stretching was applied to all frames.

Observations for this set were unobstructed by cloud cover, and streaks of dynamic aurora with thin embedded black arcs are observed around 22:40:00 UT. What appeared to be mainly diffuse aurora filled the FOV up until around 22:59:20 UT during which time a long black arc came into view. This was chosen as event 2A when it reached roughly the middle of the FOV at around 22:59:17 UT, seen in Figure 4.7. Here a broad black arc can be seen stretched across the FOV in all four frames. The time range when this event was visible, as well as its width are noted in Table 4.1. The corresponding brightness profile is shown on the right-hand side of each frame in Figure 4.7. The units are in normalised pixel units due to the raw frames being divided by the normalised median of a set of flat field frames. This is discussed in more detail in the next chapter, in Section 5.2.2. Less temporal variation of the intensity was noticed here compared to the 2006 campaign. This is probably due to the longer time integration for the 2009 campaign during recording, which would average out intensity fluctuations on short time scales. Thus for the 2009 set the brightness profiles seen on the right-hand side of the figures are all on the same scale. Here the background diffuse aurora is brighter on the top side of the black arc band seen in the middle of the frame, with a normalised pixel unit count around 1.2. Below the black arc band the diffuse aurora has a normalised pixel unit count of around 1.0, and this is true for all the panels. The normalised pixel unit count for the black arc band seems to be around 0.9 in all the panels. The radar pointing direction is again shown by the dotted circle, and is completely filled by the bright diffuse aurora in all the panels.

This event gave way to a mostly uniform diffuse auroral surface which grew fainter and finally disappeared. Dynamic, pulsating aurora appeared again around 23:25:20 UT. By 23:39:01 UT several arcs and eastward drifting arc segments, along with diffuse aurora, appeared in the FOV. The arcs and arc segments tended to merge into each other whilst drifting in the FOV, making it sometimes difficult to discern between structures. Event 2B was chosen from this set, drifting past close to the middle of the FOV at 23:43:21 UT shown in Figure 4.8. Here an arc segment is seen just below the radar pointing direction indicated by a dotted circle. By

the fourth panel it seems to have evolved into two separate arc segments. The segment has a normalised pixel unit count ranging between 0.93 and 0.96 over the selected time range. The normalised pixel unit count for the surrounding diffuse aurora is higher, ranging between 1.03 and 1.07 in this time range. Note that the two middle panels appear dimmer, but not due to a lower intensity. It is due to linear contrast stretching that was applied to better identify events during the selection step. From the brightness profiles these frames clearly fall in the same intensity range. The time this event was visible in the FOV, as well as its width are shown in Table 4.1. Although this can be classified as an arc segment, the length and drift speed for this event could not be determined with absolute certainty due to the tendency of the structures to merge into each other. Dark structures became more pronounced, and broad black arcs started to appear at 23:52:01 UT, and black arc segments continued to appear until around 23:54:00 UT. Diffuse aurora was for a short period replaced by bright, dynamic aurora around 23:55:41 UT. Here a dark region at 00:32:10 UT was seen wedged between two bright arcs. The southern arc was brighter than the northern arc, and ripples (shear vortices) could be seen cascading southward. Uniformly luminous aurora appeared again from 00:41:00 UT, up until 01:16:39 UT. After this, no significant structures were observed until camera shut-down.

4.4 Events from 2016 EISCAT campaign

Two cameras were placed next to each other at the EISCAT radar site on three separate evenings: 2016-03-07, 2016-03-10, and 2016-03-12 UT. The EMCCD was mounted with a 427.8 nm filter, and pointed into magnetic zenith ($180^\circ, 77^\circ$), given in azimuth and altitude, with a 30° FOV. The DASI camera was mounted with a 844.6 nm filter, and pointed into local zenith ($180^\circ, 90^\circ$), given in azimuth and altitude, with a 50° FOV. The images produced have a 256×256 pixel resolution. The frame rate was 0.33 Hz.

The EISCAT UHF radar was fixed in the magnetic zenith ($180^\circ, 77^\circ$) pointing direction during observations. The raw data was recorded, processed and analysed by the author.

As with the previous section, contrast stretching was applied to each frame.

Events chosen are those that show reasonable black aurora characteristics mentioned by *Trondsen and Cogger* [1997]. For many instances where black patches and arc segments are mentioned together, they appeared to have similar features and seemed to evolve from one type to another. Many black structures drifting eastward also had a southward component. Frames from the EMCCD detector mounted with the 427.8 nm filter are shown in this section.

4.4.1 Event 3A from 7 March 2016

Observations during the first part of the evening were obstructed by thick cloud cover, which slowly started clearing up around 19:31:11 UT. Discrete, dynamic aurora could be observed

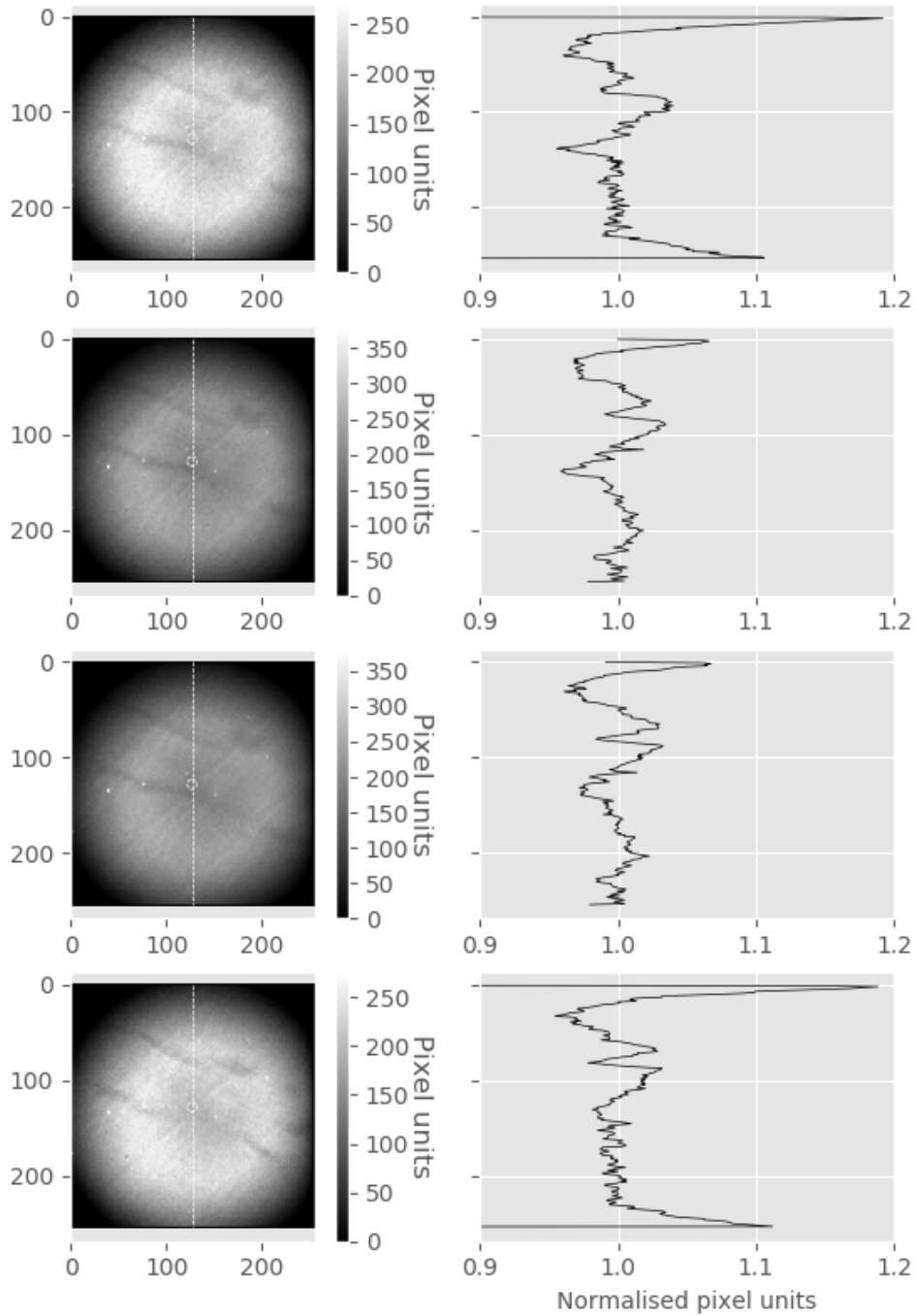


Figure 4.9: Select frames from 427.8 nm event 3A on 2016-03-07. The dotted circle represents the EISCAT beam projected to 105 km, and each frame has a field of view of $30^\circ \times 30^\circ$. The frames on the left-hand side are given in pixel coordinates. The dotted line represents the intensity sampling line shown in the right-hand column of panels. Times were 23:49:53, 23:49:56, 23:49:59, and 23:50:02 UT from top to bottom panel. Note that the intensity scale is variable.

behind the cloud cover. Clear skies by 19:48:35 UT showed discrete aurora, with some intermittent flickering apparent, especially around 20:16:14 UT. Dynamic aurora gave way to homogeneous diffuse aurora at 20:55:14 UT. Possible weak, thin, black arcs appeared at 21:03:44 UT. Uniformly luminous aurora appeared at 21:11:14 UT. This gave way to flickering, dynamic aurora at 21:13:44 UT. This was short-lived though, as it gave way to uniformly luminous aurora again around 21:45:44 UT. Clusters of black aurora patches and arc segment structures drifted in an east-west direction from 21:58:44 until 22:10:00 UT. Here dynamic, flickering aurora appeared again by 22:11:04 UT. Discrete vertical lines were seen drifting through the FOV at 23:07:44 UT, followed by uniformly luminous aurora at 23:41:14 UT. A cluster of black patches and arc segments appeared at 23:48:44 UT. From this set, event 3A was chosen, seen drifting past close to the middle of the FOV at 23:49:53 UT, and shown in Figure 4.9. The dotted line that represents the brightness profile on the right-hand side of the panels cuts through two prominent black arc segments in Figure 4.9. On the right-hand side of all the frames there is an indication of black patches, or possibly segments, coming into view. These two prominent black arc segments do not show significant intensity variation in the frames, and the normalised pixel unit count is around 0.97 for the top arc segment. The bottom arc segment has a normalised pixel unit count of around 0.96. In the fourth panel the normalised pixel unit count cannot be discerned from the count of the surrounding diffuse aurora. In all the frames the surrounding diffuse aurora has a normalised pixel unit count of around 1.0. When this event drifted closest to the radar beam it started to merge with the adjacent arc segments, and completely merged after crossing the middle of the FOV until it disappeared. Due to this the length and drift speed could not be determined, and only the time the event was visible and the width is shown in Table 4.1.

Black structures that appeared as smoky trails that didn't strictly speaking classify as either patches or arc segments came into the FOV. Aurora structures having uniform luminosity, with intermittent dynamic aurora, was seen from 00:03:44 UT onwards. Bright pulsating and flickering structures were also observed for the last period before observations ended.

4.4.2 Events 4A - 4E from 10 March 2016

As with the previous dataset, this evening also started with significant cloud cover. Possible dynamic, discrete aurora was observed at 20:38:23 UT behind the cloud base. Most of the cover began to disperse. Dynamic aurora, that interchanges with uniform luminosity aurora, appeared. By 21:28:23 UT possible black arcs became visible. Mostly a diffuse auroral surface with uniform luminosity was visible around 22:08:23 UT. At 22:23:23 UT a cluster of dark arc structures were seen, showing clearly and drifting close to the middle of the FOV at 22:45:47 UT. This is taken as event 4A, shown in Figure A.1. Here the events are not as clear as the previous examples and the morphology of the black aurora structures are difficult to classify. Two black patches, or possibly black arc segments, drift past roughly in the middle of the FOV, just below the radar pointing direction. The presence of these two structures is confirmed

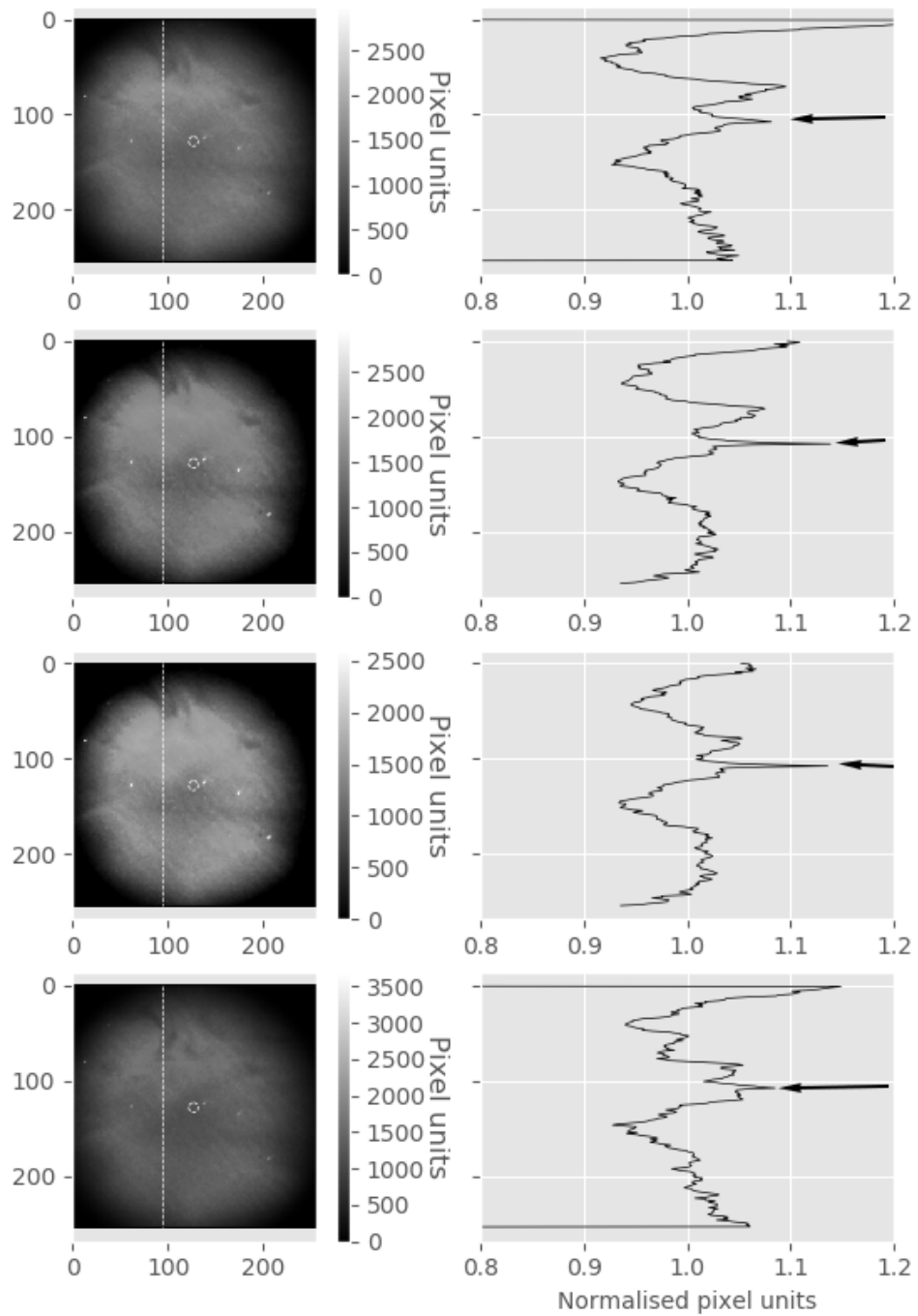


Figure 4.10: Select frames from 427.8 nm event 4D on 2016-03-10 in the same format as Figure 4.7. Times were 00:12:38, 00:12:41, 00:12:44, and 00:12:47 UT from top to bottom panel. A star is indicated by the arrows.

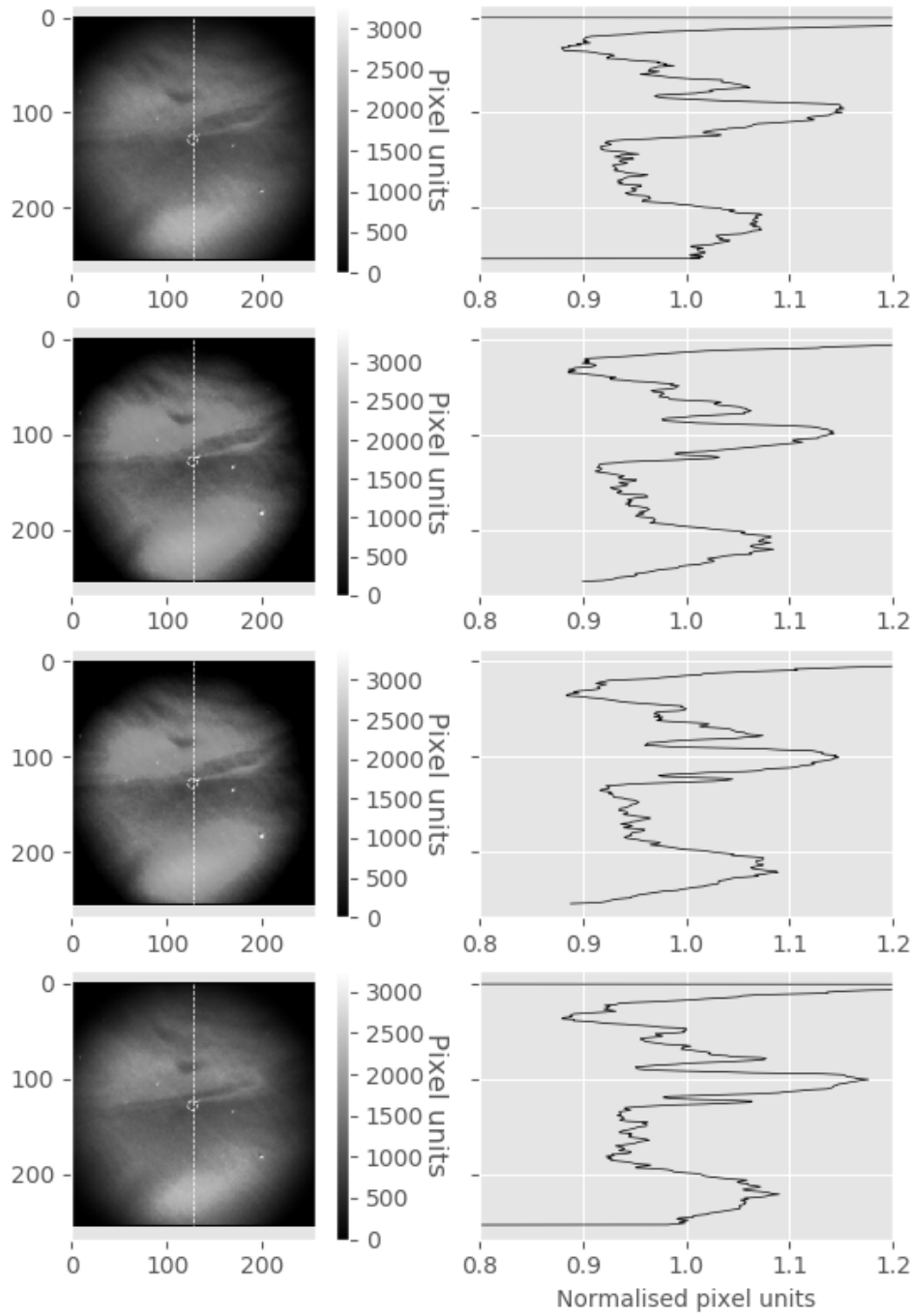


Figure 4.11: Select frames from 427.8 nm event 4E on 2016-03-10 in the same format as Figure 4.7. Times were 00:16:53, 00:16:56, 00:16:59, and 00:17:02 UT from top to bottom panel.

by the two troughs, separated by a small peak, seen in the brightness profiles on the right-hand side of each frame. The normalised pixel unit count is between 0.96 and 0.98 for all four panels. The bright diffuse aurora surrounding these two structures on either side have an average normalised pixel unit count of about 1.04. The horizontal boundaries of this structures were unclear, and intermittently faded into the diffuse background in some frames, thus the length and drift speed could not be measured with absolute certainty. The width is shown in Table 4.1. Intermittent dynamic aurora was observed during this event.

Dynamic aurora along with flickering or pulsation was identified around 22:45:53 UT. A cluster of black structures was observed at 22:50:53 UT. This was initially classified as event 4B but later discarded because it is more likely to be gaps in the diffuse aurora, and not black arcs. It is shown in the Appendix, Figure A.2. Clusters of black arc structures were observed again at 00:07:29 UT, and classified as event 4C, shown in Figure A.3. In the top right corner a black patch or arc segment comes into view just above a much brighter auroral structure. Although this event is not close to the centre of the FOV, it shows a significant dip in intensity compared to the surrounding diffuse aurora. It has a normalised pixel unit count of 0.95 seen in the brightness profiles for all four panels. The surrounding diffuse aurora has an average normalised pixel unit count of just slightly over 1.0. By looking at the brightness profiles, there might be another black aurora structure just below the very bright patch, but this can't be verified from the frames. The bright structure itself has a normalised pixel count of over 1.1. The structure faded into the diffuse background in the following frames, and the length and drift speed could not be determined with absolute certainty. The width is shown in Table 4.1. These, as well as possible anti-black aurora structures, continued until the end of the recording.

From these, structures drifting close to the middle of the FOV were chosen as event 4D at 00:12:38 UT shown in Figure 4.10, and event 4E at 00:16:53 UT shown in Figure 4.11. In Figure 4.10 several black patches are seen drifting past in the top section of the frames. The clearest one has a normalised pixel unit count of between 0.92 and 0.95. Note how it changes shape and drifts southwards as time passes. From the brightness profiles on the right-hand side of the panels there seems to be another black structure, possibly a black arc, of similar intensity as the black patch right below the radar pointing direction. This structure could not be verified by looking at the frames. Figure 4.11 shows black patches similar to those seen at an earlier time in Figure 4.10. They are also located in the top (Northern) section of the FOV. The normalised pixel unit count for the black patch just above the radar pointing direction is around 0.88. There is a possible black arc segment in the centre of the frame, with a slightly higher pixel count than the aforementioned patch. It ranges between 0.92 and 0.97. If this is a black arc, it means that for this event the radar beam is partially filled by a black aurora. The average width, length and drift speed of these two events are shown in Table 4.1.

Overall the geometry and drift velocity, especially direction, of these structures varied greatly in the FOV.

4.4.3 Events 5A - 5J from 12 March 2016

For the final data set, the evening also started overcast. From 20:30:53 UT there seemed to be signs of dynamic aurora behind the cloud cover. It started to clear around 21:40:53 UT, and black arc structures of varying widths appeared around 21:45:53 UT, drifting past close to the middle of the FOV at 21:46:01 UT. The most prominent of this cluster is classified as event 5A, shown in Figure A.4 with the dotted line passing through its border. The structure was very dynamic and was never prominent enough for the length or drift speed to be determined. The width is shown in Table 4.1. This arc has a normalised pixel unit count of around 0.91, and the surrounding diffuse aurora has a normalised pixel unit count between 1.0 and 1.1.

Dynamic aurora was observed around 21:50:53 UT. A cluster of possible black arc segments and patches drifted by up until 22:07:56 UT, and then was replaced by a cluster of anti-black aurora and black aurora pairs, moving close to the middle of the FOV at 22:08:01 UT (Figure 4.12). They present as a white patch and a black patch pair, drifting together at the same speed. In this figure the dotted line that represents the brightness profile on the right-hand side of the frames cuts through the most prominent anti-black aurora and black aurora pairs of this group. It is indicated by a white arrow on the bottom left side of the frames. From the brightness profiles it is clear that the normalised pixel unit count for the anti-black aurora is higher than that of the surrounding diffuse aurora. The black aurora has a lower normalised pixel unit count than the surrounding diffuse aurora. The location of the pixel count for this anti-black aurora and black aurora pair is indicated by the bottom black arrow. The normalised pixel unit count for the anti-black aurora is between 1.06 and 1.12. The normalised pixel unit count for the black aurora is around 0.93, and for the surrounding diffuse aurora is around 0.97. The difference between the pixel counts for the smaller anti-black aurora in the top left corner of the frames and the surrounding diffuse is less clear. This might be because the column over which the pixel counts are averaged might include pixel counts from the surrounding diffuse aurora. These anti-black aurora and black aurora pairs present as a black patch and white patch moving at the same velocity, similar to what was observed in Figure 2.18. This has been classified as event 5B. This is the first ever, unique, multi-spectral data set (in conjunction with radar data) of anti-black aurora recorded. The length, width and drift speed is indicated in Table 4.1.

Thick black arcs were observed in the northern section at 22:11:59 UT, embedded in a brighter, homogeneous diffuse aurora. At 22:12:04 UT the arcs drift close to the middle of the FOV, and is shown in Figure A.5 as event 5C. Here the possible black arc has a normalised pixel unit count of 0.9, and the surrounding diffuse aurora is around 1.0. This would have been a good candidate for black vortex street arrays, but no curls were ever noticed [Trondsen and Cogger, 1997]. The northern section of the aurora ('above' the black aurora) had a very bright section, compared to the bottom section. It's a black arc, and the length and drift speed could not be determined. The width is indicated in Table 4.1.

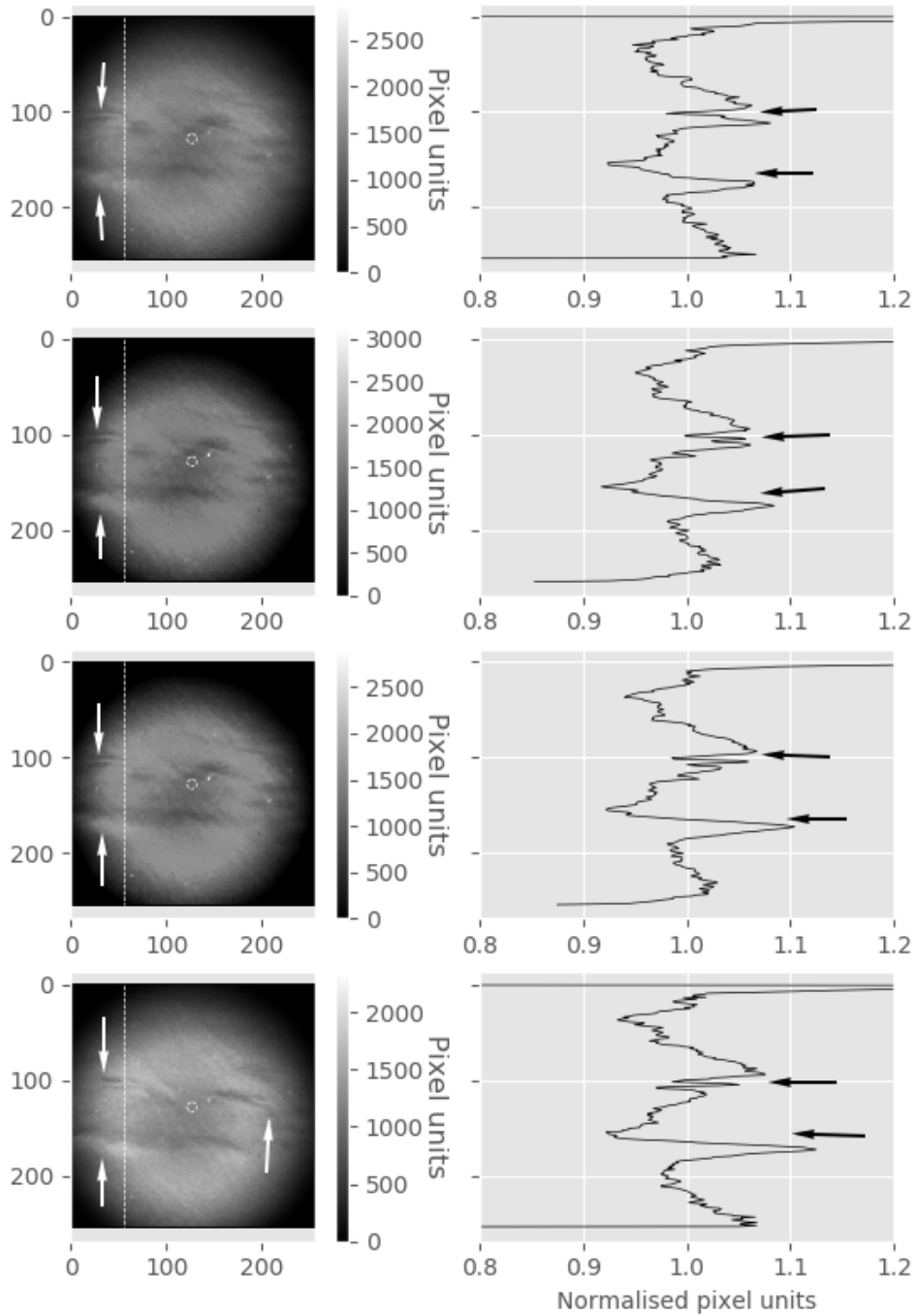


Figure 4.12: Select frames from 427.8 nm event 5B on 2016-03-12 in the same format as Figure 4.7. In the left panels the white arrows show the position of the anti-black aurora and black aurora pair. In the right panels the black arrows show the position of the black and anti-black aurora pairs on the brightness profile. Times were 22:08:01, 22:08:04, 22:08:07, and 22:08:10 UT from top to bottom panel.

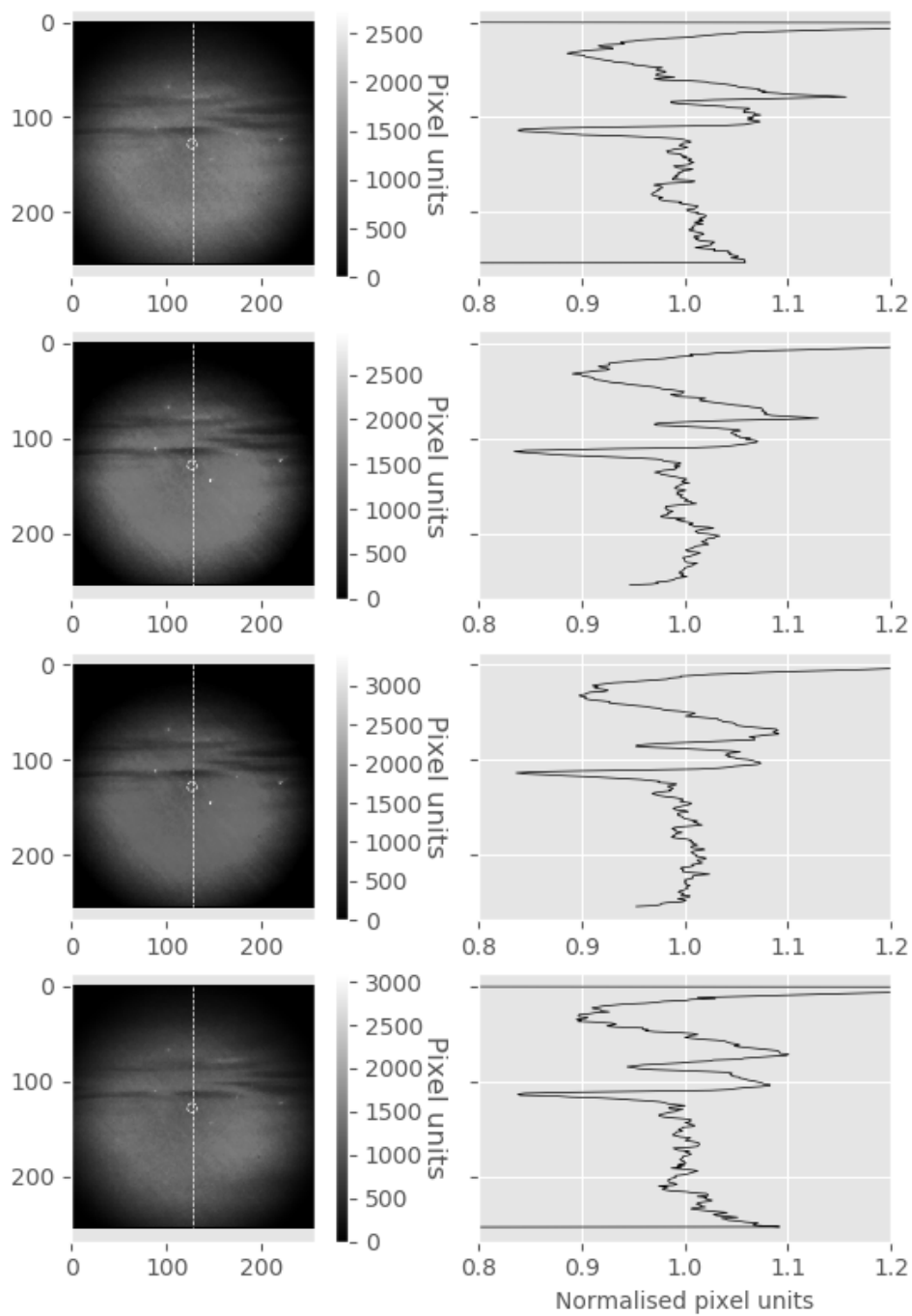


Figure 4.13: Select frames from 427.8 nm event 5F on 2016-03-12 in the same format as Figure 4.7. Times were 22:56:19, 22:56:22, 22:56:25, and 22:56:28 UT from top to bottom panel.

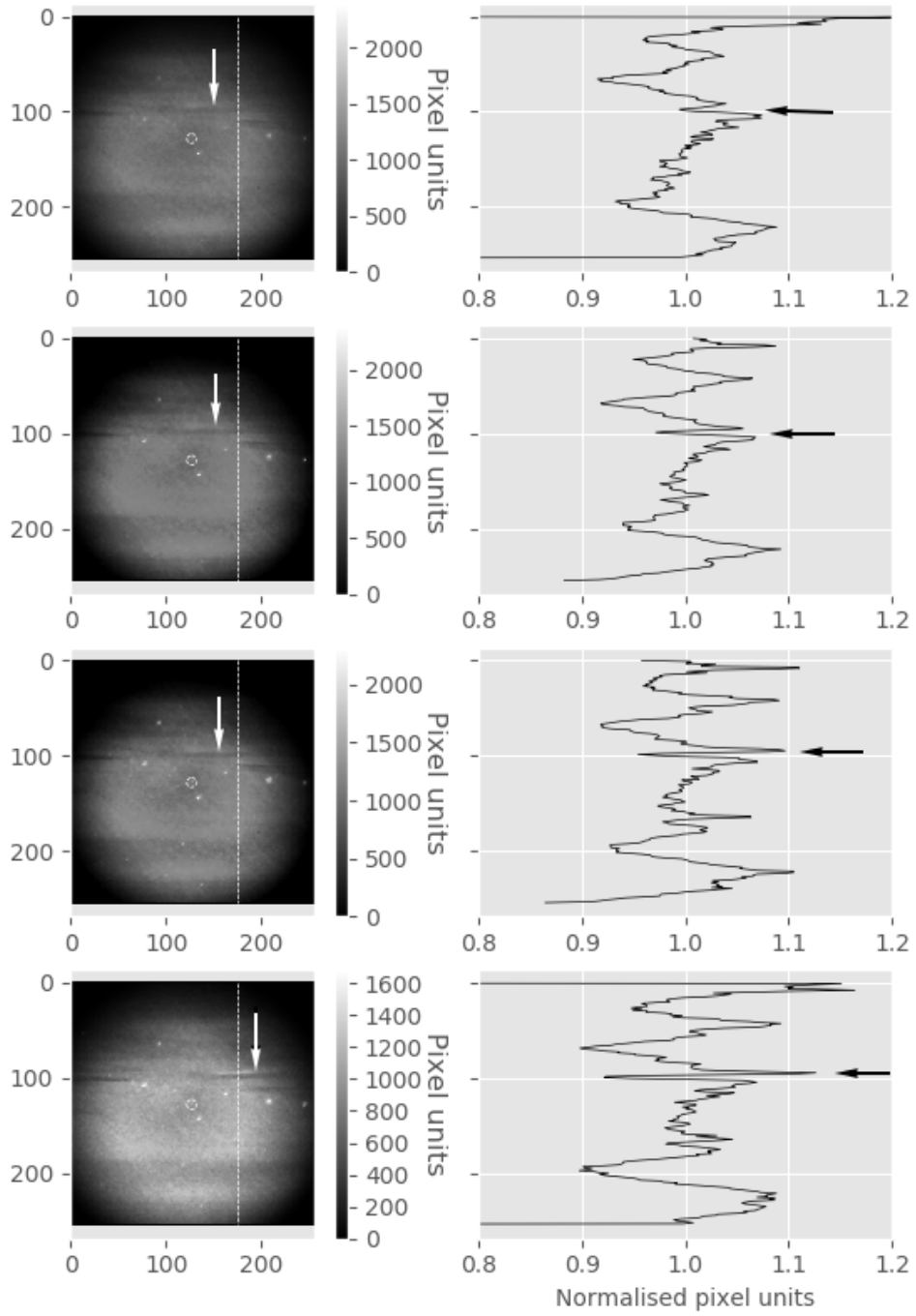


Figure 4.14: Select frames from 427.8 nm event 5H on 2016-03-12 in the same format as Figure 4.7. In the left panels the white arrows show the position of the anti-black aurora and black aurora. In the right panels the black arrows show the position of the black and anti-black aurora pairs on the brightness profile. Times were 23:05:55, 23:05:58, 23:06:01, and 23:06:04 UT from top to bottom panel.

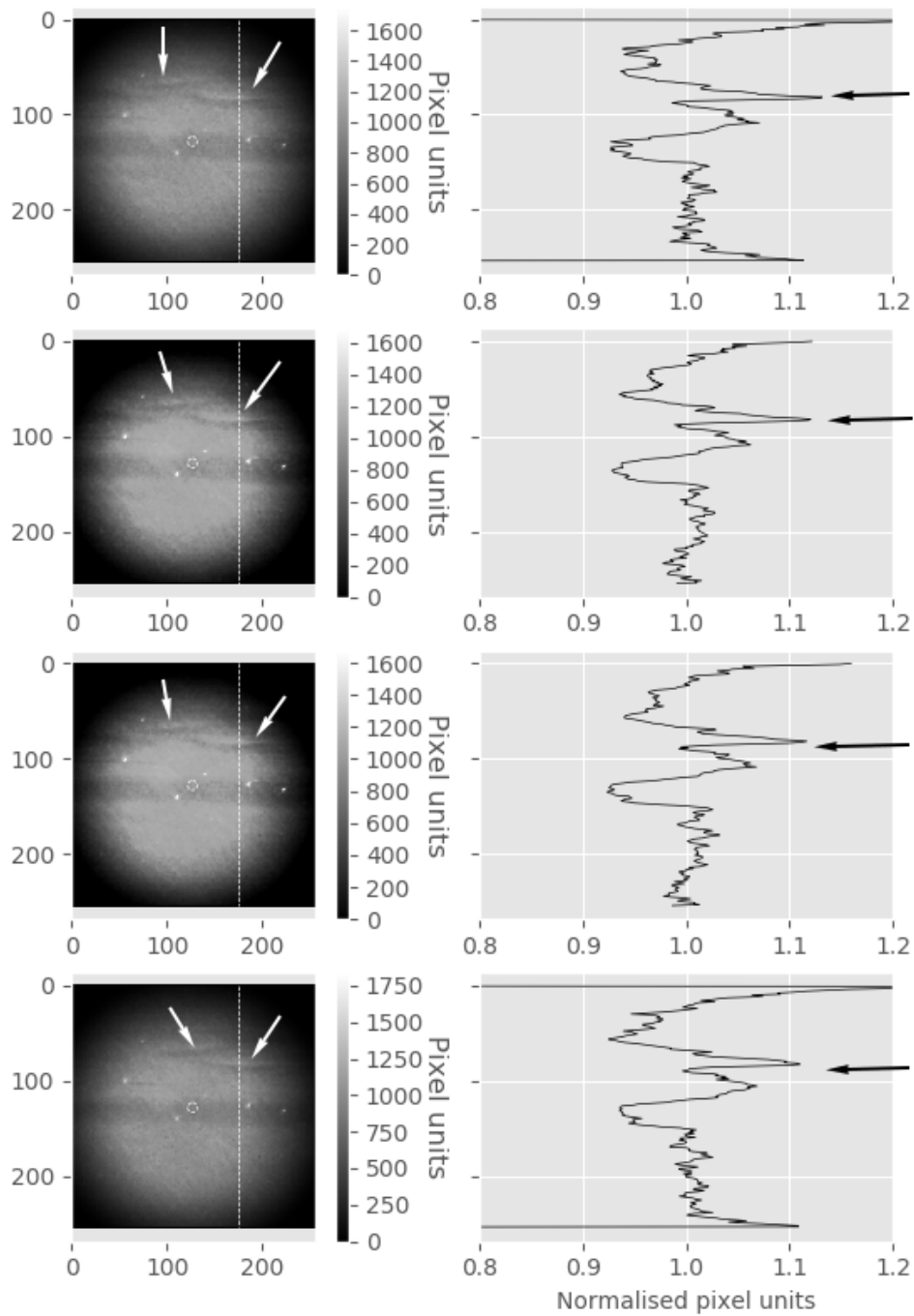


Figure 4.15: Select frames from 427.8 nm event 5J on 2016-03-12 in the same format as Figure 4.7. In the left panels the white arrows show the position of the anti-black aurora and black aurora. In the right panels the black arrows show the position of the black and anti-black aurora pairs on the brightness profile. Times were 23:24:58, 23:25:01, 23:25:04, and 23:25:07 UT from top to bottom panel.

This was followed by several faint patches and arc segments at 22:15:11 UT. Possible, large, anti-black aurora and black aurora pair were identified at 22:32:19 UT and the structure closest to the middle of the FOV classified as event 5D, drifting past in the northern section shown in Figure A.6. The brightness profile shows a lot of fluctuation, making it difficult to discern between the different structures. There is a sharp spike that is the normalised pixel count of the anti-black aurora at around 100 pixel coordinate on the y-axis. It varies between 1.09 and 1.15 normalised pixel unit counts. By panel 4 it seems to have disappeared, or is too faint to be picked up. The normalised pixel unit count can still be clearly seen in panel 1, and is 0.99. In panels 2-4 it is difficult to discern between the normalised pixel unit count of the black patch and the background.

After this event traces of faint, dark segments drifted past, embedded in a uniformly luminous aurora. Clusters of distinct black arc segments were observed at 22:52:29 UT, drifting close past the middle of the FOV at 22:52:34 UT. This is event 5E, shown in Figure A.7. In the brightness profiles there is a clear, sharp, dip where the dotted line crosses the third black arc segment. The normalised pixel unit count varies between 0.88 and 0.94. The diffuse aurora directly adjacent it has a normalised pixel unit count of around 1.1.

Anti-black aurora structures, along with dark segments, moved into the FOV at 22:56:14 UT, drifting close to the middle at 22:56:19 UT. These are classified as event 5F shown in Figure 4.13. Here several distinct black arc segments drift by in the top half section of the frame. Roughly six segments can be identified. The black arc segment that drifts by closest to the centre of the FOV is directly adjacent the radar pointing direction. Looking at the brightness profile, there is a clear sharp dip with a normalised pixel unit count of around 0.84. The surrounding diffuse aurora has a normalised pixel unit count of about 1.0. Above this black arc segment, there is what appears to be an anti-black aurora. This anti-black aurora and black aurora pair presents as a thin black patch paired with a dim white patch above it. From looking at the brightness profile, the black patch has the same pixel count than the surrounding diffuse aurora, so whether this can be classified as a black aurora is disputable.

Arc segments evolved to thin black arcs at 23:03:08 UT, drifting close to the centre of the FOV at 23:03:13 UT, shown in Figure A.8. The most distinct of this group was classified as event 5G. It is on the left-hand side of the FOV, with the dotted line crossing it. It has a normalised pixel unit count of between 0.88 and 0.9. The surrounding diffuse aurora is around 1.0, with a brighter section in the top section of the frames with a normalised pixel unit count of 1.15.

Anti-black aurora came into view again at 23:05:50 UT, drifting close to the middle of the FOV at 23:05:55 UT, see Figure 4.14 event 5H. Here the dotted line crosses the most distinct anti-black aurora and black aurora pair, indicated by a white arrow, close to the centre of the FOV. The dotted line was aligned to cut through the middle of the anti-black aurora and black aurora pair in the fourth frame. Looking at the brightness profile in the fourth panel, there is a sharp peak when crossing the anti-black aurora, with a normalised pixel unit count of around 1.13. Immediately afterwards there is a sharp dip as it crosses the black aurora, with a normalised

pixel unit count of around 0.93.

Thin, small (stretched out) arc segments appeared at 23:18:23 UT (Shown crossing close to the middle of the FOV at 23:18:28 UT in Figure A.9 and classified as event 5I). The most distinct of these thin arc segments have a normalised pixel unit count of around 0.96. The other relatively distinct black arc that is close to the edge of the FOV has a slightly lower normalised pixel unit count. The brightness profiles show that the intensity in the frames fluctuates significantly during this event. The average normalised pixel unit count seems to be around 1.0. There is a section where there is a significant dip at around 150 pixel coordinates on the y-axis. It has a normalised pixel unit count of around 0.94, and slightly lower than the black arc segments, in the first two panels, and then increases in intensity in the last two panels. In the first two panels there might be background airglow appearing between the diffuse aurora.

More anti-black aurora and black aurora pairs were observed at 23:24:53 UT before recording for the evening ended. The last event, seen clearly at 23:24:58 UT, is shown Figure 4.15. The most distinct anti-black aurora and black aurora pair, indicated with a white arrow on the right-hand side, is classified as event 5J. It has a normalised pixel unit count of around 1.13 for the white section, and around 0.98 for the dark section. A smaller anti-black aurora and black aurora pair, close to the edge of the FOV, is also indicated by a white arrow. The surrounding diffuse aurora has a normalised pixel count of around 1.0. There is a dark band that stretches through the middle of the FOV with a normalised pixel unit count of around 0.94, which is lower than the black aurora and could be background airglow. All clusters of patches, anti-black aurora, and arc segments held an approximately constant geometry and drift velocity.

The length, width, and drift speed for events 5D, 5E, 5F, 5H, 5I, and 5J-2 is indicated in Table 4.1. Events 5G and 5I was only partially visible, and tended to intermittently merge and split with other surrounding structures, thus the length and drift speed was not determined. The widths are shown in Table 4.1. Event 5J-1 is a black arc, and the width is indicated in Table 4.1.

4.5 Summary

Observations from three different campaigns in 2006, 2009, and 2016 were presented. The 2006 campaign took place at the EISCAT facility outside Trømsø, Norway. The ASK multi-spectral instruments ran in parallel with the EISCAT UHF radar. This raw data, recorded by the University of Southampton, was acquired, processed and analysed by the author. The 2009 campaign also took place at the EISCAT facility in Norway, and a pair of EMCCD detectors ran in parallel with the EISCAT UHF radar. Here too the raw data was acquired from the group running the campaign and processed and analysed by the author. The 2016 campaign took place at the same EISCAT facility in Norway, where EMCCD and DASI cameras ran in conjunction with the nearby EISCAT UHF radar. The author recorded these raw datasets and was also responsible for the processing and analysis of these sets.

Table 4.1 shows a summary of all events chosen for this study. For about half of the events the width and length could be measured. The assumed altitude for the events was taken as 105 km, as discussed in Section 4.1. The mean width and length for events identified as anti-black aurora are 2.1(1.6) km and 13.1(5.0) km respectively, and 1.8(0.9) km and 13.1(5.0) km for the black aurora travelling alongside it, where values in brackets refer to the standard deviation. The mean width and length for all events identified as either arc segments or patches are 3.9(3.2) km and 13.0(4.5) km. The mean width for events identified as black arcs is 1.7(0.7) km. The drift speed for some events during the early morning of 2016-03-11 and evening of 2016-03-12 was calculated, and for the events drifting in a mostly easterly direction, the mean drift speed was $1.1 \text{ km.s}^{-1}(0.7)$. These results will be discussed in more detail in the next chapter.

Chapter 5

Analysis and Results

5.1 Introduction

As discussed in Chapter 2, several theories about the origin of the underlying mechanism causing black aurora events have been put forward. The goal in this chapter is to use calibrated data to determine the host plasma sheet electron energies in the magnetosphere and make comparisons with the energies of the ionospheric precipitating particles inside the events. Using these results, a hypothesis as to the cause of the results will be proposed.

In this chapter, the preprocessing calibration methods used on the raw frames are shown, as well as the conversion from pixel intensity to photon flux (Section 5.2). The intensity measurements are discussed in Section 5.3.3, and then the ratio of these frames for different filters shown in Section 5.3. It is then used to determine the characteristic energy both inside and outside the chosen black aurora events by using the ion chemistry model. After this step, the methods in processing the radar data, that ran in parallel with the optical instruments, are shown. This is followed by the resulting differential energy flux spectra for the chosen events in Section 5.4. The optical and radar results are then compared in Section 5.5, to provide verification. The electron energy in the magnetosphere is then calculated in Section 5.6 and possible explanations for the results are discussed in Section 5.7. All results are shown and will be discussed in more detail in Chapter 6.

5.2 Calibration of ground-based optical imagers

Before meaningful data can be extracted from the images, several calibration steps need to be done on the raw output frames. These include dark subtraction, flat fielding, background subtraction, star mapping, and intensity calibration. These steps were done for the 2006 dataset by the University of Southampton Physics and Astronomy group, thus only the steps for the 2009 and 2016 datasets will be shown in the following sections.

5.2.1 Dark subtraction

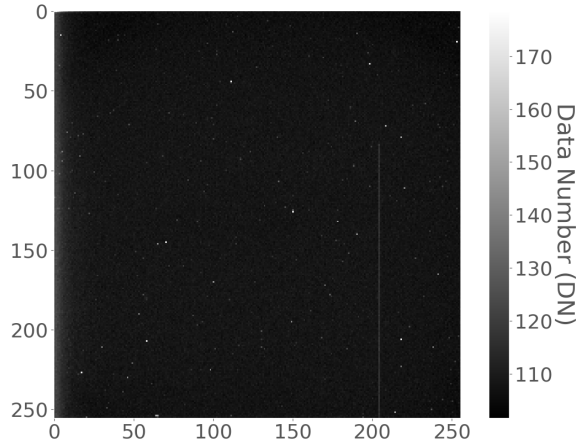


Figure 5.1: Dark frame for the iXon-888 back-illuminated EMCCD used for both the 2009 and 2016 campaign. Frame resolution is 256×256 , and the data number (DN) shown on the intensity bar. Several bad pixels (showing up as white pixels) are visible, as well as a column of bad pixels on the right-hand side.

Dark current refers to the unintentional leakage current due to thermal electrons in the detector pixels of CCD detectors. This effect is very temperature dependent and is common in all circuits containing reverse-biased diodes [Grubbs *et al.*, 2016]. To get rid of this unwanted signal, dark frames F_d can be subtracted from the raw frames F_r . Dark frames are created by closing the shutter of the camera at some point during measurements and taking the median of these dark frames. Two sets of dark frames were created. For the iXon-888 back-illuminated EMCCD, as mentioned in Section 3.3 the shutter was closed for a 100 frames (5 minutes) on 2017-02-28 at 20:54:43. The back-illuminated CCDs dark frame was created on 2016-03-07 by closing the shutter from 16:55:37 UT to 16:55:43 UT. Both are shown in Figure 5.1 and Figure 5.2, respectively. In Figure 5.1 the dark frame for the iXon-888 back-illuminated EMCCD has a frame resolution of 256×256 and several bad pixels (white pixels) are visible scattered across the frame, with a column of bad pixels on the right-hand side. Figure 5.2, the dark frame for the back-illuminated CCD, has the same resolution as the prior dark frame as well as bad pixels, albeit less than the EMCCD. What is apparent here though is the presence of vertical waves running across the frame. This might be due to electromagnetic interference, probably from the nearby radar, made more obvious by the baseline (counts are close to 0).

5.2.2 Flat fielding

Flat fielding is a method used to minimize the effect of the non-uniform lens transfer function on image frames. Some effects of lens imperfection include vignetting and optical etaloning [Grubbs *et al.*, 2016]. Vignetting is the reduction of brightness due to the effective aperture of

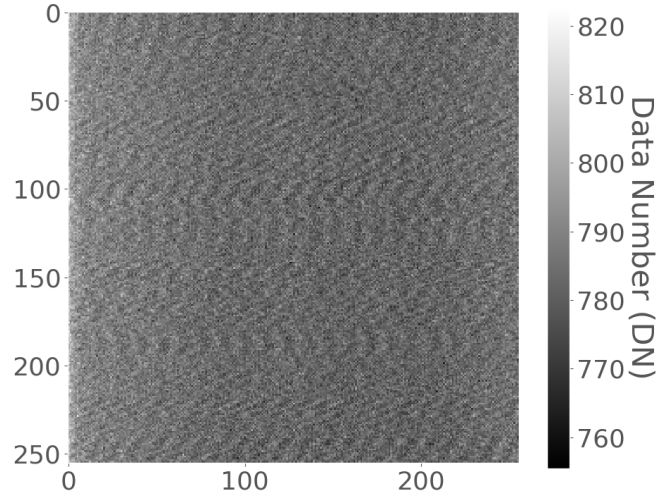


Figure 5.2: Dark frame for the back-illuminated CCD used in the 2016 campaign. The frame resolution is 256 x 256, and data number is shown on the intensity bar. Vertical waves running across the frame can be seen.

the lens reducing on moving away from the optical axis towards the image edges. Etaloning is interference fringes caused by light waves passing through the CCD, and usually seen in the near-infrared. Both these effects can clearly be seen in Figures 5.3 and 5.4. These are the flat field frames F_f for the iXon-888 back-illuminated EMCCD with the 427.8 nm filter, and the back-illuminated CCD with the 844.6 nm filter respectively. Flat fielding is dividing the raw frames by the normalised median of a set of flat field frames, which minimises the effects mentioned above.

The steps are summarised in the equation below,

$$F_{DN} = \frac{F_r - F_d}{F_f} \quad (5.1)$$

where F_{DN} is the corrected image with the intensity given in raw counts, also referred to as data number (DN).

No flat field frames were available for the 2009 sets, so artificial flat field frames were created by fitting each intensity profile with a third-order polynomial curve and then dividing with the resulting curve. An example of event 2A is shown in Figure 5.5.

5.2.3 Median filtering

Median filtering is applied to the corrected images to increase the signal to noise ratio while preserving the edges of any objects in the image. Median filtering is done by scanning from

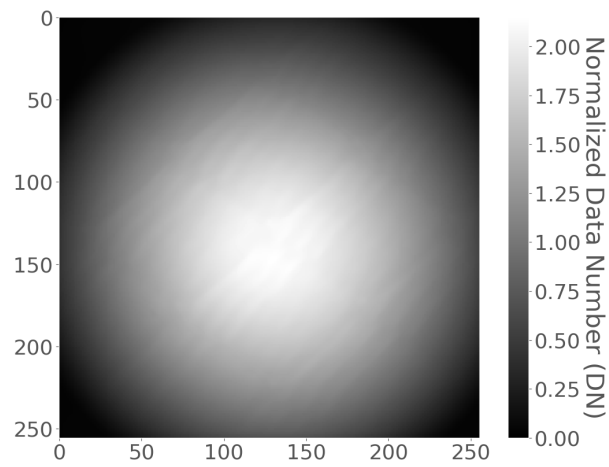


Figure 5.3: Flat field frame for the iXon-888 back-illuminated EMCCD equipped with the 427.8 nm spectral filter used for both the 2009 and 2016 campaign. Frame resolution is 256×256 , and pixel count shown on the intensity bar.

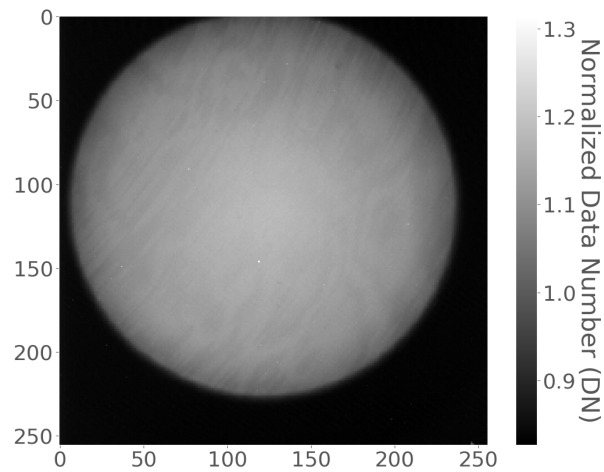


Figure 5.4: Flat field frame for the back-illuminated CCD equipped with the 844.6 nm spectral filter used in the 2016 campaign. The frame resolution is 256×256 , and pixel count is shown on the intensity bar.

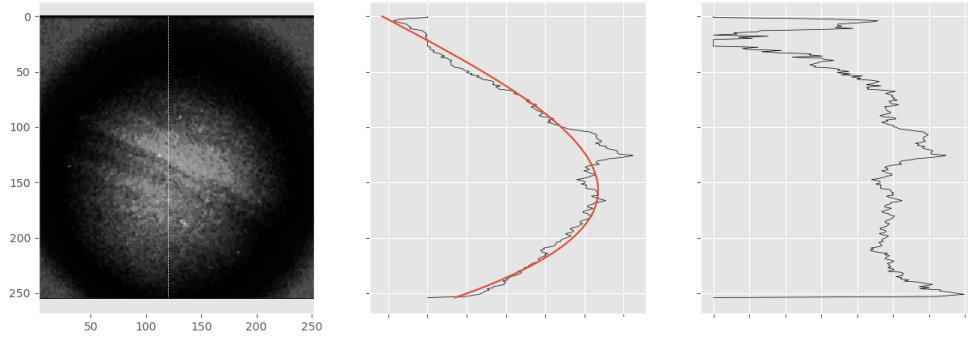


Figure 5.5: Each brightness profile for the 2009 set were fitted with a third-order polynomial function (red curve in second panel), and used as an artificial flat field frame. The image frame on the left-hand side is from event 2A, and is given in pixel coordinates. The dotted line shows the position of the intensity sample, which has been flat fielded (right panel). This frame is from event 2A.

pixel to pixel in the image frame and replacing that pixel with the median value of neighbouring pixels. The median is the value that is considered the middle value of the neighbouring pixels, i.e. it is a ranking filter. The amount of neighbouring pixels used can vary, and in this study, a 3×3 window is used.

5.2.4 Star Mapping

After flat fielding and dark subtraction, the camera pointing direction is verified by overlaying the images with star maps. This is also necessary to identify bright stars in the FOV, which will be used in the next section to measure star intensity for the respective filters. In Figures 5.6 and 5.7 examples of star map overlaying are shown for event 5B.

The star maps for each event and specific geographical location were created by using the Smithsonian Astrophysical Observatory Star (SAO) catalogue. Celestial coordinates of magnitude 6 and brighter, as well as the location (in geodetic coordinates) and time (in universal time), are needed as input to create a unique star map for each event.

Celestial coordinates are converted to decimal hours and degrees, as well as the universal time of events to their Julian day number. The Julian day number is then converted into Greenwich mean sidereal time (GST), and that in turn to local sidereal time [Duffett-Smith, 1990]. Local sidereal time is then converted using

$$H = LST - \alpha \quad (5.2)$$

where H is the hour angle, LST is local sidereal time, and α is right ascension in units of time [Duffett-Smith, 1990]. Next the newly converted hour angle and declination, are converted to azimuth and altitude

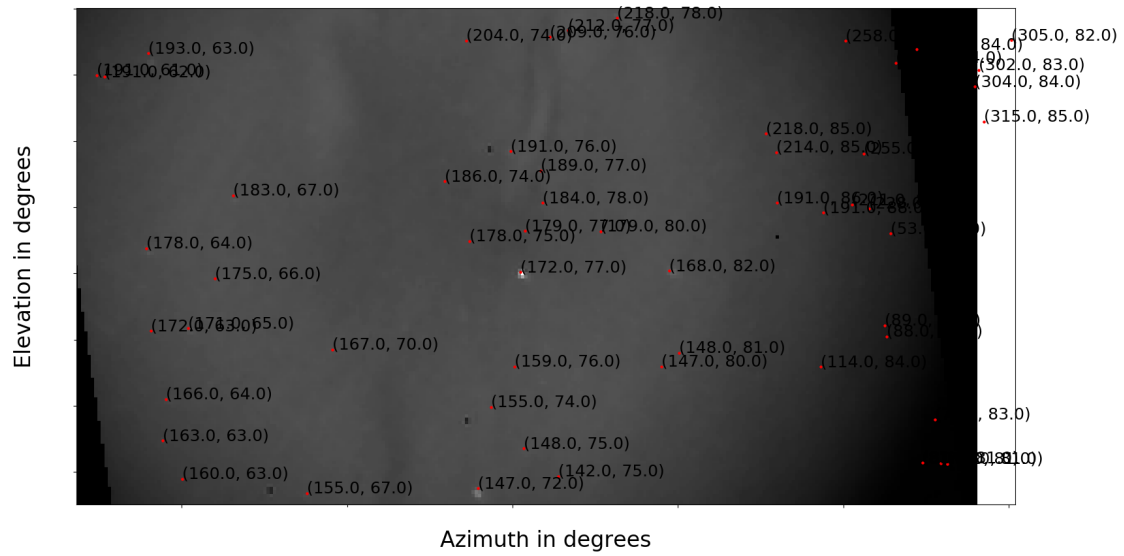


Figure 5.6: Star map overlay during event 5B taken by the iXon-888 back-illuminated EMCCD, and mounted with the 427.8 nm filter. Horizon coordinate system is used (azimuth and elevation) and units are in degrees.

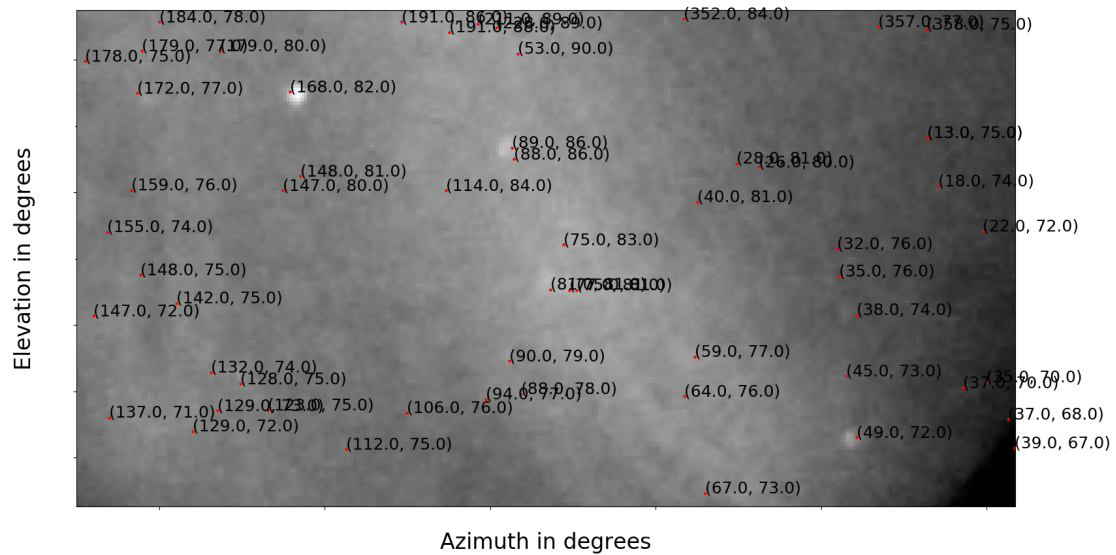


Figure 5.7: Star map overlay during event 5B taken by the back-illuminated CCD, and mounted with the 844.6 nm filter. Horizon coordinate system is used (azimuth and elevation) and units are in degrees.

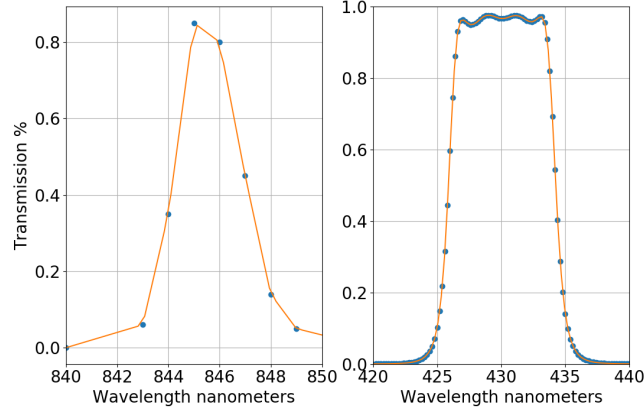


Figure 5.8: Filter response range for 845 nm on the left, and 430 nm on the right. Both have an approximate width of 10 nm.

$$a = \arcsin (\sin \delta \sin \phi + \cos \delta \cos \phi \cos H) \quad (5.3)$$

where a is altitude, δ is declination, and ϕ is the observer's geographical latitude. Azimuth A is calculated using

$$A = \arccos \left(\frac{\sin \delta - \sin \phi \sin a}{\cos \phi \cos a} \right). \quad (5.4)$$

Finally, stereographic projection needs to be applied to project the celestial map onto a plane,

$$x = \frac{\cos A \tan (90^\circ - a)}{2} \quad (5.5)$$

and

$$y = \frac{\sin A \tan (90^\circ - a)}{2} \quad (5.6)$$

where x and y are in Cartesian coordinates. The stars that have now been identified will be used in the next sections to convert each image from DN to photon flux in SI units.

5.2.5 Star Calibration

The apparent photon flux of an object that is measured is dependent on its spectral output, as well as the spectral band of the filter. The effect of the filter passbands, shown in Figure 5.8, on the eventually measured flux of the photons reaching the camera aperture, needs to be taken into account [Grubbs *et al.*, 2016]. This is done by convolving the passband, $T_{pass}(\lambda)$, of each filter with the incoming photon population,

$$f_s = \iint f(\lambda) I_{AE} T_{pass}(\lambda) d\theta d\lambda \quad (5.7)$$

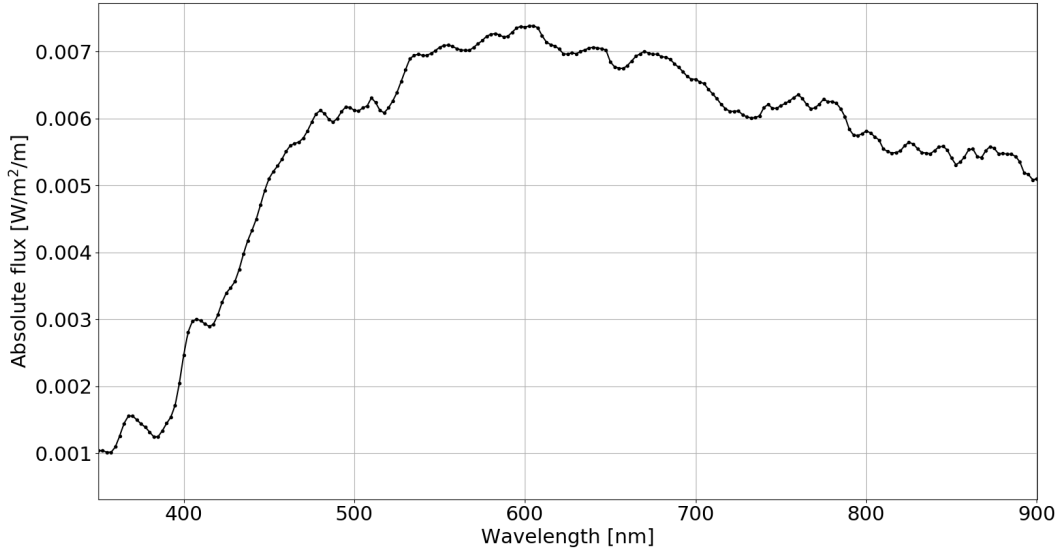


Figure 5.9: The spectral photon flux range in nanometers for UMa Alpha, taken from the Pulkovo spectrophotometric catalog [Alekseeva *et al.*, 1996]. The absolute flux of UMa Alpha appears lowest at wavelength 400 nm and below. At 400 nm, the absolute flux starts to increase with higher wavelengths. It reaches maximum absolute flux at the 550 nm to 650 nm range, approximately at $0.007 \text{ W/m}^2/\text{m}$

where f_s is the predicted photon flux, $f(\lambda)$ is the spectral photon flux, and I_{AE} is the intensity after atmospheric extinction correction. For the spectral photon flux the Pulkovo spectrophotometric catalogue is used, which consists of the spectral ranges of 320 - 1080 nm of bright stars in absolute energy units $\text{W/m}^2/\text{m}$. The atmospheric extinction correction can be omitted, seeing as all the stars, as well as auroral events, are viewed near vertical above the atmosphere and will suffer extinction equally. Figure 5.9 shows the spectral photon flux range of Ursa Major Alpha that was in the FOV for each camera setup. Three other stars also used for calibration are shown in the Appendix; Figures A.10, A.11, and A.12

5.2.6 DN to photon flux conversion

The conversion from pixel data number (DN) to photon flux (W/m^2) is determined by fitting the linear relationship between photon counts in the image and the predicted photon flux, referred to as the imager response (I_{response}). This relationship, and corresponding I_{response} value, is shown in Figures 5.10 and 5.11 for cameras used during the 2009 and 2016 campaigns, with their respective filters. All optical data used for star calibration are from images averaged over 10 frames to increase the signal to noise ratio. It is then corrected using Equation 5.1, as well as subtracting the background intensity by taking the average of a neighbouring 5×5 block of pixels.

All events are calibrated with methods shown in the previous sections: After 9 second temporal averaging and 3×3 median filter spatial averaging is applied, each event set is calibrated

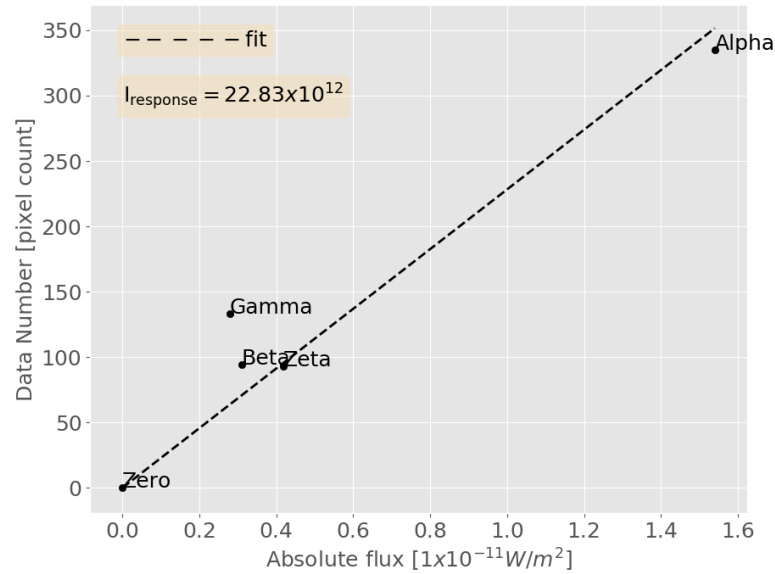


Figure 5.10: Photon count versus photon flux for the EMCCD camera mounted with the 844.6 nm filter. From a selected set of bright stars taken on the evening of 2009-01-25. UMa Gamma, UMa Beta, and UMa Zeta all fall in approximately in the same range between 90 and 140 counts. UMa Alpha has significantly more counts, approximately 340, and also measured higher absolute flux than the other three stars.

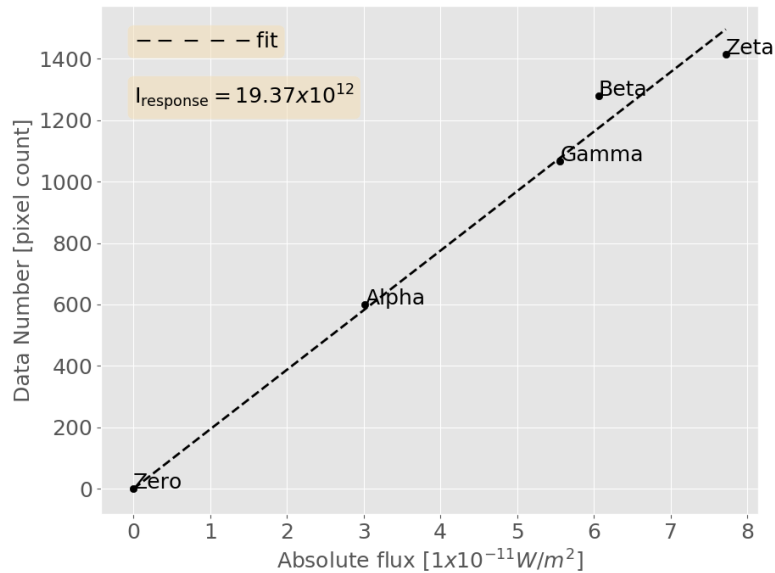


Figure 5.11: Photon count versus photon flux for the EMCCD camera mounted with the 427.8 nm filter. From a selected set of bright stars taken on the evening of 2016-03-05. UMa Gamma, UMa Beta, and UMa Zeta all fall in approximately in the same range between 1000 and 1400 counts. UMa Alpha has significantly less counts, approximately 600, and also measured lower absolute flux than the other three stars.

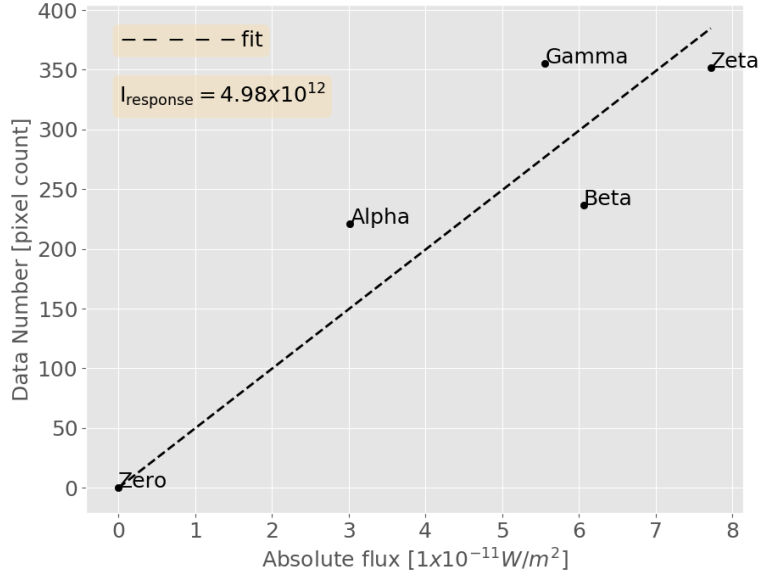


Figure 5.12: Photon count versus photon flux for the EMCCD camera mounted with the 427.8 nm filter. From a selected set of bright stars taken on the evening 2009-01-25. UMa Gamma and UMa Zeta have the highest pixel counts of approximately 350, but UMa Zeta has a higher absolute flux than UMa Gamma. UMa Alpha and UMa Beta also have approximately the same pixel count of about 340, but UMa Beta has a higher absolute flux than UMa Alpha.

using Equation 5.1, as well as background subtracted. Using the linear relationship shown in Figure 5.10 for the EMCCD camera mounted with the 844.6 nm filter during the 2009 campaign and Figure 5.11 for the EMCCD camera mounted with the 427.8 nm filter during the 2016 campaign, the DN is converted to photon flux in W/m^2 . The same was done for the EMCCD camera mounted with the 427.8 nm filter during the 2009 campaign, and for the DASI camera mounted with the 844.6 nm filter during the 2016 campaign, and is shown in Figures 5.12 and 5.13 respectively.

In Figures 5.10 and 5.13 a zero value was inserted and used during linear fitting. This is because of the assumption that when there is no absolute flux, the pixel count measured by the optical instrument should be zero. This was added to increase fitting accuracy. Note that UMa Alpha has a higher photon flux value in the infrared spectral range (844.6 nm filter, Figure 5.10) than in the blue spectral range (427.8 nm filter, Figure 5.11) by a factor of two. UMa Gamma, UMa Beta, and UMa zeta have all similar absolute flux values in the infrared, and is seen clustered together in Figure 5.10, and slightly more scattered in Figure 5.11. The three aforementioned stars have a lower flux value than UMa Alpha in the infrared line in Figure 5.10, and a higher flux value than UMa Alpha in the blue line.

The linear relationship for the EMCCD camera mounted with the 427.8 nm during the 2009 campaign filter and for the DASI camera mounted with the 844.6 nm filter during the 2016 campaign is shown in Figures 5.12 and 5.13. Note that data count numbers are dependent on

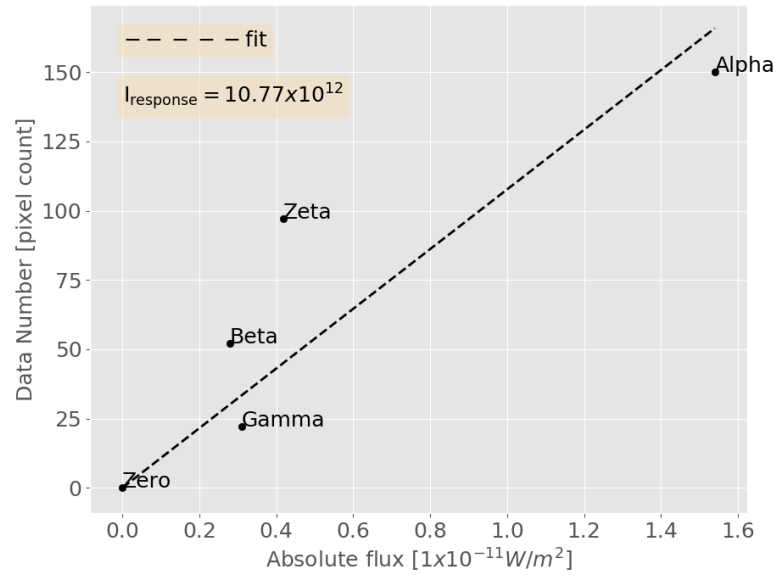


Figure 5.13: Photon count versus photon flux for the DASI camera mounted with the 844.6 nm filter. From a selected set of bright stars taken on the evening of 2016-03-05. UMa Alpha has a much higher pixel count and absolute flux than the other measured stars, a pixel count of approximately 150 and an absolute flux value of $1.55 \times 10^{-11} \text{ W.m}^{-2}$. UMa Zeta has the second-highest pixel count of 100, followed by UMa Beta with approximately 50 pixel counts, and UMa Gamma with the lowest pixel count of approximately 25 pixel counts. The three aforementioned stars have absolute flux values of between $0.3\text{-}0.4 \times 10^{-11} \text{ W.m}^{-2}$.

the type of optical instrument used for measurement, the setup of said optical instrument, as well as the type of filter used. For example, during the 2009 campaign UMa Alpha had around 340 counts with the EMCCD camera mounted with a 844.6 nm filter in Figure 5.10, but less than 230 counts when an identical EMCCD was mounted with a 427.8 nm filter (Figure 5.12). Both instruments had a one second exposure time set during recording. This means that UMa Alpha emits more towards the near-infrared part of the spectrum than the blue.

When comparing Figures 5.11 and 5.12 which was recorded with the same EMCCD camera, and mounted with the same 427.8 nm filter, showed different data numbers. The four stars for the 2009 case range from 200 to 400 counts, and the same four stars for the 2016 case range from 600 to 1400 counts. The reason is that the EMCCD used in both the 2009 and 2016 campaigns had different exposure times: one second during the 2009 campaign and three seconds during the 2016 campaign. Increased exposure time leads to an increase in pixel counts. The author was not in control of the optical instrument settings during the 2009 campaign. For the 2016 campaign it was decided that it was possible to increase the exposure time to three seconds without causing smearing or overexposed pixels, which would lead to a better Signal-to-Noise ratio during analysis. Note that when comparing these two figures the y-axis scales differ, and the stars in Figure 5.12 may appear more scattered than in Figure 5.11, but is in fact not. This is also true when comparing the cameras mounted with the 844.6 nm filter during the 2009 campaign (Figure 5.10) and 2016 campaign (Figure 5.13).

Lastly, for both the 2009 and 2016 cameras mounted with an 844.6 nm filter in Figures 5.10 and 5.13, the three stars UMa Beta, UMa Gamma en UMa Zeta has a lower pixel count and absolute flux than UMa Alpha, and for the 427.8 nm filter a higher pixel count and absolute flux than UMa Alpha. This means that UMa Alpha emits more towards the near-infrared spectrum compared to the three other stars.

5.3 Intensity ratio and characteristic energy

5.3.1 Ion chemistry model

Because of advances in optical detectors, high spatial and temporal resolution optical data have become available more recently. These have shown the existence of a variety of dynamic, small-scale auroral structures such as black auroras observed in this study. These small-scale structures can be observed in the distribution of emitted light [Lanchester *et al.*, 2009]. A range of emissions can be observed due to the collision of precipitating particles, in particular, electrons with atmospheric constituents.

It is possible to infer the energy of the precipitating electron flux from photon emission rate ratios and absolute emission rates by looking at the relationship between auroral electron fluxes and spectroscopic emission features in aurora [Rees and Luckey, 1974]. What needs to be taken into account however are various interactions within the neutral atmosphere, for example,

neutral heating and recombination rates. Ground-based optical techniques have been used extensively to study the effects of auroral energy deposition on the composition in the ionosphere [Hecht *et al.*, 2006]. Bright auroral emissions are measured that is dependent on, among other things, the number density of atomic oxygen [OI], and the number density of molecular nitrogen [N_2].

The Southampton ion chemistry model is a time-dependent, one-dimensional model that estimates the energy of precipitating electrons using the intensity ratios of auroral emissions. This includes the [OI]/[N_2] ratio [Lanchester *et al.*, 2001; Archer, 2009], and more recently a method to estimate the characteristic energy of precipitating electrons using the [O]/[N_2^+] ratio was added to the model (Dan Whiter *private communication*, 2018).

The precipitating electron energy estimation depends on the excitation threshold for producing different emissions. The permitted OI (777.4 nm) emission and the permitted OI (844.6 nm) atomic oxygen emission line correspond to lower energy particles because the density of atomic oxygen dominates over molecular nitrogen at higher altitudes where lower energy precipitating electrons are deposited. This energy dependence that the ionization rate of precipitating particles at various altitudes has was shown in Figure 2.11. The permitted N_2 (673.0 nm) emission and the permitted N_2^+ (427.8 nm) molecular band emission respond to higher energy particles because the density of molecular nitrogen dominates at lower altitudes where higher energy precipitating electrons are deposited.

The 777.4 nm and 844.6 nm emission lines are two of the strongest allowed oxygen emission lines in the aurora [Hecht *et al.*, 1985], and both the advantages and disadvantages of these two emission lines have been discussed extensively in the literature. The 777.4 nm emission line has a secondary excitation mechanism, a dissociative excitation due to O_2 molecules, but this only accounts for less than 5% of the emission line rate [Hecht *et al.*, 1985]. The 844.6 nm emission line also has an additional excitation mechanism, electron impact on molecular oxygen O_2 , but this secondary excitation mechanism is also small compared to the electron impact on atomic oxygen OI. Even so, it might still have the possibility to distort results under certain conditions [Hecht *et al.*, 2006], which has lead to some studies rather focusing on the narrow component of the atomic oxygen (777.4 nm) emission line. This does not mean that the other strong oxygen (844.6 nm) emission line is not usable in measurements, because in theory under normal conditions about 80% to 90% of the 844.6 nm emission line arises from the atomic oxygen excitation. It is only when there are very large storms and strong atomic oxygen depletion occurs, which can lead to underestimating the depletion of OI due to excess OI emission from dissociative excitation of molecular oxygen, that the use of this emission line could be problematic [Hecht *et al.*, 2006].

The optical emission ratio is indicative of the precipitating particle energies present. The impact excitation cross-section as a function of energy is known for each species, which allows the characteristic energy to be estimated. Several precipitating electron energy distributions (i.e., Particle flux vs. Energy) are available for the model, (eg. Gaussian and Maxwellian), but

for this study, the Maxwellian distribution was chosen, seeing as it best represents the energy spectrum of electrons incident on the atmosphere [Kosch *et al.*, 2001].

The author obtained the IDL scripts of the model, which included the more recent addition of the $[O]/[N_2^+]$ ratio as mentioned earlier, from the University of Southampton group to determine the characteristic energies of the 2006, 2009, and 2016 campaigns. This model is dependent on the atmospheric composition in regards to atomic oxygen and molecular nitrogen, which varies with time. Thus the density altitude profile had to be added as an input to the model for each set of events. For example Figure 2.10 shows the density altitude profile of atomic oxygen and nitrogen obtained from the NRLMSISE-00 atmosphere model for 2016-03-12 at 22:00:00 UT, which was used for events 5A-5J. The script first reads the relevant emission rates that have been added to the model (eg., for OI and N_2^+ for the optical emissions mentioned earlier). Other inputs are the F10.7 index for each event. F10.7 is a measure of the output flux generated by the Sun, and is used as an input parameter of the ionospheric and thermospheric models [Chen *et al.*, 2011].

5.3.2 Model limitations

The model is limited by the fact that it cannot process very small or very large $I[777.4\text{ nm}]/I[673.0]$ and $I[844.6]/I[427.8]$ ratio values. Higher energies, above 30-40 keV, can in principle be added to the model, but as the energy increases there appears a spike for the emission brightnesses around 35 keV, depending on factors like the F10.7 index. After this sharp spike in the emission ratio, a linear decrease on a log plot is observed. In regards to the model limitation in the lower range, it is probably due to its inability to deal with high energy precipitation. It is also possible that there aren't enough mesopause/mesospheric neutral and negative ion species included to properly model high energy precipitation.

The brightness in ASK has been estimated to have deviations of up to 50% [Dahlgren *et al.*, 2011]. The main uncertainties identified are background reduction and atmospheric conditions, and the systematic uncertainty of the modelled emission brightness was determined to be 35%. This could lead to an overestimation of electron energies. In previous studies there was however good agreement found between ASK emissions and the modelled brightness from EISCAT radar data, which leads to the conclusion that the uncertainty due to the offset in the calibration of the data is smaller than this estimate [Dahlgren *et al.*, 2011].

Another limitation of the model is that the energy spectrum distribution is unknown and is inferred. As mentioned earlier the Maxwellian distribution assumed here is a good estimation [Kosch *et al.*, 2001].

It has been mentioned in previous studies that the modelled $I[OI]$ has been different from what was observed, and is possibly due to an overestimate of the OI density in the MSIS atmosphere at auroral latitudes [Dahlgren *et al.*, 2011]

It is also important to note that this model calculates the mean energy of the distribution and not the peak energy. The mean energy of an energy distribution is the average energy taken over all the particle energies. The peak energy, as the name suggests, is the most prevalent energy, and the most probable energy in the distribution. The relation between the mean energy $\bar{E}$ and the characteristic energy E_p is given by $\bar{E} = 2 \sqrt{\frac{2}{\pi}} E_p$ [Weisstein]. The reason the mean energy and peak energy is not the same for the Maxwellian distribution is because of its long tail on the high energy side of the peak. With a Gaussian distribution, this would have been irrelevant seeing as the mean energy is also the peak energy. When working with the Maxwellian distribution however it needs to be kept in mind when comparing with radar data results. The relationship between the mean and peak energy for an assumed spectrum is fixed, and whether it is the mean energy or peak energy that is determined is irrelevant because the relationship between these two energy measurements is constant for a given distribution. The peak energy is also referred to as the characteristic energy in the literature and will be referred to as the characteristic energy below.

5.3.3 Intensity measurements

Only events at or near the radar pointing direction from 2009 and 2016 that presents discernible boundaries between black aurora and the neighbouring diffuse aurora have been analysed. A sample of each of the 2009 and 2016 events, with their corresponding brightness profiles, are shown in Figures 5.14a - 5.15b, and the rest of the events are in the Appendix: Figures A.13a - A.17b. These are pre-processed frames (i.e. flat-fielding, dark frame subtraction etc. has been applied) where the event in question is clearly discernible from the surrounding diffuse aurora and as close as possible to the middle of the FOV. In each frame, for both the 427.8 nm and 844.6 nm sets, a vertical column in the image frame is chosen where the boundary between the chosen event and the background is as clear as possible. For example in Figure 5.14a - 5.14b the column was chosen to go through the anti-black aurora and black aurora pairs where they are discernible from the surrounding background diffuse aurora, and the boundary lines distinguishable. Next the two adjacent columns on each side is added, and the average of these five columns is taken as the absolute flux value, shown in the right panel for figures discussed here.

The emission reductions for the different filters between the black aurora and the brighter diffuse aurora next to the structure are shown in Tables 5.1 and 5.2. Emission intensity comparisons between the anti-black aurora with the diffuse aurora are shown in Table 5.3. Because different emission line filters were used in the 2006 campaign than in the 2009 and 2016 campaign the black aurora and diffuse aurora comparisons were split up in Tables 5.1 and 5.2. The brightness reductions from the brighter diffuse aurora to the black aurora event adjacent to it was determined by taking the average flux of a block of pixels inside the black aurora events, and calculating its flux reduction percentage by comparing it with the average flux of a block of pixels of the same size in the diffuse aurora adjacent it. The size of the block of pixels inside

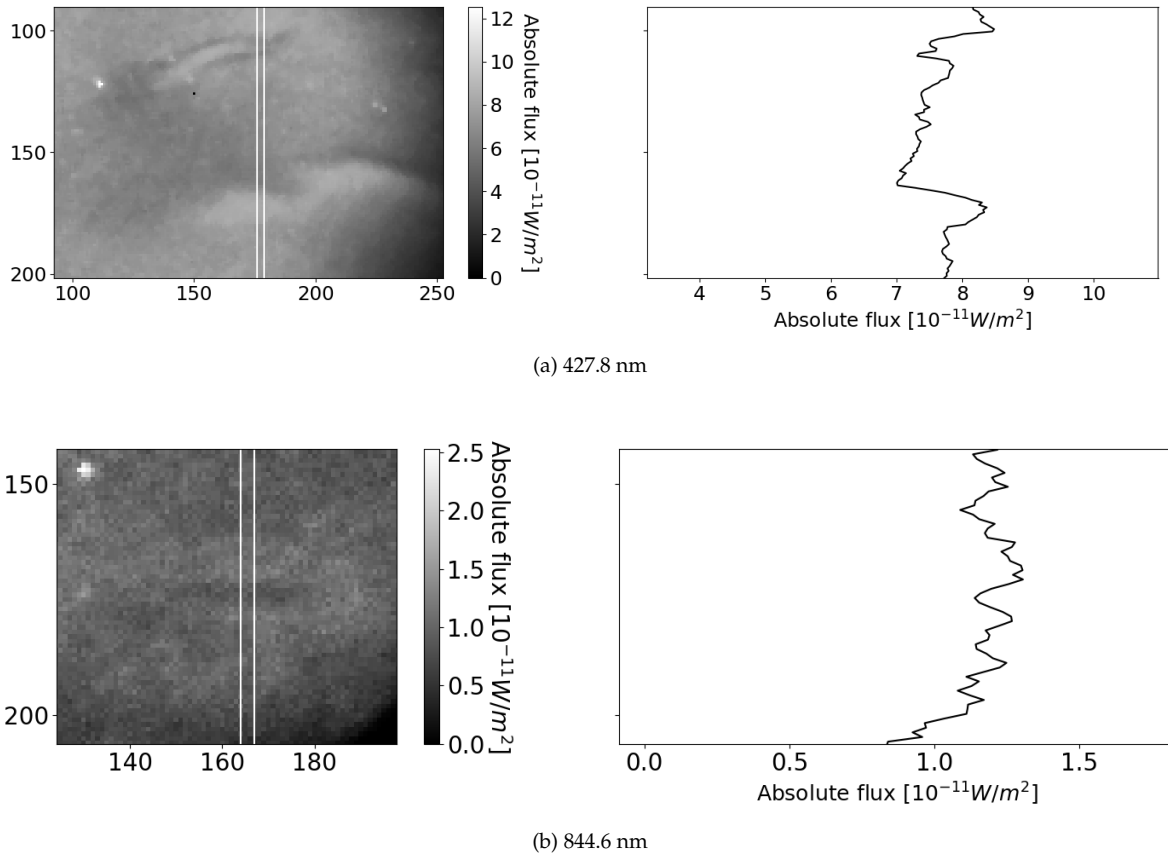


Figure 5.14: Event 5B intensities for both 427.8 nm and 844.6 nm with their respective brightness profiles averaged between the solid white lines shown in the right-hand column. There are three anti-black aurora and black aurora pairs visible here, and the most prominent object was classified as event 5B. This is the object seen in the bottom half of the image on the left-hand side, between 150 and 200 pixel coordinates on the y-axis, and 150 and 200 pixel coordinates on the x-axis for the 427.8 nm filter. It is not as clear in the image with the 844.6 nm filter, and is located roughly in the middle of the image. The solid white lines cross it through their centres, and the corresponding dip and peak in the brightness profile can be seen when it crosses the black aurora and anti-black aurora respectively for the 427.8 nm filter. This dip and peak is not as clear for the 844.6 nm filter image.

the black aurora that was used to determine the average differs from event to event, because the size of black auroras differ. The primary objective for this step was to choose an area inside events that do not cross the black aurora patch, arc segment, or arc boundaries (i.e., not 'contaminated' by the surrounding diffuse aurora). The block of pixels for the diffuse auroras was not directly adjacent to the black aurora events, but usually 5 pixels away, to avoid including a section of the black aurora. The same method was applied for the diffuse aurora and anti-black aurora comparisons shown in Table 5.3.

Events 1A, 1B, and 1C in Table 5.1 from the 2006 campaign in Figures 4.3 - 4.5 showed a 29%, 36% and 63% reduction for the *OI* emission line intensity (777.4 nm) and a 61%, 56%, and 88% reduction for the *N₂* emission line intensity (673.0 nm) from the diffuse aurora to within the black aurora respectively. Event 1C showed a higher reduction for both emission lines than Events 1A and 1B, by almost a factor of two. Although these reductions were determined by

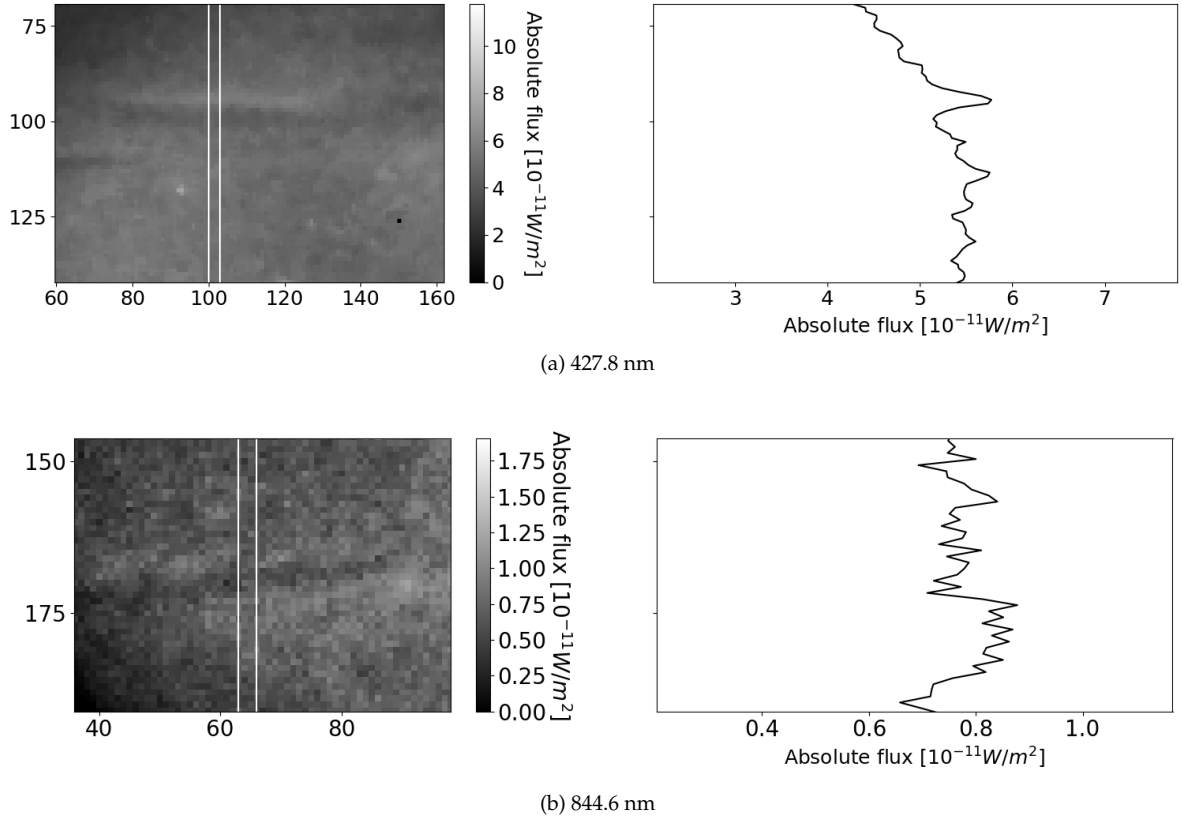


Figure 5.15: Event 5H intensities for both 427.8 nm and 844.6 nm with their respective brightness profiles averaged between the solid white lines. The anti-black aurora and black aurora pair classified as event 5H is very prominent here, especially in the image taken with the 427.8 nm filter. It is roughly at 100 pixel coordinates on the y-axis, and stretches from 70 to 130 pixel coordinates on the x-axis. The solid white line crosses it at 100 pixel coordinates and the peak and dip pair can be seen on the brightness profile on the right-hand side as it crosses the anti-black aurora and black aurora respectively. In the image taken with the 844.6 nm filter the anti-black aurora and black aurora pair is located at about 170 pixel coordinates on the y-axis, and stretches from about 35 to 90 pixel coordinates on the x-axis. The solid white line cuts it through its centre, and here the dip in the brightness profile as it crosses the black aurora is visible, but the peak as it crosses the anti-black aurora is less prominent than for the 427.8 nm image.

Event	Date	Time UT	Percentage reduction for 777.4 nm	Percentage reduction for 673.0 nm
1A	20061022	20:50:22 - 20:51:47	29	61
1B	20061022	20:51:57 - 20:53:07	36	56
1C	20061022	20:54:03 - 20:54:13	63	88

Table 5.1: Emission intensity comparisons between the black aurora and the brighter diffuse aurora for the selected events are shown. The first column indicates the event, the second column the date of the event, and the third column the time of the event in UT. The last two columns show how much each emission reduces when moving from the brighter diffuse aurora to the black aurora.

Event	Date	Time UT	Percentage reduction for 844.6 nm	Percentage reduction for 427.8 nm
2A	20090125	22:58:12 - 23:01:28	48	27
2B	20090125	23:42:59 - 23:43:38	11	14
5B	20160312	21:54:22 - 22:11:13	12	15
5F	20160312	22:55:46 - 23:00:22	21	23
5H	20160312	23:05:43 - 23:06:19	19	22
5J	20160312	23:15:53 - 23:26:01	12	35

Table 5.2: Emission intensity comparisons between the black aurora and the brighter diffuse aurora for the selected events are shown. The first column indicates the name of the event, the second and third column shows the date and time range in UT respectively. The last two columns show how much each emission reduces when moving from the diffuse aurora to the black aurora. For events that are an anti-black aurora and black aurora pair, only the black aurora intensity is taken into consideration.

using mean intensities, the difference in reduction range could be explained by the fact that the black aurora intensities varied greatly over time and space, and is also surrounded by bright and rapidly changing bright aurora that could affect the measurements.

The reduction for the OI emission line intensity was between 29% - 63%, i.e. a range of 34%. For N_2 it is between 56% - 88%, i.e. a range of 32%. That is an average of 43% reduction for the OI emission intensity, and 68% reduction for the N_2 emission intensity, which means that there is a higher reduction in high-energy electron precipitation within the black aurora than the neighbouring diffuse aurora for all three instances. This indicates a softening of the precipitating electron energy spectrum in the black aurora.

Events 2A and 2B in Table 5.2 from the 2009 campaign shown in Figures A.13a - A.14b show a 48% and 11% reduction for the $O(3p^3P)$ (844.6) emission, and a 27% and 14% reduction for the N_2 (427.8 nm) emission. There is a 30% average reduction for the 844.6 nm emission line and a 20% average reduction for the 427.8 nm emission line. For event 2A there is a higher reduction

Events	Date	Time UT	Percentage increase for 844.6 nm	Percentage increase for 427.8 nm
5B	20160312	21:54:22 - 22:11:13	3	7
5H	20160312	23:05:43 - 23:06:19	5	10
5J	20160312	23:15:53 - 23:26:01	6	16

Table 5.3: Emission intensity comparisons between the anti-black aurora with the diffuse aurora. The first three columns show the name of the event, the date, and the time range in UT respectively. The last two columns show the intensity shift from the diffuse aurora to the anti-black aurora.

in the low-energy electron precipitation, which does not agree with the conclusions of previous studies of black aurora [Gustavsson *et al.*, 2008]. Both events are quiet arcs with little or no drift motion. This leads to the question whether these events are in fact black aurora structures, and its classification remains inconclusive.

Event 5F from the 2016 campaign in Figure A.16a, A.16b show a 21 % reduction for the 844.6 nm emission, and 23% reduction for the N_2^+ (427.8 nm) emission. For event 5C the black band seen in Figures A.15a and A.15b however, show a shift more towards the 427.8 nm emission, and it's classification remains inconclusive.

Events 5B, 5H, and 5J show anti-black aurora and black aurora pairs. These events are shown in Figures 5.14a, 5.14b, 5.15a, 5.15b, A.17a and A.17b. For the 427.8 nm emission there is a sharp increase in intensity seen in the brightness profile over the anti-black aurora compared to the surrounding diffuse aurora. This is seen to a lesser degree for the 844.6 nm emission. The black auroras adjacent the anti-black auroras are clearly at lower intensities than the surrounding diffuse auroras. When comparing the black aurora intensity (those that are paired with anti-black aurora) with the surrounding brighter diffuse aurora, there is a 12%, 19%, and 12% reduction seen for the 844.6 nm emission, and 15%, 22%, and 35% reduction for the N_2 emission. That is an average of 16% reduction for the 844.6 nm emission, and 24% reduction for the 427.8 nm emission. This corresponds with the slightly larger reduction for the 427.8 nm emission in the black aurora shown in Gustavsson *et al.* [2008]. This also indicates a higher reduction in high-energy electron precipitation within the black aurora than the neighbouring diffuse aurora. These are all shown in Table 5.2

For events 5B, 5H, and 5J in Table 5.3 that shows anti-black aurora and black aurora pairs, but now comparing the intensity shift of the anti-black aurora with the surrounding diffuse aurora. The 844.6 nm emission intensity shift from the diffuse aurora of the anti-black aurora shows an average of 5% increase and a similar shift for the 427.8 nm emission intensity shows an 11% increase. This indicates higher-energy electron precipitation within the anti-black aurora when comparing with the surrounding diffuse aurora.

5.3.4 Intensity ratio results

Figures 5.16a to 5.19c show cropped frames of certain events at two wavelengths along with their ratios. The rest of the events are shown in the Appendix, Figures A.18a - A.22c. All the ratios with the corresponding energies are shown in Tables 5.4 and 5.5, and the energies were determined with the ion chemistry model as discussed in Section 5.3.1. The ratios were determined using the same method determining the average flux of black auroras, anti-black auroras and diffuse auroras described in Section 5.3.3, i.e., the average of the area inside the object is taken as the ratio of said object.

Figures 5.16a, 5.16b, 5.17a, and 5.17b are from frames where the 777.4 nm and 673.0 nm filters were mounted on the ASK instruments during the 2006 campaign. These emission lines were

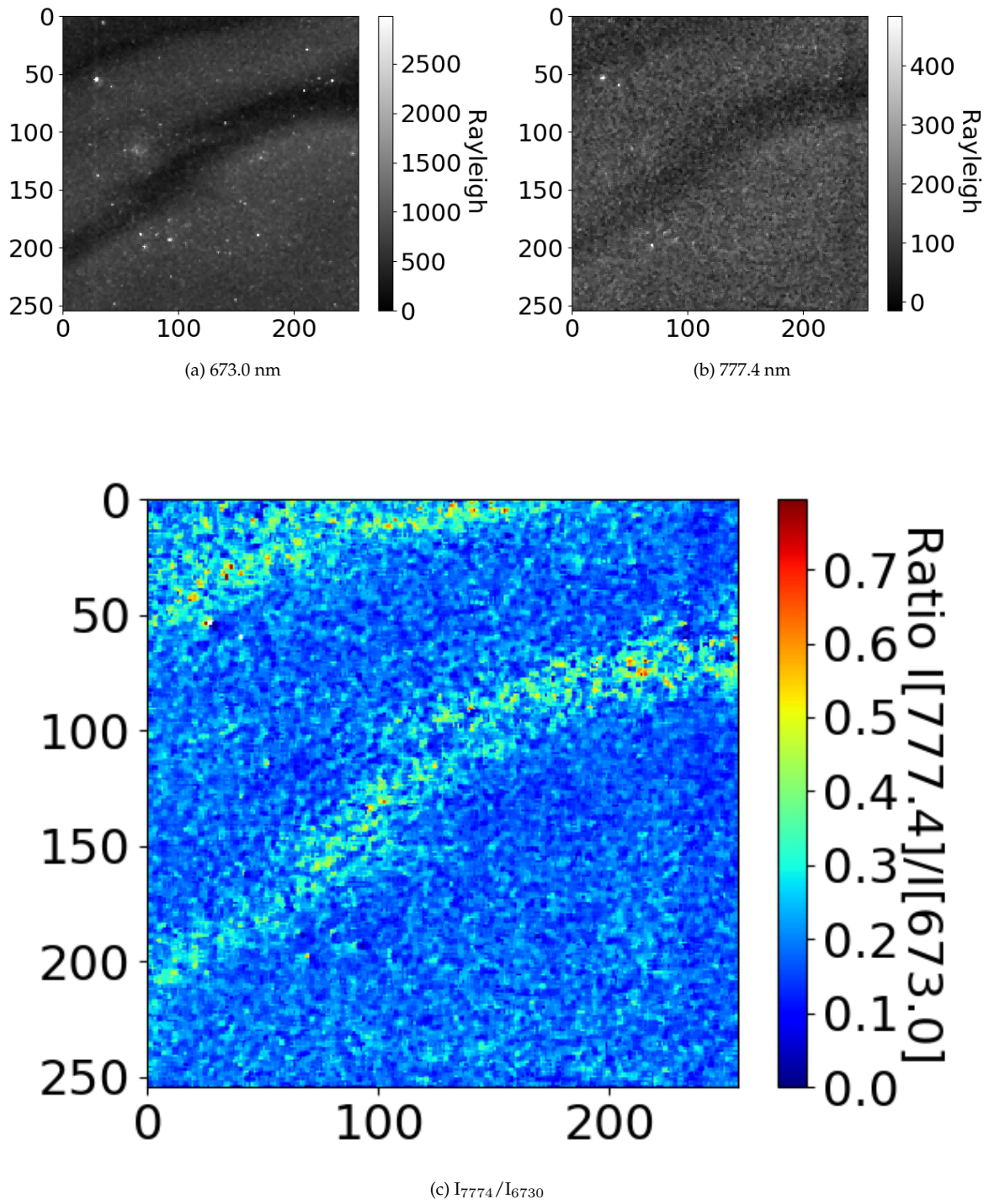


Figure 5.16: Images from event 1A given in Rayleighs with filters 673.0 nm, 777.4 nm, and their ratio. All are shown in pixel coordinates.

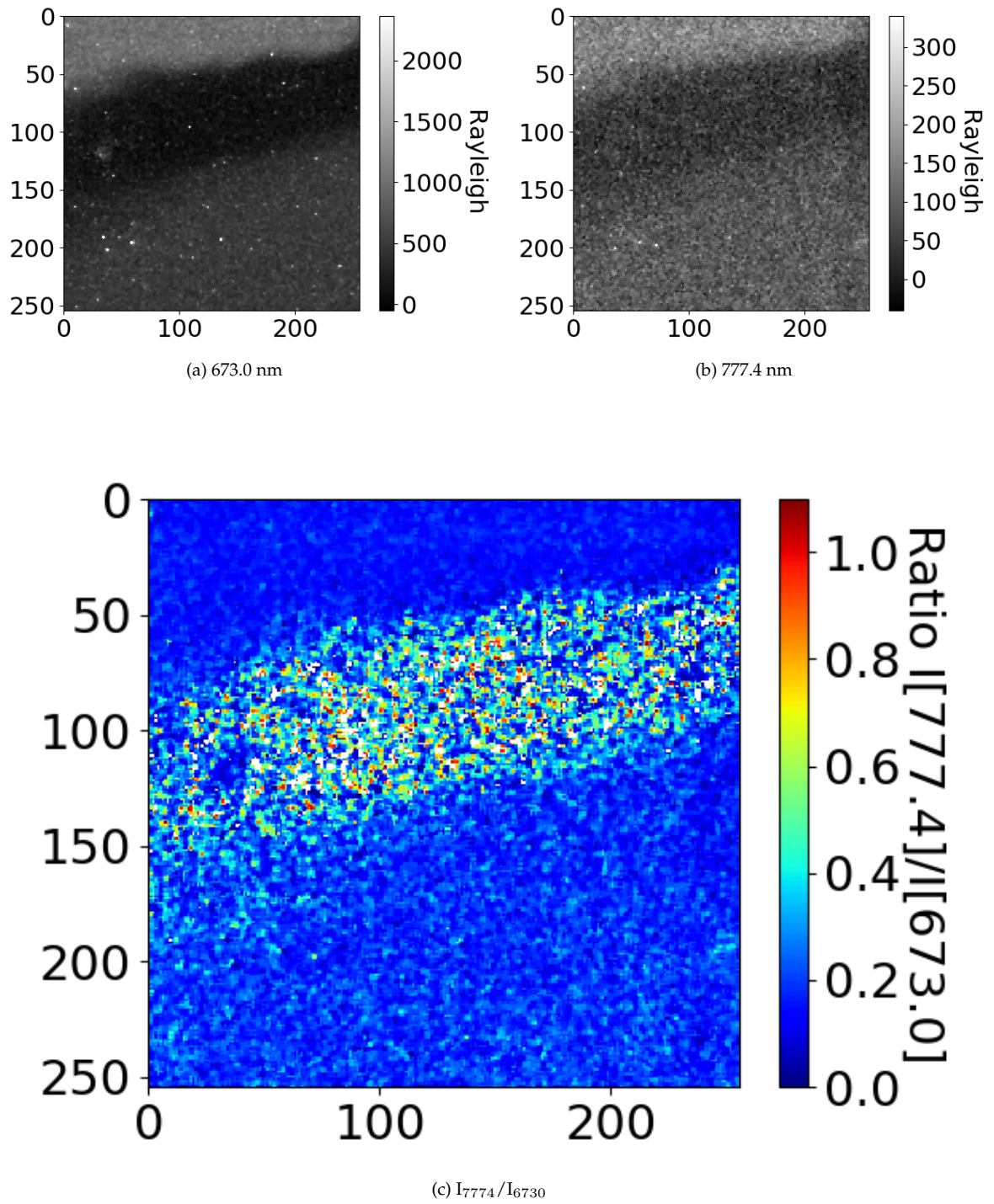


Figure 5.17: Images from event 1C given in Rayleighs with filters 673.0 nm, 777.4 nm, and their ratio. All are shown in pixel coordinates.

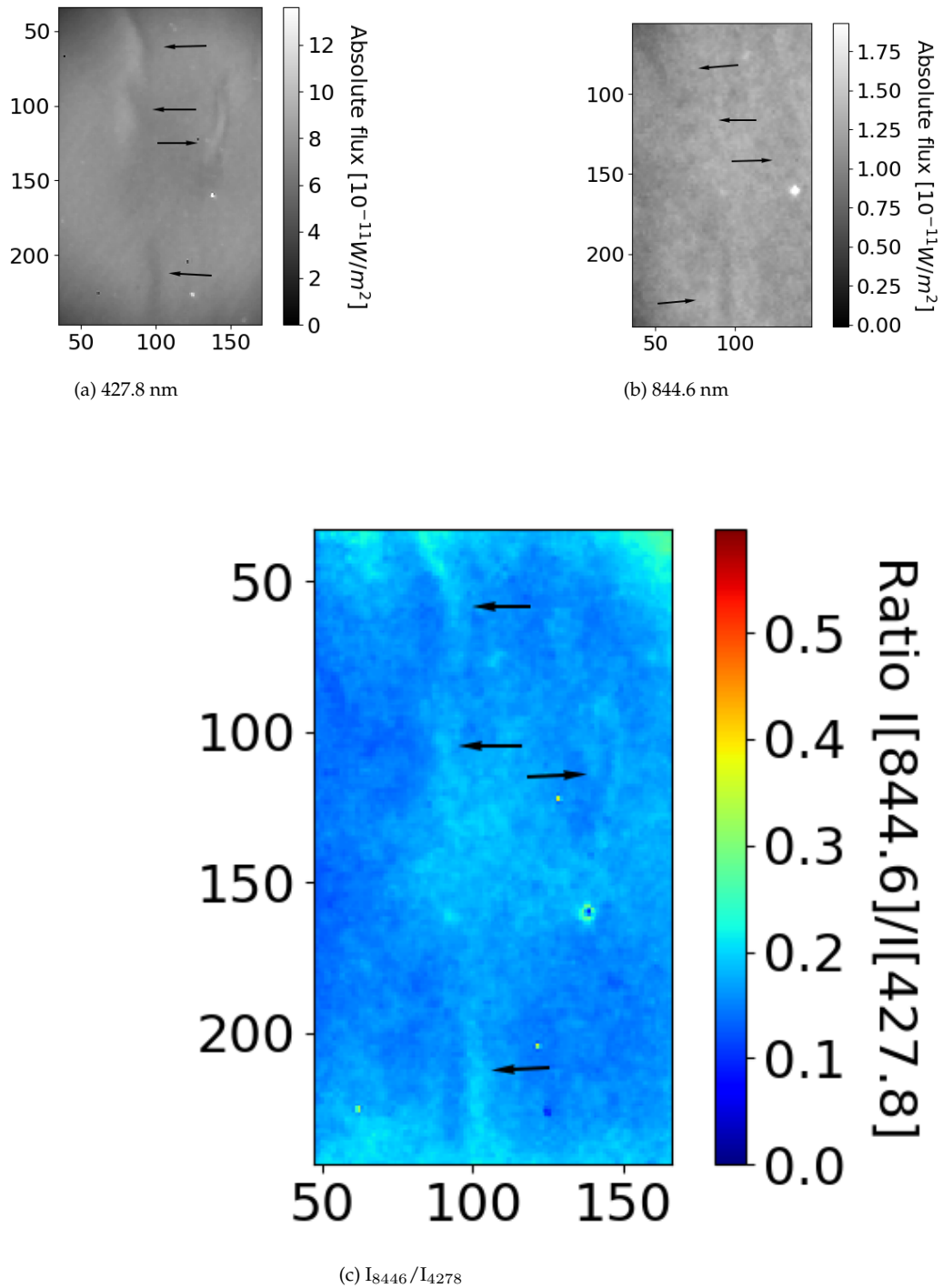


Figure 5.18: Images from event 5B given in W/m^2 with filters 427.8 nm, 844.6 nm, and their ratio. All are shown in pixel coordinates. Four anti-black aurora and black aurora pairs are visible, three at the top of the image, and the other close to the bottom indicated by arrows. See printable version in Appendix, Figure A.19c.

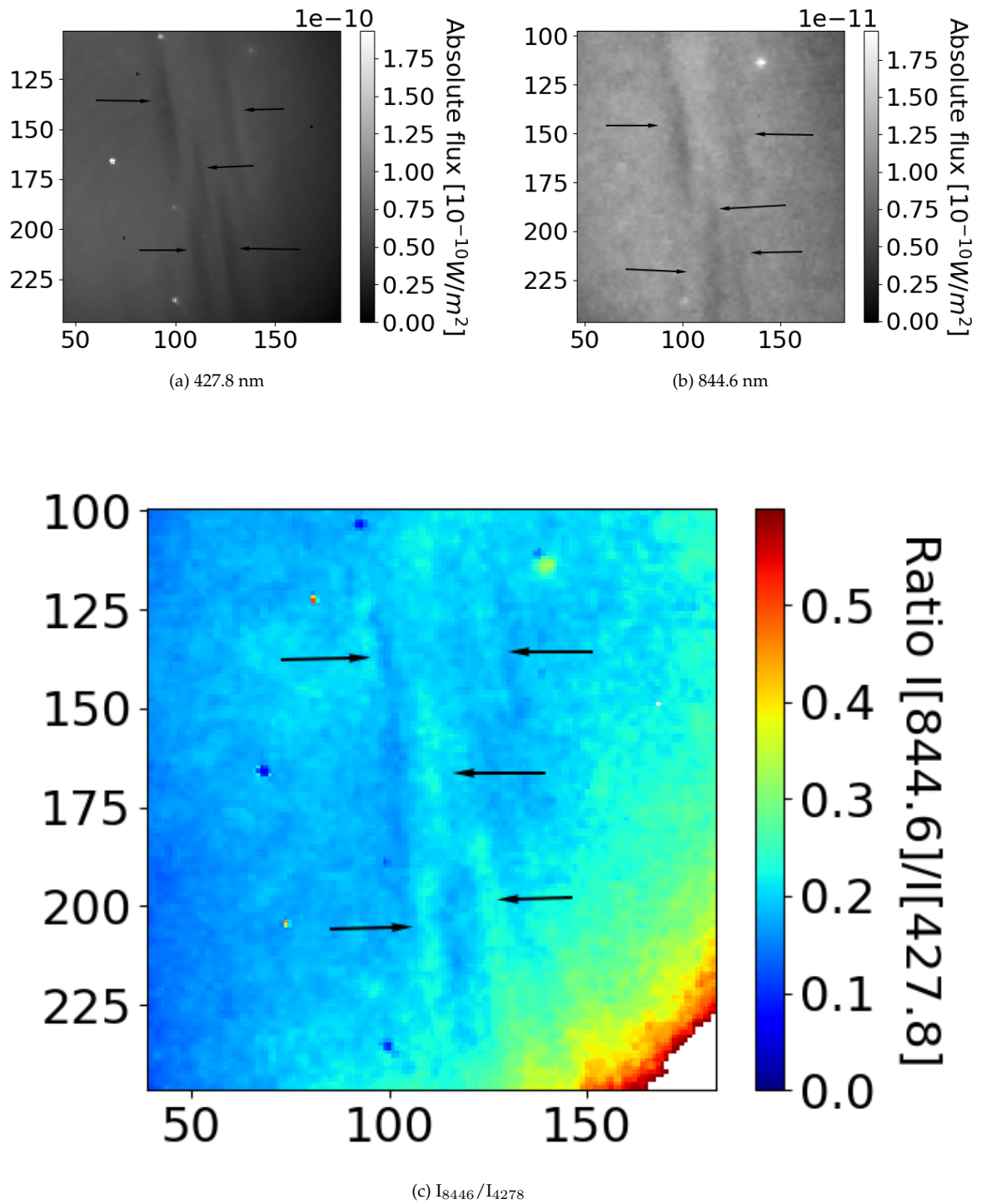


Figure 5.19: Images from event 5F given in W/m^2 with filters 427.8 nm, 844.6 nm, and their ratio. All are shown in pixel coordinates. A cluster of four arc segments are seen here indicated by arrows. See printable version in Appendix, Figure A.20c.

Event	Drift velocity	Optical ratio inside black aurora (BA)	Optical ratio inside diffuse aurora	Mean E inside BA (keV)	Mean E next to BA (keV)
1A	–	0.268	0.180	2.81	7.64
1B	–	0.274	0.174	2.67	8.79
1C	–	0.210	0.162	2.90	16.22
5C	–	0.123	0.106	–	–
5F	0.95 km.s ⁻¹ E	0.239	0.187	3.29	6.21

Table 5.4: Table showing drift velocities of selected black aurora events that was measured in Section 4.1 in column 2. Only event 5F had a measurable drift speed. Ratio's inside and next to events measured using optical data are shown in columns 3 and 4 respectively. Mean energies inside events, as well as the mean energies outside events estimated using photon emission rate modeling discussed in Section 5.3.1 are shown in columns 5 and 6 respectively. Note that the ratio of $[OI]/[N_2^+]$ is shown for events 1A-C, and the ratio of $[O]/[N_2^+]$ for events 5C and 5F.

Event	Drift velocity	Ratio inside black aurora (b) and anti-black aurora (w))	Ratio next to BA and ABA	Mean E inside BA and ABA (keV)	Mean E outside BA and ABA (keV)
5B	0.87 km.s ⁻¹ E	0.204 (b), 0.175 (w)	0.177	4.82 (b), 7.9 (w)	7.58
5H	2.26 km.s ⁻¹ E	0.208 (b), 0.165 (w)	0.173	4.57 (b), 11.3 (w)	8.37
5J-1	–	0.189 (b), 0.162 (w)	0.178	5.99 (b), 14.2 (w)	7.40

Table 5.5: Table showing drift velocities of selected anti-black aurora/black aurora events that was measured in Section 4.1 in column 2. Only events 5B and 5H had measurable drift speeds. Optical ratio's inside and next to black aurora (b) and anti-black aurora (w) events and optical ratio of diffuse background measured using optical data are shown in columns 3 and 4 respectively. Mean energies inside anti-black aurora (w) and black aurora (b), as well as the mean energies outside events estimated using photon emission rate modeling discussed in Section 5.3.1 are shown in columns 5 and 6 respectively. These all show the ratio of $[O]/[N_2^+]$.

discussed in detail in Section 5.3.1, and will only be briefly touched on again. Analysis using the ratio of this pair is possible because both emissions are present along the magnetic field line where black aurora observations and measurements are made [Archer *et al.*, 2011]. Seeing as it is mainly low energy electron precipitation of interest when investigating black aurora structures, the atomic oxygen emission of ASK3 (777.4 nm) was best-suited [Lanchester *et al.*, 2009]. It is also one of the strongest allowed oxygen emissions in the aurora [Hecht *et al.*, 1985]. The downside of this emission line is that it has a secondary excitation mechanism, most probably dissociative excitation of O_2 molecules, but studies have shown that this might only account for 5% or less of the 777.4 nm line emission rate [Hecht *et al.*, 1985]. This 673.0 nm and 777.4 nm emission lines pair have been proven to determine the energy distributions of low-energy electrons precipitating into the atmosphere within small scale structures well, as is the case with black auroras [Lanchester *et al.*, 2009].

Figures 5.18a, 5.18b, A.20a, and A.20b are from frames where the 427.8 nm and 844.6 nm filters were mounted on optical instruments during the 2016 campaign. These emission lines were also discussed in detail in Section 5.3.1, and will only be briefly reviewed again. These two emission lines are both prompt emissions, which is necessary to observe dynamic aurora with a short time resolution, that are only excited by direct electron impact [Gustavsson *et al.*, 2008]. As is the case for ASK3 777.4 nm emission line, the 844.6 nm emission line used for the aforementioned campaigns is also a prominent atomic oxygen line, and is well known in the auroral spectrum [Hecht *et al.*, 1985; Lanchester *et al.*, 2009]. Its excitation threshold is above 10 eV, and suited for low energy electron precipitation observations. As mentioned earlier, the permitted 427.8 nm emission requires electron precipitation with energy deposition at lower altitudes (i.e., with higher energy) compared to the 844.6 nm emission line. The $I[844.6]/I[427.8]$ ratio can therefore be used to map precipitating particle characteristics.

Note that the black aurora events seen in the filtered images are seen as darker structures, and for the image showing the optical ratio $I[O]/I[N_2]$ Again looking at the black aurora events appear lighter. The reason for this is that the black aurora structures are shifted towards longer wavelengths compared to the surrounding diffuse aurora, as discussed in Section 5.3.3. So for event 1A, 1B, and 1C the $I[777.4]/I[673.0]$ ratio is also bigger for black aurora structures compared to diffuse aurora. For the other events, the $I[O]/I[N_2^+]$ ratio is bigger for black aurora structures compared to the diffuse aurora which indicates that it is due to lower energy electrons.

When the ratio was determined for event 5C, which presented as a dark band in Figure A.15 in the Appendix, it showed shift towards blue which inconsistent with the red-shifted black aurora events discussed above. Both the ratios inside and outside the black band are too small for the energies to be determined by the ion chemistry model, and is not shown in Table 5.4. The same was true for events 2A and 2B and omitted from the results.

For events 5B, 5H, and 5J in Figures 5.18c, A.21c, and A.22c the white patches next to black patches are anti-black auroras, and these are clearly shifted more towards shorter wavelengths,

i.e. due to higher-energy electrons as shown in Table 5.5.

5.4 Radar data

In this section, the processing of raw EISCAT radar data is discussed, and the results are shown. This will, in turn, be compared with the energies determined by optical methods shown in the previous section. The energy determined by optical data is verified by comparing to the energy distribution inside the radar beam pointing direction.

5.4.1 GUISDAP

The Grand Unified Incoherent Scatter Design and Analysis Package (GUISDAP) is used to analyse incoherent scatter radar measurements. It works by fitting theoretically calculated spectra to measured values [Lehtinen and Huuskonen, 1996]. It is used in this study to analyse incoherent scatter radar observations. The package gives several outputs, including electron density, electron temperature, ion temperature, and line of sight ion velocity. The measured electron density during 2006 events is shown in Figure 5.20 and 2016 events are shown in Figure 5.21, both in the top panel.

5.4.2 ELSPEC

The ELection SPEctrum estimation technique (ELSPEC) is used to determine the differential energy flux of electrons precipitating into the ionosphere [Virtanen *et al.*, 2018]. The electron density profile with altitude is an EISCAT parameter it takes as input, and is inverted to extract the energy spectrum of the precipitating electrons. This is dependent on the electron density altitude profile: the electron density at a given altitude before and during particle precipitation is measured, and this difference is compared to the modelled atmospheric plasma loss rate. This then gives the incoming flux of ionizing particles at each altitude, from which the electron energy distribution is determined. The MATLAB toolbox takes as input GUISDAP processed incoherent scatter radar observations of the ionospheric electron density profile and covers the auroral energy range 1 - 100 keV, which is in the ionization range of 80 - 150 km [Virtanen *et al.*, 2018]. The ISR inversion procedure and ELSPEC method will be discussed in more detail next.

The estimation of auroral electron spectra using ground-based techniques has been established as a valid tool for understanding the temporal changes in the auroral acceleration region [Semeter and Kambaldi, 2005]. This technique firstly uses the electron continuity equation,

$$\frac{\partial n}{\partial t} = q - \alpha n^2 \quad (5.8)$$

where n is the electron number density, t is time, q is the electron production rate, and α is the effective recombination coefficient [Semeter and Kambaldi, 2005; Virtanen *et al.*, 2018]. The

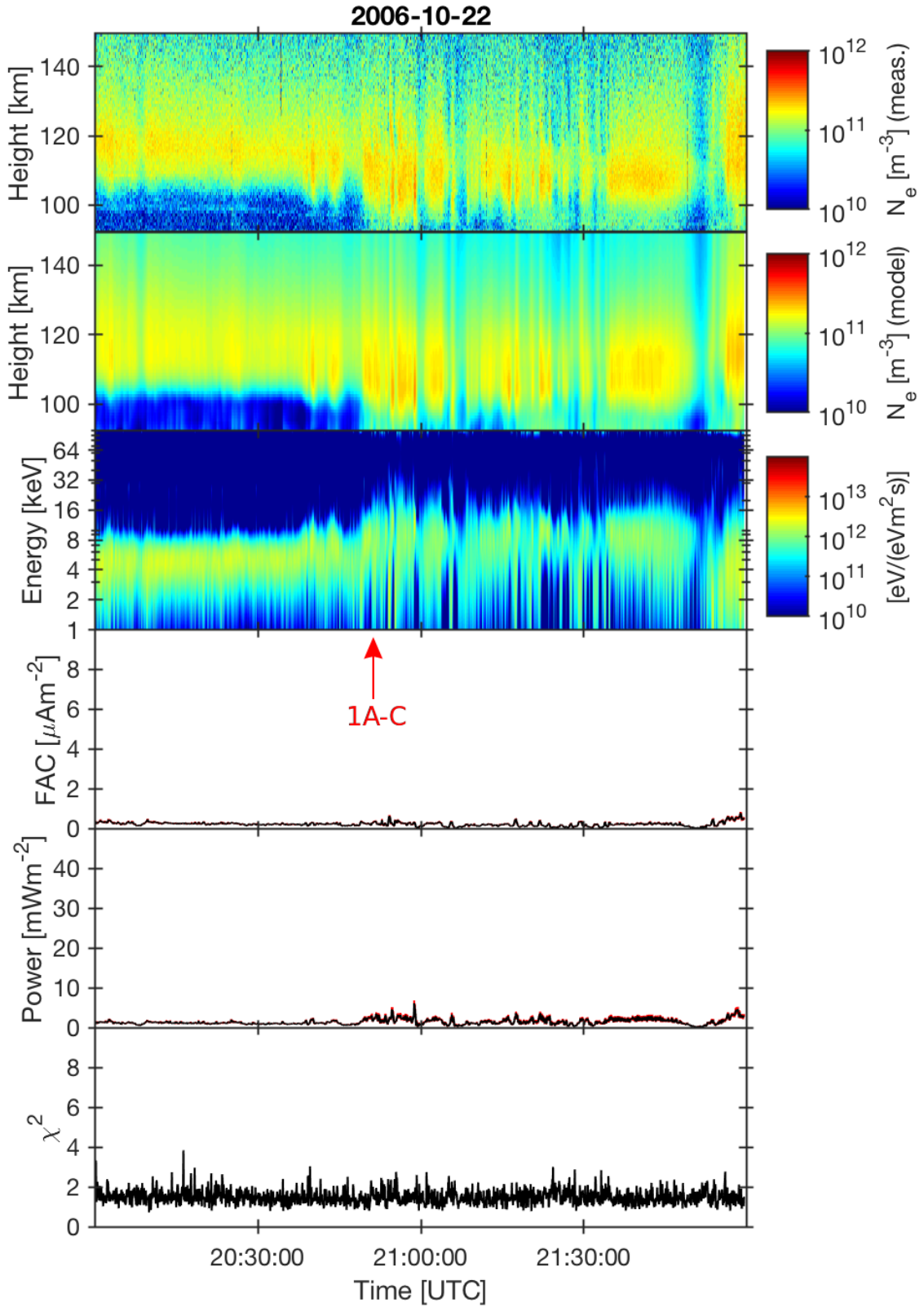


Figure 5.20: ELSPEC analysis results for the 22-10-2006 campaign dataset. From top to bottom panel are shown the observed electron density, modeled electron density, differential energy flux, upward FAC, total energy flux, and χ^2 , which is a measurement of how expectations compare to results, are shown. The red arrow indicates the approximate time events 1A, 1B, and 1C occurred.

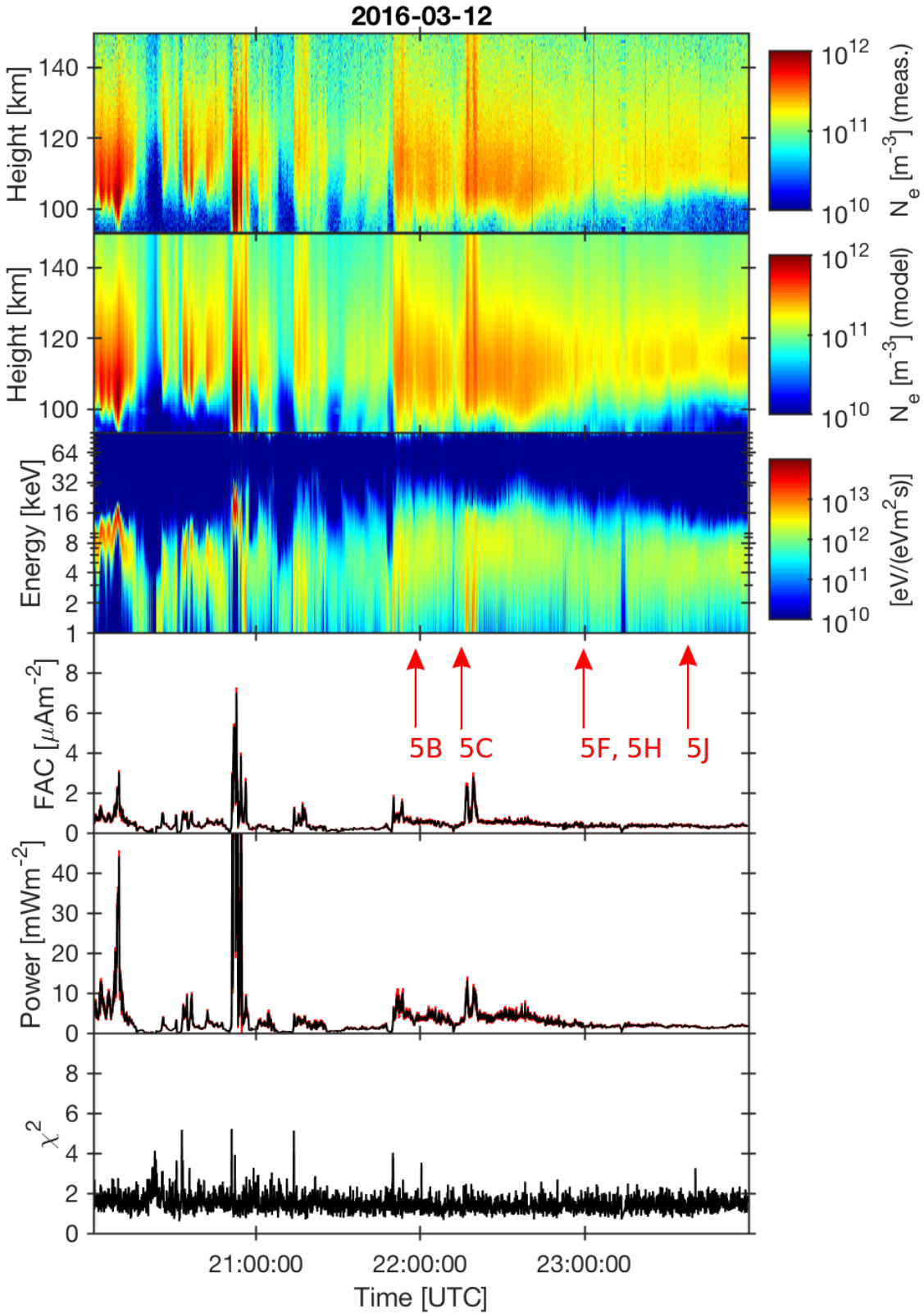


Figure 5.21: ELSPEC analysis results for the 12-03-2016 campaign dataset. Same format as Figure 5.20. The red arrow indicates the approximate time events 5B, 5C, 5F, 5H, and 5J occurred.

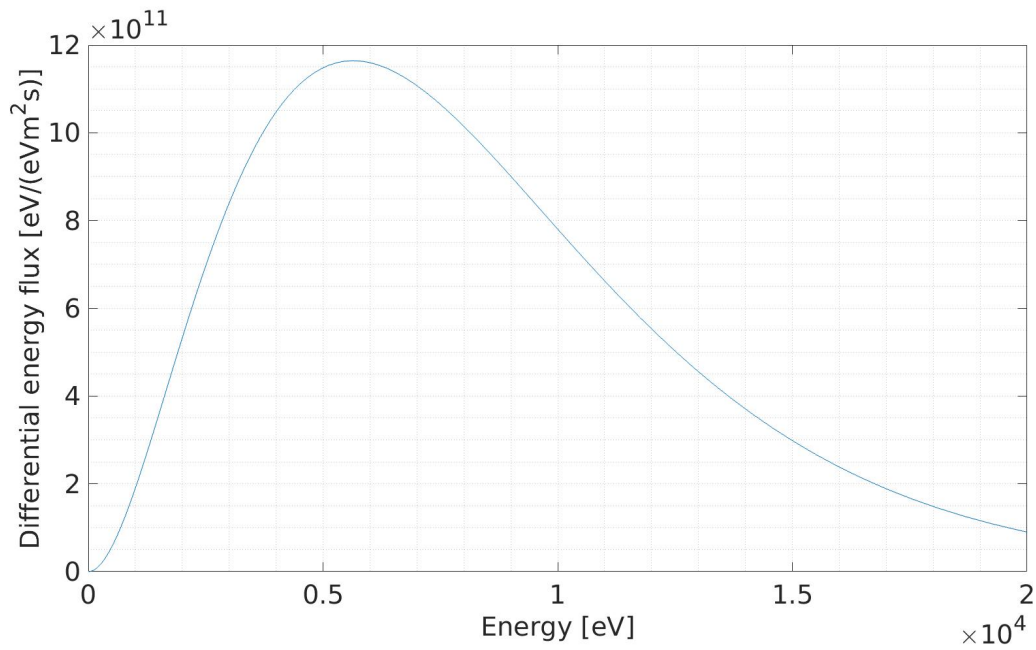


Figure 5.22: Energy [eV] versus differential number flux [eV/(eVm²s)] for event 1A. The characteristic energy is 5.8×10^3 eV.

electron production rate needs to be determined. A numerical model is used for this, for a discrete set of monoenergetic electron beams. This production rate is related to the discretized incident number flux spectrum Φ by a discrete forward model A by

$$\mathbf{q} = A\Phi. \quad (5.9)$$

The differential number flux spectrum is then estimated by the inversion of A [Semeter and Kambaldi, 2005].

The program was run by B. Gustavsson (*private communication*, 2018) and the outputs are shown in Figures 5.20 and 5.21. Note that the EISCAT radar beam was either fully or partially filled with a diffuse background, and not black aurora or anti-black aurora, for all instances except event 1C. The second panel shows the modelled electron density, and the third panel shows electron flux versus energy. For both 2006 and 2016, the electron flux was variable over the measured period, with 2016 showing much more intense peaks intermittently, reaching a maximum of 16 keV in the first third of the evening. The fourth panel shows precipitation induced upward Field-Aligned Current (FAC) in the fourth panel, and energy flux in the fifth panel. For the 2006 evening, no significant FAC's or energy flux is observed. Several peaks were seen during the 2016 evening, with a significant peak around 20:50 UT, with a current density of around $7 \mu\text{Am}^{-2}$. These occur in the earlier part of the evening before black aurora events were observed. The bottom panel, χ^2 test, indicates how well the match between observed and modelled densities are.

The differential number flux of precipitating electrons are used to infer precipitating electron energy spectra for the selected events. The shape of the energy spectrum of electrons precipitating from the magnetosphere into the ionosphere is dependent on the source population and the mechanism causing precipitation [Virtanen *et al.*, 2018]. Diffuse aurora, for example, is associated with Maxwellian and kappa distribution fluxes, which are due to electrons precipitating from the plasma sheet. As mentioned in Section 5.3.1, a Maxwellian distribution was also assumed for the neighbouring black aurora structures. In Figure 5.22, and Figures A.23 - A.28 in the Appendix, the precipitating electron energy spectra are shown for all processed events, determined by ELSPEC.

No energy measurements were determined for the 2009 events in Section 5.3 because the optical ratios were outside the range that could be determined by the model, and therefore events 2A and 2B are omitted from the list. The black auroras shown in Chapter 4 were identified by eye, and after analysis some did not fit the criteria of black aurora characteristics. From intensity measurements discussed in Section 5.3.3 event 5C was assumed to not be a black arc, and is omitted from the list.

The assumed energy distribution function is Maxwellian, given of the form,

$$F(E) = kE^\gamma e^{-\frac{E}{E_0}} \quad (5.10)$$

where F is flux, k is a constant of proportionality, E is energy, and E_0 is the characteristic energy, which will be compared with the optical data results. To obtain a Maxwellian distribution, γ is set to 1. As mentioned earlier, it represents best the observed primary auroral flux spectra [Kosch *et al.*, 2001].

One limitation of the model is that the radar beam isn't always filled uniformly with the structure being analysed (i.e., diffuse aurora, black aurora) [Dahlgren *et al.*, 2011]. This leads to an averaging effect when the electron density is estimated and when modelling the precipitating particle energy based on this radar data.

Incoherent scatter radar analysis techniques using EISCAT data (and processing with GUIDAP) is dependent on the International Reference Ionosphere (IRI) empirical model. The IRI provides statistical average plasma density and ion composition profiles between 50 - 1500 km [Bilitza *et al.*, 2011]. Due to additional ionisation from auroral precipitation, IRI predictions tend to be inaccurate. Ion composition predictions are the weakest part of this IRI model, mainly due to too few observations [Bilitza and Reinisch, 2008]. This is especially relevant during geomagnetic storms, when molecular ions tend to dominate the F-region. Thus the ion composition in the high-latitude lower F-region transition region is not well known and its effect on incoherent scatter data analysis needs to be kept in mind when interpreting the results.

Other limitations of the model worth mentioning is the effect of plasma convection, static electric fields, and the energy grid range of the model. Convection could shift plasma out of the

Events	Optical data mean energy (keV)	Radar data mean energy (keV)
1A	7.6	9.2
1B	8.8	11.0
1C	2.9	3.8
5B	7.6	11.6
5F	6.2	9.6
5H	8.3	4.5
5J	7.4	9.2

Table 5.6: Comparison of estimated mean energies, using the ion chemistry model and ELSPEC. Chosen events are shown in column 1, whose date and time can be referred to in Table 4.1. Events 1A-1C are from the 2006 campaign. Events 5B-5J are from the 2016 campaign. Column 2 shows the mean energy estimated with the University of Southampton ion chemistry model (photon emission rate modeling). The area in which this mean energy was estimated corresponds to the area in the sky filled by the EISCAT radar beam. Column 3 shows the mean energy estimated with the ELSPEC model using electron density profile inversion techniques. It estimates characteristic energy, but is converted to mean energy for comparison purposes, as discussed in Section 5.5.

radar beam if the horizontal electric field is large enough [Virtanen *et al.*, 2018]. In the ionosphere, however, electric fields are significantly small enough to not have an effect on the results. The presence of static electric fields could affect the electron density profile shape [Virtanen *et al.*, 2018]. This effect is only significant when the electron density is very low, allowing ions to move before they recombine [Virtanen *et al.*, 2018]. The energy grid for this model ranges from 10 eV to 100 keV, but energies less than 1 keV are considered unreliable because energies less than this produce ionization above 150 km, the upper boundary of this model. The model is limited to this altitude due to the effect of O^+ dominated ion chemistry and ion convection. Correspondingly is the 100 keV energy limit for the lower boundary at 80 km in altitude and the model is limited to this altitude due to complex ion chemistry present below here, for example the presence of positive and negative molecular ions. In this study however, the energy of the structures analysed fall within the reliable energy range determined by this model.

5.5 Comparing radar and optical data

As discussed in the previous sections of this chapter, the energy of a structure can be measured in one of two ways. One is using photon emission rate modelling by determining the ratio of two observed wavelengths, as discussed in Section 5.3.1. This photon emission is due to the interaction of precipitating particles, mostly electrons, with atmospheric constituents. The other method is to invert ionospheric electron density height profile data, measured by the EISCAT radar, which was described in Section 5.4. Both these models are based on the fact that precipitating particles entering the ionosphere leads to ionization and photon emission simultaneously.

Energies of events were determined using optical data. The reason why energies are also de-

terminated using radar methods is to cross-check the results of the optical analysis. This is done by comparing the measured energy inside the radar beam using the electron density inversion model (ELSPEC) with the measured energy using photon emission rate methods (ion chemistry model). The volume where the energy is determined for the radar data set needs to correspond with the volume where the energy is determined for the optical data set. The beam location in the sky was indicated with a dotted circle in Figures 4.3 - 4.15 in Chapter 4 for each event. The radar beam was for the most part pointing outside the black aurora events and thus filled, or partially filled, with diffuse aurora. These energies for events 1A, 1B, 1C, and 5F were first shown in Table 5.4, and for events 5B, 5H, and 5J first shown in Table 5.5. Comparisons between the results using radar and optical methods will be discussed next.

The mean energies determined by the ion chemistry model were always higher than the characteristic energy measured by ELSPEC, aside from two instances. This is because the ion chemistry model measures the mean energy and not the characteristic energy of the distribution as discussed in Section 5.3.1. The mean energy $\bar{E}$ of the ELSPEC derived distributions can be determined from the characteristic energy E_p using $\bar{E} = 2 \sqrt{\frac{2}{\pi}} E_p$ [Weisstein]. The corrected values are shown in Table 5.6.

After this correction, the measurements from ELSPEC compares well with that of the ion chemistry model. For event 1A and 1B shown in Figures 5.16a and 5.16b the radar beam was only partially filled with black aurora and the mean energy was measured as 9.2 and 11.0 keV respectively. From the ion chemistry model the volume within the radar beam are measured as 7.6 and 8.8 keV, as shown in Table 5.6. For event 1C shown in Figure 5.16c where the beam was completely filled with black aurora for approximately ten seconds, the mean energy is measured as 3.8 keV from the energy spectrum in Figure A.24 which compares well with the measured 2.9 keV mean energy determined from the optical data seen in Table 5.6.

During event 5B the measurement in the radar-derived electron mean energy was 11.6 keV using ELSPEC, and 7.6 keV using the ion chemistry model for the same volume. During event 5F the mean energy in the radar beam, which was right next to the event, is measured as 9.6 keV using ELSPEC, and 6.2 keV using the chemistry model. For event 5H and 5J using ELSPEC, it is 4.5 keV and 9.2 keV respectively. Using the ion chemistry model it was 8.3 keV and 7.4 keV measured next to the black aurora events.

The average energy discrepancy between these two methods is 2.5 keV, and only event 5H shows a significant discrepancy between radar and optical methods. Using the results from select events, the energies of the host electron population in the magnetosphere will now be determined.

5.6 Determining energies of host electron population

Earth's dipolar magnetic field creates a natural magnetic mirror and particles drift along the magnetic field lines and bounce from pole to pole. If the particles have a small enough pitch angle (e.g., through collision or wave-particle interaction) they are not magnetic mirror-confined anymore and will consequently reach the ionosphere [Kamide, 2007; Chen, 2010]. The total magnetic drift perpendicular to the magnetic field line is given by the combined gradient and curvature drift

$$\mathbf{v}_B = \left(v_{\parallel}^2 + \frac{1}{2} v_{\perp}^2 \right) \frac{\mathbf{B} \times \nabla B}{\omega_g B^2} \quad (5.11)$$

where $v_{\parallel}$ and $v_{\perp}$ represent the parallel and perpendicular velocity components of the particle to the magnetic field at a given point, ∇B is the magnetic field gradient, and $\mathbf{B}$ is the magnetic field strength, as discussed in Chapter 2. If the underlying mechanism causing black aurora patches are magnetospheric in origin, then the drift speed of the precipitating particles causing the optical emissions are directly dependent on the total magnetospheric drift speed of the host electron population projected into the ionosphere. Assuming that the electron perpendicular velocity is significantly smaller than the parallel velocity and that only the normal component of the magnetic field changes significantly with distance in the radial direction, Equation 5.11 can be rewritten as

$$v_B \approx v_{\parallel}^2 \frac{m \nabla B_r}{q B_n^2} \quad (5.12)$$

where B_n is the normal component of the total magnetic field determined using the Tsyganenko model and is assumed to be perpendicular to the equatorial plane, and ∇B_r indicates the gradient of the magnetic field, which is dominated by B_n , in the radial direction.

If the assumption is that the blocking mechanism drifts with the source electron population in the magnetosphere, then black auroras drift with a velocity that increases with energy, since ∇B curvature drift is energy dependent [Blixt *et al.*, 2005]. Also, black auroras are due to structures in the host electron population (Kimball and Hallinan [1998b]) so the relation of the drift of the black auroral structures to the energies of the source population is used to estimate the latter. Given that E_{eq} is the host electron population energy at the equatorial region of the L-shell, Equation 5.12 can be rewritten as

$$E_{eq} \approx \frac{q B_n^2 v_B}{2 |\nabla B_r|}. \quad (5.13)$$

The total magnetospheric drift speed v_B is determined by mapping the black aurora zonal drift speed in the ionosphere out to the equatorial plane for each event which a drift velocity could

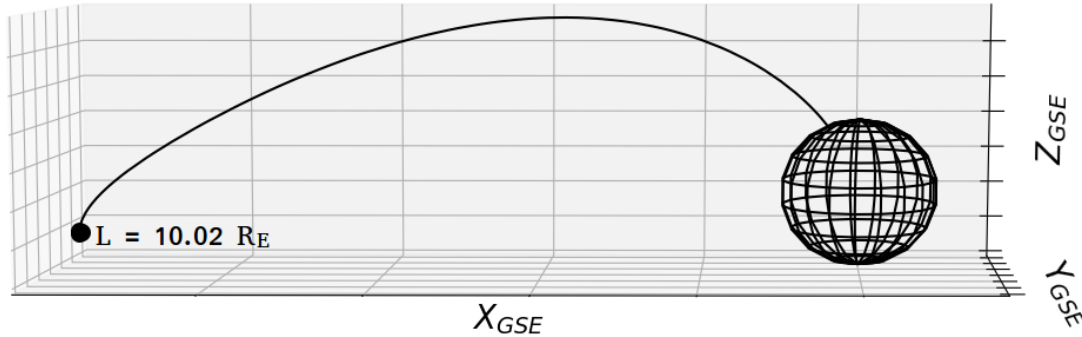


Figure 5.23: Fieldline coordinates from EISCAT ground footpoint ($69^{\circ}35'11''\text{N}$ $19^{\circ}13'38''\text{E}$) for event 5B, using The Tsyganenko magnetic field model and solar wind and IMF data as input.

Event	Ionospheric drift velocity (km.s^{-1})	Mean $E_{\text{ionosphere}}$ (keV)	L-shell distance (R_E)	B_r (nT)	Velocity in equatorial plane (km.s^{-1})	∇B_r (nT.m^{-1})	Mean E_{eq} (keV)	Φ (10^4V)
5B	0.87 E	4.82	10.02	558	12.68	5.02×10^{-6}	23	1.8
5F	0.95 E	3.29	9.49	556	16.47	5.44×10^{-6}	35	3.2
5H	2.26 E	4.57	9.49	1321	16.47	5.44×10^{-6}	84	7.8

Table 5.7: Table shows for selected events the drift velocity, mean energy of precipitating particles in the ionosphere, distance of source electron population from Earth along the magnetic field line, velocity of the host electron population in the equatorial plane, magnetic field strength at the L-shell, gradient magnetic field strength, energy of source electron population at the L-shell, and in the last column the electrostatic potential along the magnetic field line for each event.

be determined (5B, 5F, and 5H), of which the location is determined by using the Tsyganenko model [Tsyganenko, 2002]. The drift speeds are shown in Table 5.7, in column 6.

The Tsyganenko model is a semi-empirical, best-fit magnetospheric magnetic field model using solar wind and IMF data as input [Tsyganenko and Sitnov, 2005], as discussed in Chapter 2. This data is acquired from several spacecraft, for example the WIND, IMP, Geotail, and GOES satellites. Data gaps are common, and estimates for these data gaps have been made by Qin *et al.* [2007]. An updated set has been acquired for this study (Denton, R.E. *Private communication*, 2018). The output is geomagnetic field components at the selected point in 3D space in GSM coordinates. This is used to determine ∇B_r and B_r^2 at the L-shell for the chosen events. L-shell, in this case, refers to magnetic field lines crossing Earth's magnetic equator a certain radial distance, given in Earth radii (R_E). An example of the L-shell during event 5B is shown in Figure 5.23.

Using Equation 5.13, E_{eq} is determined for each event and shown in Table 5.7. The L-shell distance was only determined for these three events, where ionospheric drift velocity could be determined and thus calculate the electron population energy in the equatorial region. Comparing $E_{ionosphere}$ and E_{eq} in the table, there is clearly a loss of energy as the electron population travels from the magnetosphere to the ionosphere for all three events, and a hypothesis as to the reason for this will be proposed in Section 5.7. Ideally, these energy values at the L-shell should be cross-checked with host electron population energies determined from in-situ satellite data. This is discussed in the following subsection, Section 5.6.1.

5.6.1 Comparing with satellite data

Ideally, the electron energies determined at the L-shell should be compared with measurements from nearby satellites with the necessary instrumentation onboard. Several satellites were considered by looking at their payload and orbits, which should preferably be around $10 R_E$ (as shown in Table 5.7) in the magnetotail. Figure 5.24 shows the position of just some of the satellites considered during black aurora events occurring on 2009-01-25. Most of the satellites are in elliptical orbits with apogees reaching no more than $6 R_E$.

The best candidate was determined to be the GEOTAIL satellite. One of its payloads consists of a Low Energy Particles Experiment (LEP) which, amongst other things, takes measurements of electrons from 6 eV to 40 keV. The satellite is in a highly elliptical orbit, and interchanges between two different orbits. One of these is a low inclination orbit at geocentric distances of around 8 - $20 R_E$ [Kramer, 2018 - Accessed 08-10-2018].

Figure 5.25 shows its orbit from 2016-03-09 20:00:00 UT to 2016-03-13 23:00:00 UT. During the early afternoon of 2016-03-11, the satellite passes where the magnetic field line is perceived to be, at around $L=10 R_E$, as determined by the Tsyganenko model example shown in Figure 5.23. No instance exists where the satellite was situated in the same location as the magnetic field line mapped out from the black aurora footpoint, for any of the events studied in this thesis.

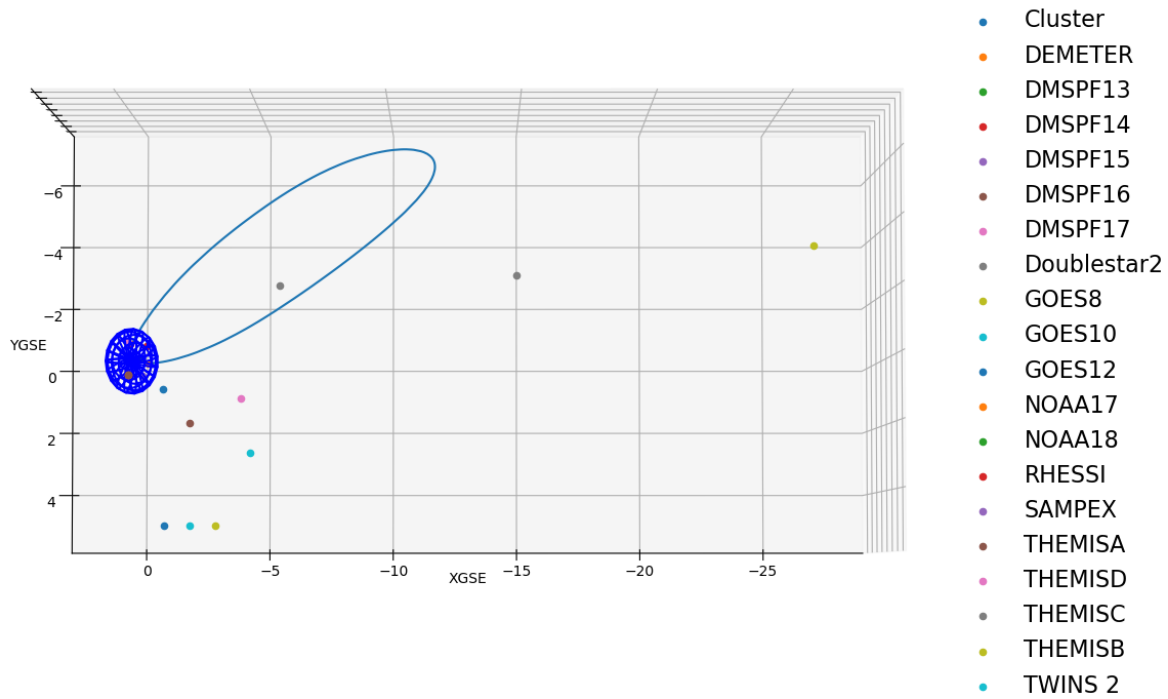


Figure 5.24: The position of several satellites w.r.t. Earth is shown. This plot shows the Y- and X-axes in GSE coordinates..

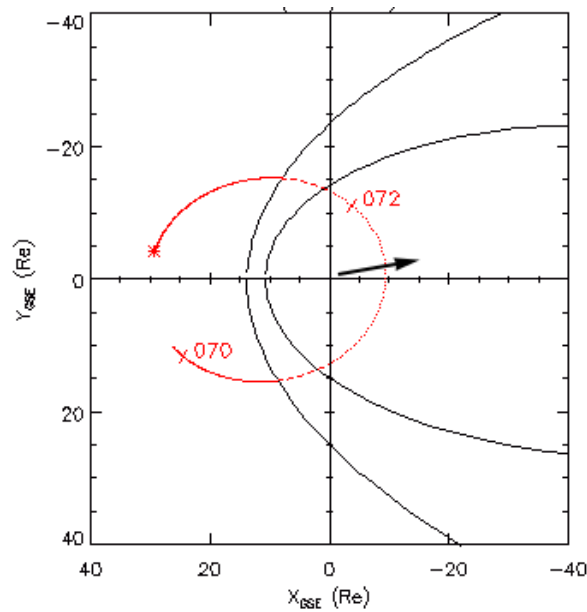


Figure 5.25: Geotail satellite orbit shown with red dashed lines from 2016-03-09 20:00:00 UT to 2016-03-13 23:00:00 UT, with 070 and 072 referring to the day of the year. Most of the black aurora events that were observed occurred on the evening of 2016-03-12 between 21:00:00 UT to 23:00:00, with the camera view direction indicated by the arrow. This plot shows the Y- and X-axes in GSE coordinates, with the Sun's position on the left-hand side of the figure.

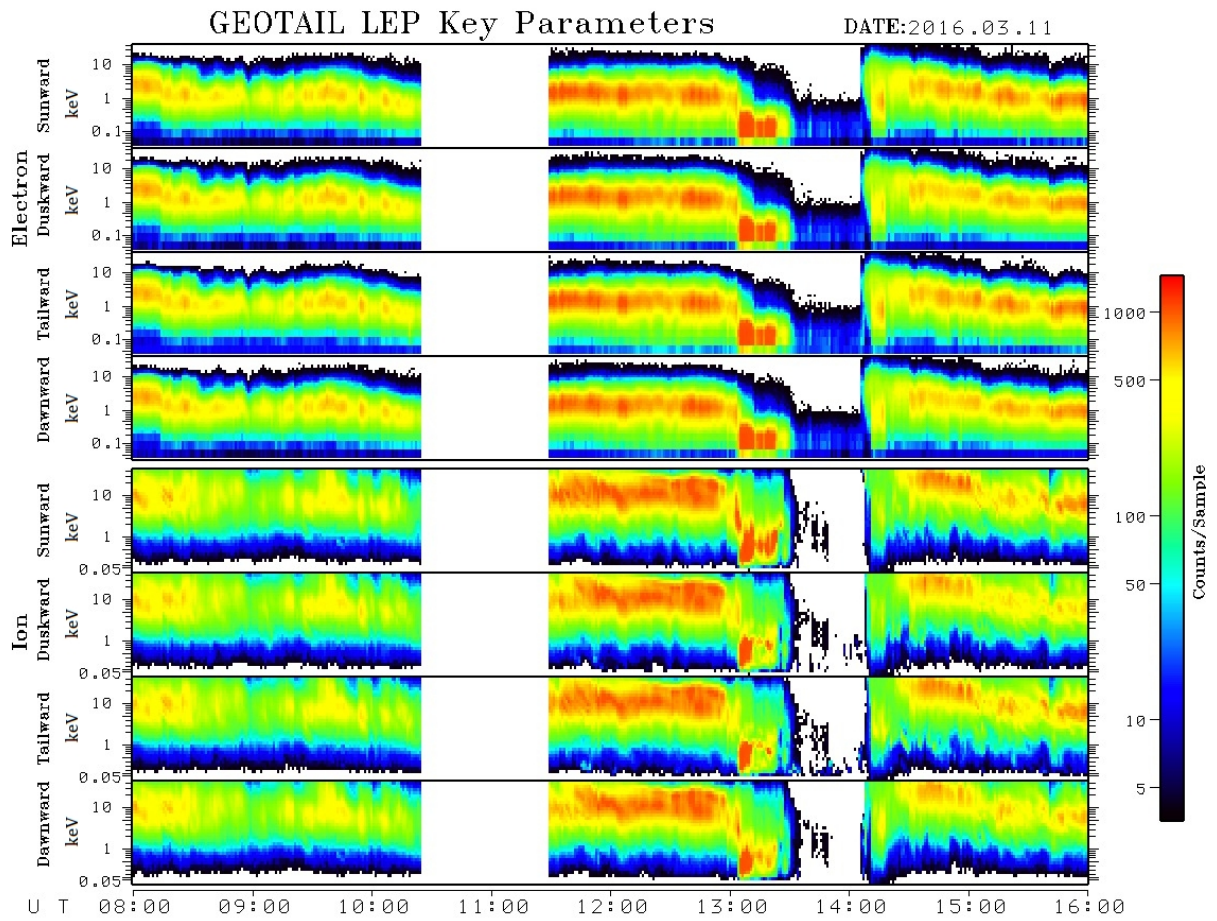


Figure 5.26: Geotail low energy particle output on 2016-03-11 08:00:00 - 16:00:00 UT. The first four panels show the sunward, duskward, tailward, and dawnward electron energies in keV, and the last four panels show similar energies for ions in keV.

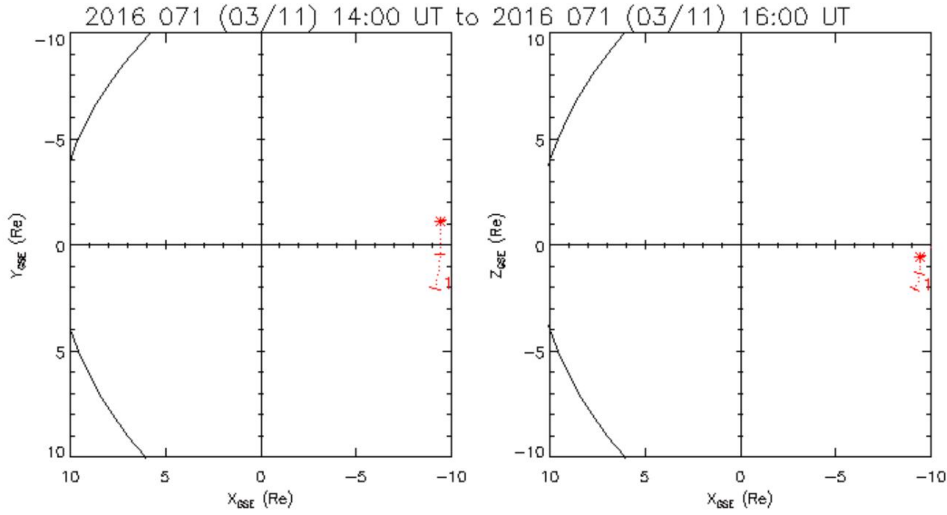


Figure 5.27: The geotail orbit shown with red dashed lines on 2016-03-11 from 14:00:00 to 16:00:00 UT. This plot shows the Y- and X-axes in GSE coordinates on the left and the X- and Z-axes in GSE coordinates on the right, with the solid black line on the left-hand side indicating the magnetopause. The Sun's position is on the left-hand side of the figure.

Thus for this study, there are no in-situ data available to compare the calculated energies of the host electron population with. There is however a sample of the LEP output shown in Figure 5.26, which shows electron and ion energies in four different directions. The corresponding Geotail orbit is shown in Figure 5.27 where the red dashed curve shows the orbit from 14:00:00 - 16:00:00 UT on 2016-03-11. During the orbit from 14:00:00 to 16:00:00 UT the electron energies goes up to 40 keV as it reaches the magnetotail. This is consistent with our estimates.

5.7 Anomalous electric field

One possible explanation for this loss of energy shown in Section 5.6 is the presence of a field-aligned anomalous electric field. Anomalous field-aligned resistance is caused by ion acoustic waves whose oscillating electrostatic field can scatter drifting electrons [Kosch *et al.*, 2014]. This will be investigated.

Electrostatic potential Φ are obtained by dividing the energy difference between two points ΔE by the electron charge q ,

$$\Phi = \frac{\Delta E}{q}. \quad (5.14)$$

The energy difference for each event is obtained by subtracting the energy of the source electron population in the equatorial plane with the mean energy of precipitating particles in the ionosphere, shown in Table 5.7 columns 3 and 8 respectively. The resulting electrostatic potential for each event is shown in the last column.

If a typical anomalous electric field of $1.6 \mu\text{V}\cdot\text{m}^{-1}$ is assumed (*Kosch et al.* [2014]), then the distance over which it is acting would be 1.1×10^7 km, 1.9×10^7 km, and 4.9×10^7 km respectively. This is inconsistent with the height range over which low-energy auroral precipitation above the ionosphere might occur, i.e., between 800 and 1700 km [*Mozer and Kletzing*, 1998; *Marklund et al.*, 1997].

5.8 Summary

Several preprocessing techniques are applied to the raw optical data. Dark subtraction is necessary to remove leakage current due to thermal electrons from pixels in CCD detectors. To do this, dark frames are created for each camera by closing the shutter, for the same integration time for each camera, and then subtracting these dark frames from the original frames. The frames are also corrected using flat field frames. Flat-fielding is used to reduce the effect of non-uniform lens transfer function on image frames. For the 2016 campaign, these frames were created by covering the camera dome with a uniformly white surface. For the 2009 campaign, no flat field frames were available, and artificial flat field frames were created by fitting each intensity profile with a third-order polynomial curve and dividing with the resulting curve. To increase the signal to noise ratio of these frames, median filtering is applied.

Star mapping is applied to verify the camera pointing direction for each observed set, as well as to identify bright stars in the FOV which is used to measure the star intensity. The SAO catalogue is used for this step. Then the spectral photon flux for each of these identified stars are looked up in the Pulkovo spectrophotometric catalogue, and also taking into consideration the spectral band of each filter, the conversion from pixel data number to photon flux is applied to each frame.

By looking at spectroscopic emission features of auroral structures the energy of the precipitating electron flux can be inferred. Auroral emissions are usually dependent on the density of atomic oxygen [OI] and the density of molecular nitrogen [N_2] composition at various altitudes. The Southampton ion chemistry model can estimate the energy of precipitating electrons using the intensity ratio of auroral emissions, in particular, the atomic oxygen and molecular nitrogen composition.

From the multiwavelength intensity measurements, a shift towards lower energy precipitating particles for the single black aurora events were determined, compared to the surrounding diffuse aurora.

The anti-black aurora and black aurora pairs were shown, along with the multiwavelength intensities measured within these structures. Comparing the intensity shift of the anti-black aurora with the surrounding diffuse aurora, it was determined that there is a hardening of the electron precipitation energy spectrum within the anti-black aurora when comparing with the surrounding diffuse aurora, and a softening of the electron precipitation energy spectrum

within the adjacent black aurora, when comparing with the surrounding diffuse aurora. This is the first multiwavelength measurements made of the anti-black aurora and black aurora pairs.

Using the ratio of these two wavelength intensities, the processed images were then used to determine the mean energies both inside and outside black auroras using the ion chemistry model. The results always show lower energy measured within the black aurora, with an average of 2.9 keV, compared to the measured energy of the diffuse aurora (average of 9.7 keV) located next to the black aurora event. The anti-black aurora showed higher average precipitating particle energies (11.1 keV) than both the adjacent black aurora (5.1 keV) and the surrounding diffuse aurora (7.8 keV). An anti-black aurora was never observed without a simultaneous black aurora present.

Using EISCAT radar data, and assuming a Maxwellian distribution for the differential energy spectrum of the precipitating particles, the mean energies inside the radar beams were inferred using ELSPEC, an inversion model. This was compared to the mean energies inferred by the ion chemistry model as a control. This is the first time mean energy comparisons have been made between the Southampton ion chemistry model and the ELSPEC toolbox. The measurements from the ion chemistry model were always slightly higher (1.4 keV) than that of the ELSPEC, aside from two instances. Events 1A, 1B, 1C, and 5J showed an increase of 11%. Event 5H showed an increase of 159%, and events 5B and 5F showed a decrease of 10%.

Energies of the host electron population in the magnetosphere and that of the precipitating particles in the ionosphere differed by a factor of ten for events where a drift velocity could be determined. For these events, a new theory is proposed, that of an anomalous electric field that could be a possible cause as to the loss of this energy. This will be discussed in more detail in the next chapter.

Chapter 6

Summary and Conclusions

6.1 Possible variations in data

Auroral activity is time-dependent and varies between daytime and nighttime, which would lead to significant compositional differences when measuring the photon emission rate ratios at various times. In this study, however, measurements of the events from all the campaigns were taken roughly during the same time range during the evenings. Events observed always occurred post-magnetic midnight during the geomagnetic substorm recovery phase when diffuse aurora was present, and before the appearance of pulsating auroras. Thus when comparing analysis results in this study, the slight time variation is irrelevant.

In regards to the geographical location, all events from 2006, 2009, and 2016 were recorded at the same location at the EISCAT facility outside Tromsø, Norway, and caused by precipitation on the night side of the auroral oval. Variations that could have been caused due to the geographical location need not be taken into consideration.

Solar wind transports magnetic flux from the dayside of the magnetosphere to the nightside, as discussed in Chapter 2 [Kivelson and Russell, 1995]. Solar wind energy enters the magnetosphere through magnetic reconnection and viscous interaction [Juusola *et al.*, 2009]. Studies have shown that there is a positive correlation between the solar wind dynamic pressure and the intensity of the auroral ionospheric currents, and an increase in auroral oval width is seen in response to a solar wind pressure pulse [Juusola *et al.*, 2009]. Although the interaction of the solar wind with the magnetosphere is responsible for large-scale auroral systems, smaller-scale systems like the black aurora and anti-black aurora are probably caused by plasma processes in extremely short spatial time-scales operating in the ionosphere and/or magnetosphere [Borovsky, 1995].

Early studies of the dependence of auroral activity on the solar cycle and geomagnetic activity were done by looking at auroral observations over several solar cycles (1973-1997), and they concluded that there is no obvious correlation between the solar cycle and auroral activity rate [Partamies *et al.*, 2014]. More recent studies, however, have shown that quiet auroral structures do have a positive correlation with the solar cycle, albeit with less variation than dynamic

aurora [Partamies *et al.*, 2014]. Diffuse aurora, in which black auroras and anti-black auroras are embedded in, classify as a quiet auroral structure. They further conclude that dynamic aurora is more directly driven by geomagnetic activity, and does not affect the occurrence of quiet aurora much. The 2006, 2009, and 2016 campaigns from this study ran during at or near solar cycle minima, which means the occurrence of quiet auroral structures would have been less than during solar maximum, and is less directly driven by geomagnetic activity.

6.2 The black aurora

In this study, the majority of black aurora events were identified as black patches and black arc segments. The objects' horizontal width from previous studies for this type of black aurora is 0.5 - 4 km [Trondsen and Cogger, 1997]. The mean width measured in this study for black patches and arc segments were 3.9(3.2) km, where the value in brackets refers to the standard deviation. Black patch horizontal length from previous studies are 2.5 - 5 km but can go up to 20 km. In this study, the mean length is 13.0(4.5) km. In general, the horizontal width and length compared well with previous studies. The average drift speed for black patches is 0.6 - 1.5 km.s⁻¹ eastward determined from previous studies [Trondsen and Cogger, 1997]. In this study, the mean drift speed is 1.1(0.7) km.s⁻¹ which is well within the range of previous observations. Some events were identified as black arcs. For these events, the mean horizontal width (and standard deviation) is 1.7(0.7) km. From previous studies, it was determined that the average horizontal width for black arcs are 0.6 km, which is slightly narrower than what was determined in this study.

Black auroral structures in this study have a reduction of 43% in 777.4 nm emission line intensity and 68% in 673.0 nm emission line intensity compared to the intensities in the surrounding diffuse aurora for 2006. In previous studies a reduction of 23% in 777.4 nm and 35% in 673.0 nm compared to diffuse aurora was determined [Archer, 2009]. Both instances indicate a softening of the electron energy spectrum in the black aurora. The same was true for the 2009 and 2016 set of black aurora structures: There was a reduction of 16% in I(O) 844.6 nm and 25% in I(N₂⁺) 427.8 nm compared to the intensities of the surrounding diffuse aurora. This compared well with previous studies that also showed a softening of the electron energy spectrum: 18% reduction in 844.6 nm and 25% reduction in 427.8 nm [Gustavsson *et al.*, 2008].

The average of the mean electron energies of black aurora events determined by the Southampton ion chemistry model in this study is 2.9(0.2) keV. Previous studies determined an average of 4.4 keV [Archer, 2009] and 6.7 keV [Blixt *et al.*, 2005] for black auroral energies. This is an average difference of 2.6 keV between the mean energy determined in this study, and the average energy from the aforementioned studies [Blixt *et al.*, 2005; Archer, 2009]. The mean energy of the surrounding diffuse aurora is 9.7(3.9) keV, which compares well with an average of 6.4 keV from previous studies [Archer, 2009]. Four black aurora events were analysed, and the energy of the precipitating electrons are higher in the diffuse aurora than in the black aurora.

The number of quantitative studies of the black aurora is so few that the statistics of expected energies is not well established.

6.3 The anti-black aurora

The six anti-black aurora and black aurora pairs presented similar horizontal widths: 2.1(1.6) km for the anti-black aurora, and 1.8(1.0) km for the black aurora, shown in Table 4.1. The mean horizontal length for the anti-black aurora is 13.1(4.8) km. The anti-black auroras morphology is very similar to that of the adjacent black aurora, as well as the single black aurora patches and arc segments described earlier. The mean drift speed of the anti-black aurora is 1.3(0.8) km.s⁻¹ eastward, which is in good agreement with the mean drift speed of the single black aurora patches and arc segments.

When comparing the intensity shift of the anti-black aurora with the diffuse aurora, a higher increase in emission intensity was observed with the 427.8 nm (11%) than with the 844.6 nm (5%) on average. For the intensity shift from the diffuse aurora to the adjacent black aurora, a 16% reduction for the 844.6 nm emission, and 24% reduction for the 427.8 nm emission was observed on average. For the adjacent black aurora this indicates a softening of the electron energy spectrum and for the anti-black aurora a hardening of the electron energy spectrum.

The mean energy of three anti-black aurora and black aurora pairs were estimated. The average mean energy of the black aurora adjacent to an anti-black aurora structure is 5.1(0.6) keV, and the average mean energy of the anti-black aurora is 11.1(2.6) keV. The average mean energy for the surrounding diffuse aurora during anti-black aurora events is 7.8(0.4) keV. This means that the average energy of the precipitating electrons for the black aurora adjacent an anti-black aurora is 3.3 keV lower than that of the surrounding diffuse aurora, and the energy of the precipitating electrons for the anti-black aurora is 2.7 keV higher than that of the surrounding diffuse aurora.

In the previous section, the average mean energy of the black aurora was measured as 2.9(0.2) keV, and the average mean energy of black auroras adjacent the anti-black auroras are 5.1(0.6) keV. Although the black aurora adjacent an anti-black aurora have higher energies than the energies measured in this study for black auroras only, it is still within the energy range measured in previous studies of black auroras [Blixt *et al.*, 2005; Archer, 2009].

From comparing the morphology, drift speed, and average mean energy of the anti-black aurora with that of the diffuse aurora, it is highly unlikely to be part of the surrounding diffuse aurora, or a diffuse aurora itself. Its drift speed is comparable to that of the black aurora events observed in this study, and its average mean energy is higher (by 2.7 keV) than the surrounding diffuse aurora.

When comparing the morphology, drift speed, and average mean energy of black auroras adjacent anti-black auroras with that of single black auroras determined in this study, there are

significant similarities. They have a similar shape (arc segments, patches) as well as widths and lengths than that of single black auroras, as mentioned at the beginning of this chapter. Their drift speed is also in good agreement with the mean drift speed of the single black aurora events in this study. As mentioned earlier, the average mean energy of the black aurora adjacent an anti-black aurora is higher than the average mean energy of the single black aurora events, but in the same energy range of black auroras measured in previous studies. From this it is unclear whether the black aurora adjacent the anti-black aurora is a typical black aurora, but with a white segment moving alongside it, or whether it is wholly a new type of aurora. The number of samples is too few to make a final conclusion. From the analysis in this study it can be classified as a black aurora, but the underlying mechanism of the anti-black aurora travelling alongside it needs to be investigated in future work.

This is the first time intensity and mean energy measurements have been done on the anti-black aurora. The author is not aware of any other anti-black aurora studies that exist for comparison.

6.4 ELSPEC and the ion chemistry model

The Southampton ion chemistry model measures the mean energy of the energy distribution when determining the energy of the events in this study from optical data. To be able to compare the results of the Southampton ion chemistry model with the ELSPEC method, which both assume Maxwellian energy distributions, the mean energies are used in the following results. The mean energies determined for the black aurora, anti-black aurora, and surrounding diffuse aurora were made using the Southampton ion chemistry model. The results of the model were checked by comparing the energies of the surrounding diffuse aurora (in the location the EISCAT radar beam was pointing) with that of the inferred mean energy determined by the ELSPEC toolbox using EISCAT radar measurements of plasma density. This is the first time comparisons are made between the Southampton model and the ELSPEC toolbox.

To make these comparisons the mean energy was determined within the area the radar beam was pointing, during seven events. These events are listed in Table 5.6 and discussed in Section 5.5. The radar beam was never completely filled with black auroras for six of these events (1A, 1B, 5B, 5F, 5H, and 5J). It was either partly filled with black aurora and diffuse aurora, or completely filled with diffuse aurora. The mean energy for these 6 instances for the ion chemistry model is 7.7(0.8) keV. The mean energy for ELSPEC is 9.2(2.3) keV. For one instance when the radar beam was completely filled with a black aurora for about ten seconds (event 1C, see Figure 4.5) the energy determined by the ion chemistry model is 2.9 keV and by ELSPEC 3.8 keV. All instances are in good agreement to within the uncertainty, thus the black aurora and anti-black aurora energies determined by the ion chemistry model based on the optical data is a good indication of their precipitating electron energies. This is important because the majority of observations occurred outside the radar beam pointing direction.

6.5 Energies at the equatorial plane of the magnetosphere

To determine energies of the source electron population of the black auroral events, the drift motion of black patches determined in the ionosphere was mapped out to the equatorial plane of the magnetosphere, origin of the source electron population. Given the gradient-curvature drift of the source population out in the magnetosphere, and determining the distance along the magnetic field line for each event L-shell using the Tsyganenko model, the electron energies in the equatorial region were determined to range between 23 - 84 keV, which is an order of magnitude greater than the precipitating particle energies within of the black aurora events in the ionosphere. From Geotail satellite data, electron energies at the corresponding L-values have been shown to go up to 40 keV, which is the highest energy that can be measured by the LEP onboard, so energies determined in this study are not unrealistic based on the motion of the aurora. Ideally, the satellite should be in the equatorial region of the magnetosphere during a black aurora event, but this was never the case here. This will be discussed further in Section 6.7.

This inferred equatorial energy can only be determined if one assumes that the source electron population is subjected to gradient-curvature drift velocity in the magnetosphere, which is consistent with the drift of the precipitating electrons in the ionosphere [Blixt *et al.*, 2005]. Findings in this study support the magnetospheric generation mechanism theory discussed in Section 2.5.2 for the black aurora patches and arc segments. However, in all cases, the particle energy in the ionosphere is lower than in the magnetosphere, so there must be a deceleration mechanism in all cases. The cause of the anti-black aurora though remains inconclusive. One hypothesis is that anti-black and black aurora pairs are due to a dual-mechanism: that its source particles energy within the pair is consistent with the motion of the gradient-curvature drift in the magnetosphere, but that each is paired with upward and downward FAC's, as the coupled ionospheric-magnetospheric generation mechanism theory proposes in Section 2.5.2. A way to test this theory is by measuring plasma density in that region: Upward FAC's correspond to local enhancements in ionospheric electron density, and downward FAC's correspond to local depletion in ionospheric electron density [Blixt *et al.*, 2005]. These FAC-pairs will be discussed in more detail in the next sections.

6.6 Anomalous electric field

Assuming that the precipitating particle drift of the black aurora maps back into the magnetosphere and that it relates to gradient-curvature drift, the reduction of the inferred electron energy from the magnetosphere to the ionosphere needs to be explained. The hypothesis made here is that of the presence of an anomalous magnetic field-aligned electric field i.e., a magnetic field parallel electric field. It is classified as anomalous because it violates MHD theory, which says that field lines are equipotential. However in the case of the ionosphere, conditions ex-

Geotail time range (UT)	X_{GSE} range (R_E)	Y_{GSE} range (R_E)	Z_{GSE} range (R_E)
2019-02-06 17:00 - 19:00	-12 to -10	2 to -2	-1 to 1
2019-02-11/12 23:00 - 01:00	-11 to -10	2 to -1	-1 to 1
2019-02-17 04:00 - 05:30	-11 to -10	2 to 0	0 to 0.5
2019-02-22 10:00 - 13:00	-8 to 10	2 to -3	0 to 2
2019-02-27 15:00 - 18:00	-10 to -9	3 to -2	0 to 2

Table 6.1: All time ranges in UT during which the satellite crosses the magnetotail at the x-line during the month of February 2019 are shown. The time range is shown in column 1, and the GSE coordinate ranges (X_{GSE} , Y_{GSE} , and Z_{GSE}) are shown in columns 2 - 4.

ist in such a way that electric fields parallel to the magnetic field may exist, due to particles propagating with substantial velocity differences [Kosch *et al.*, 2014]. These fields are known to exist, especially where high-speed precipitating electrons are occurring in the presence of auroral arcs [Kosch *et al.*, 2014].

Electric fields and FAC's have been associated with bright aurora for several decades, and have been studied using ISR methods as well as satellites and rockets [Aikio *et al.*, 2002]. Downward field-aligned currents have been suggested to be the cause of black aurora arc structures [Marklund *et al.*, 1994]. A process referred to as a current-driven mechanism which leads to anomalous resistivity has been proposed as the cause of a magnetic field-aligned electric field, the anomalous electric field, generated in the topside ionosphere [Kosch *et al.*, 2014].

Electric potential values for three events were determined in the previous chapter as 1.8×10^4 V, 3.2×10^4 V, and 1.8×10^4 V respectively. Given that the distance along the magnetic field line to the equatorial plane of the magnetosphere is known, the electric field along the magnetic field line was determined for each instance, and was found to be 1.1×10^7 km, 1.9×10^7 km, and 4.9×10^7 km respectively. In previous studies, a typical anomalous electric field was determined to be $1.6 \mu\text{V.m}^{-1}$ in the ionosphere [Kosch *et al.*, 2014]. If this is the case, then the average distance over which this electric field would be acting for the three events in this study would be 2.68×10^7 km, which is impossible given the magnetic field line lengths.

Low altitude particle acceleration typically occurs between altitudes of 800 and 1700 km, which is below the bottom of the auroral acceleration region [Marklund *et al.*, 1997]. The auroral acceleration region is defined to range over several thousand kilometres in altitude [Mozer and Kletzing, 1998]. This means that the altitude over which the proposed electric field acts is much higher than the expected altitude range over which low-altitude particle acceleration may occur, thereby disproving the proposed mechanism of an anomalous electric field, generated in the topside ionosphere, as the cause of black aurora events.

6.7 Future work

In-situ satellite data is needed: A satellite with the appropriate payload (i.e., particle sensors) in the correct location in the magnetosphere during black and anti-black aurora events is re-

quired so that the motion of said events can be mapped and compared to the host electron population energies. Most satellites in this study were found to be in geostationary orbit, with L-shell ≈ 6.2 . During substorms, however, the magnetic field lines stretch further out. In this study, using the Tsyganenko model, they were found to stretch to around L-shell ≈ 10 . Several satellites were considered and their orbits and payloads were investigated. Although several satellites do have particle sensors on board that are able to detect cold plasma populations, only one, Geotail, has an orbit that crosses the region where the possible host electron population are. Using the Geotail satellite for this purpose is proposed. Scheduling of the EISCAT radar would be in such a way as to optimise satellite conjunction.

The experiment should run when Geotail is in the correct location, at around $10R_E$ in the equatorial plane on the night side, during post magnetic midnight. Geotail inclination is 29° , thus an estimation should be made to make sure it is approximately in the equatorial plane during recording. It has a perigee of approximately $8 R_E$ and apogee of $29 R_E$, and an estimation should be made of its location when crossing the equatorial plane on the night side. Given the EISCAT location, the ideal time for night-side auroral observations is during mid-October to mid-March. All the events observed in this study fall in this period, see Table 6.1. The Geotail orbital period is 5.2 days, which means that during the months of mid-October to mid-March, which is the most ideal times for auroral observation at the EISCAT radar sites, there are at least 24 times that the Geotail satellite will cross the magnetotail. Whether it crosses at around $10R_E$ in the equatorial plane, and how long the window for data recording is, is however not established.

Using the NASA Satellite Situation Centre (SSCWeb) system, an estimate of the likelihood of such a configuration can be determined, using the month of February 2019 as an example. All time ranges during which the satellite crosses the magnetotail at the X-line (as was shown in Figure 2.3) at around $10 R_E$ is determined for this month. These instances are shown in Table 6.1, and the corresponding orbits shown in the Appendix, Figures A.29 - A.33. It is clear that the time ranges during 2019-02-06, 2019-02-22, and 2019-02-27 do not meet the requirement that it should cross the X-line during post-magnetic midnight. The 2019-02-11/12 time range is promising, crossing during the time when most events in this study occurred, and 2019-02-17 might also be a candidate, as long as it is still during post-magnetic midnight, and before pulsating auroras start to appear. For the 2019-02-11/12 time range, when Geotail crosses the X-line at midnight UT, it is exactly in the equatorial plane ($Z_{GSE} = 0 R_E$). For the 2019-02-17 time range, when it crosses the X-line at 05:30 UT it too is in the equatorial plane. Thus for these five instances one time range looks very promising, and one candidate has potential. To conclude, this estimate gives an indication of how often Geotail would be in the correct position: It is possible to find times to schedule the proposed campaign, but the time range limitations, given a 1 hour window for most potential time ranges, need to be kept in mind.

It has been suggested that there is a dual-mechanism operating here: That the source particles energy within the anti-black and black aurora pair is consistent with the motion of the

gradient-curvature drift in the magnetosphere (i.e., the magnetospheric generation mechanism), but that it is paired with upward and downward FAC's. The possible presence of FAC's can be estimated by observing local electron density enhancements and depletions, that corresponds with upward and downward FAC's [Blixt *et al.*, 2005]. The correlation between FAC's and bright auroras have been investigated extensively using simultaneous ground-based and satellite observations (e.g., [Iijima and Potemra, 1976; Kamide and Akasofu, 1976]). The author is not aware of any studies investigating the correlation between the location of FAC's, anti-black auroras, and host electron population energies in the magnetosphere.

It is proposed that EISCAT's radar plasma density observations and ground-based optical observations can be made whilst simultaneous in-situ Geotail satellite data is recorded in the magnetosphere. The date and time of recording will largely depend on the location of the Geotail satellite. It should be located around $10 R_E$ in the equatorial plane in the magnetosphere during recording. The optical data during this recording will be used to determine the precipitating particle energies inside the anti-black aurora and adjacent black aurora in the same manner that was discussed in this study. It should be noted that with the EISCAT 3D project underway, optical instruments may not be necessary for electron energy estimates as the proposed radar will have multiple beams. This increases the likelihood of observing a black aurora within one of the beams. The EISCAT plasma density measurements will be used to determine the presence of possible upward or downward FAC's in the regions of interest.

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The South African National Space Agency , Hermanus, 7200, South Africa

Appendix

Appendix A

Additional Figures

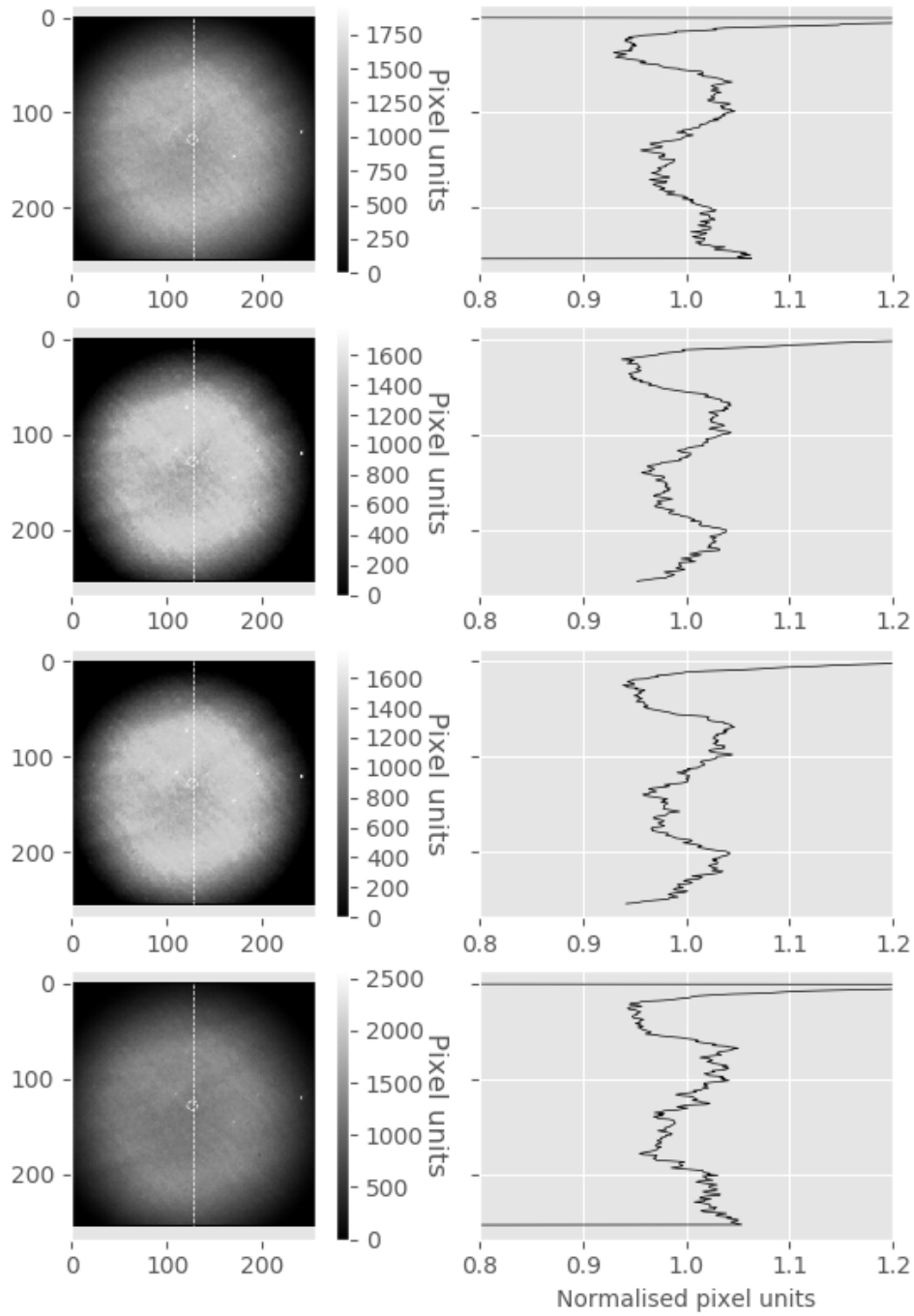


Figure A.1: Select frames from 427.8 nm event 4A on 2016-03-10 in the same format as Figure 4.9. Times were 22:45:47 , 22:45:50 , 22:45:53 , 22:45:56 UT from top to bottom panel.

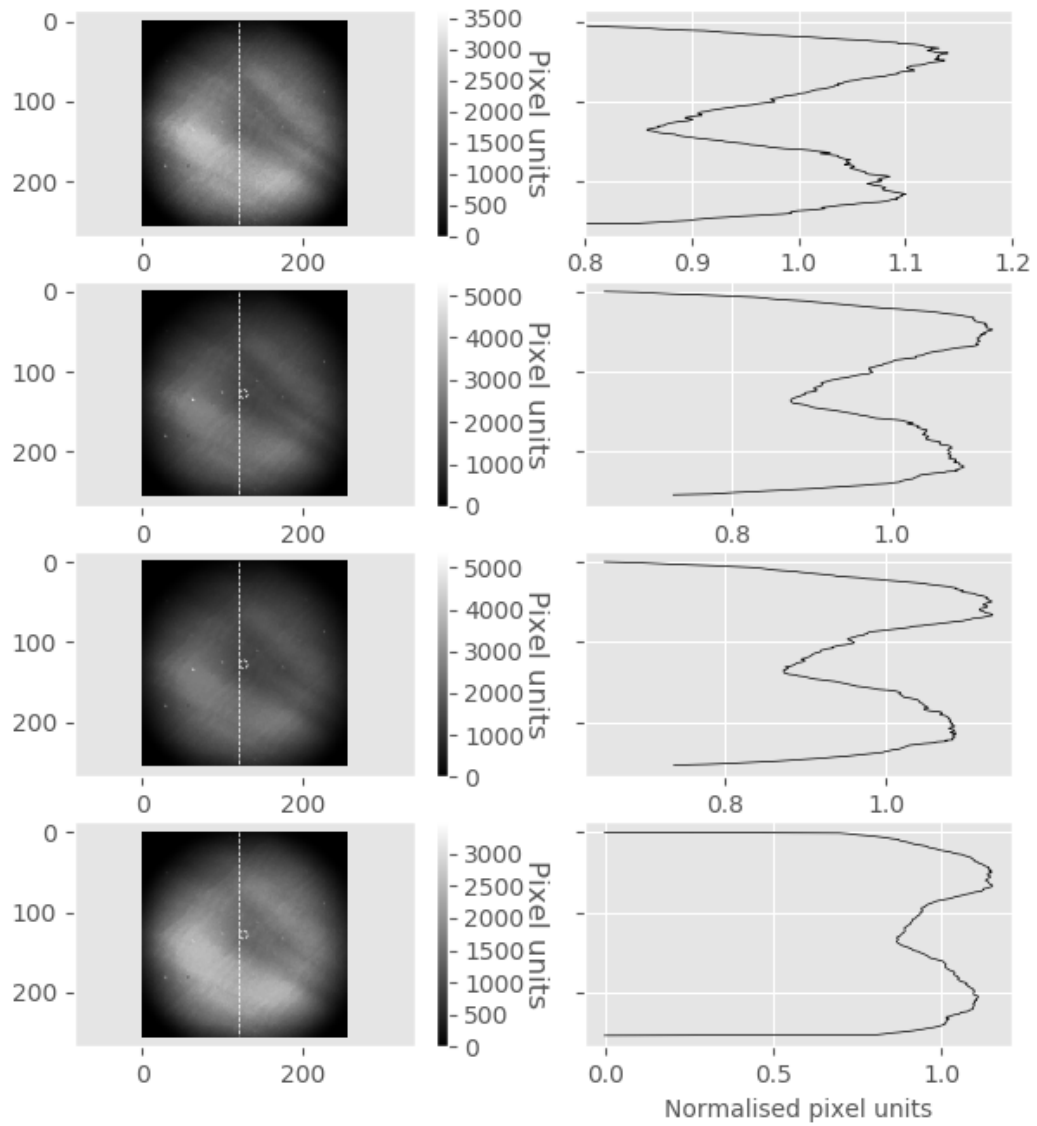


Figure A.2: Select frames from 427.8 nm event 4B on 2016-03-10 in the same format as Figure 4.9. This event was discarded because it was decided that it's highly likely to be gaps in the diffuse aurora, and not black arcs.

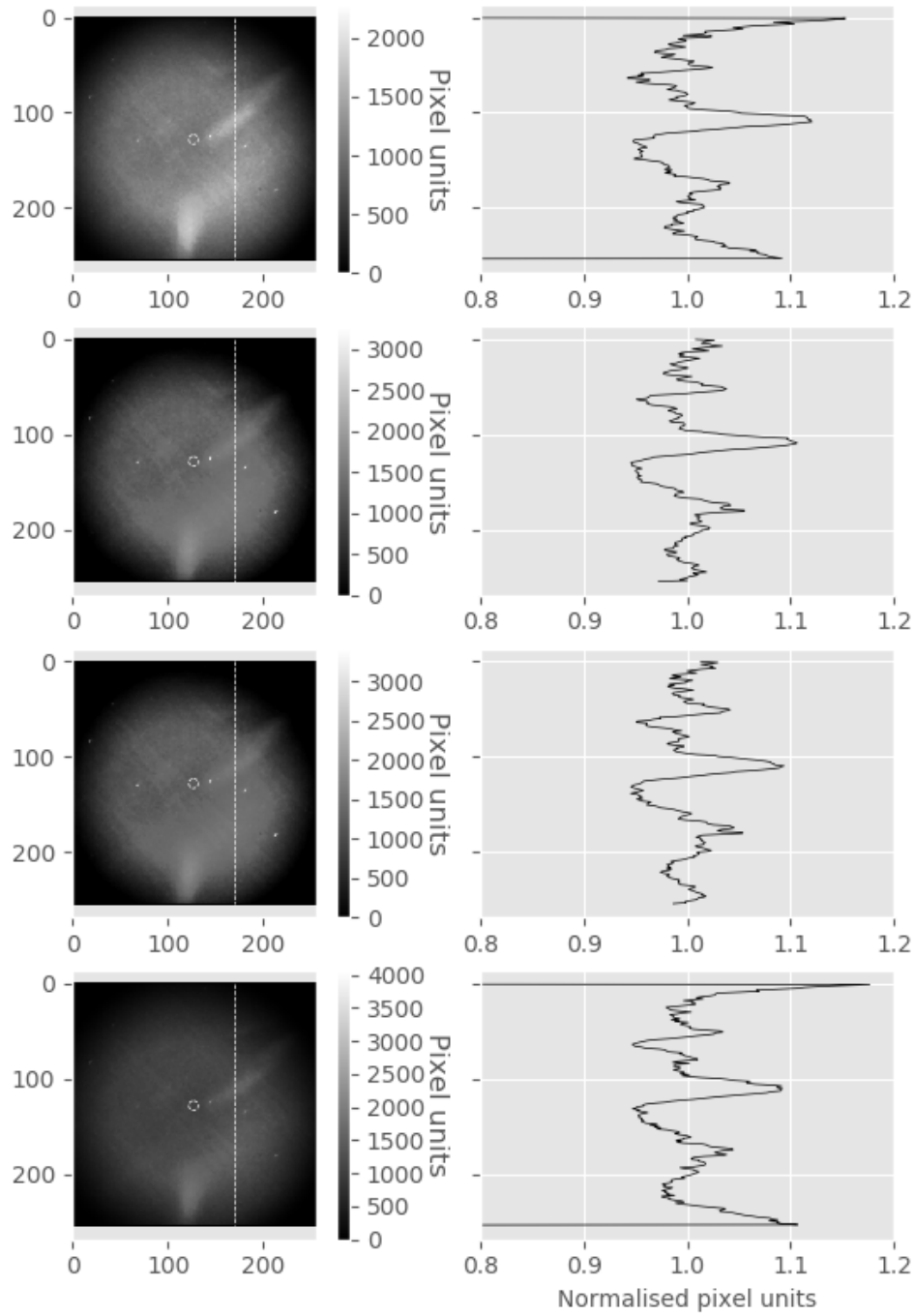


Figure A.3: Select frames from 427.8 nm event 4C on 2016-03-10 in the same format as Figure 4.9. Times were 00:07:29 , 00:07:32 , 00:07:35 , 00:07:38 UT from top to bottom panel.

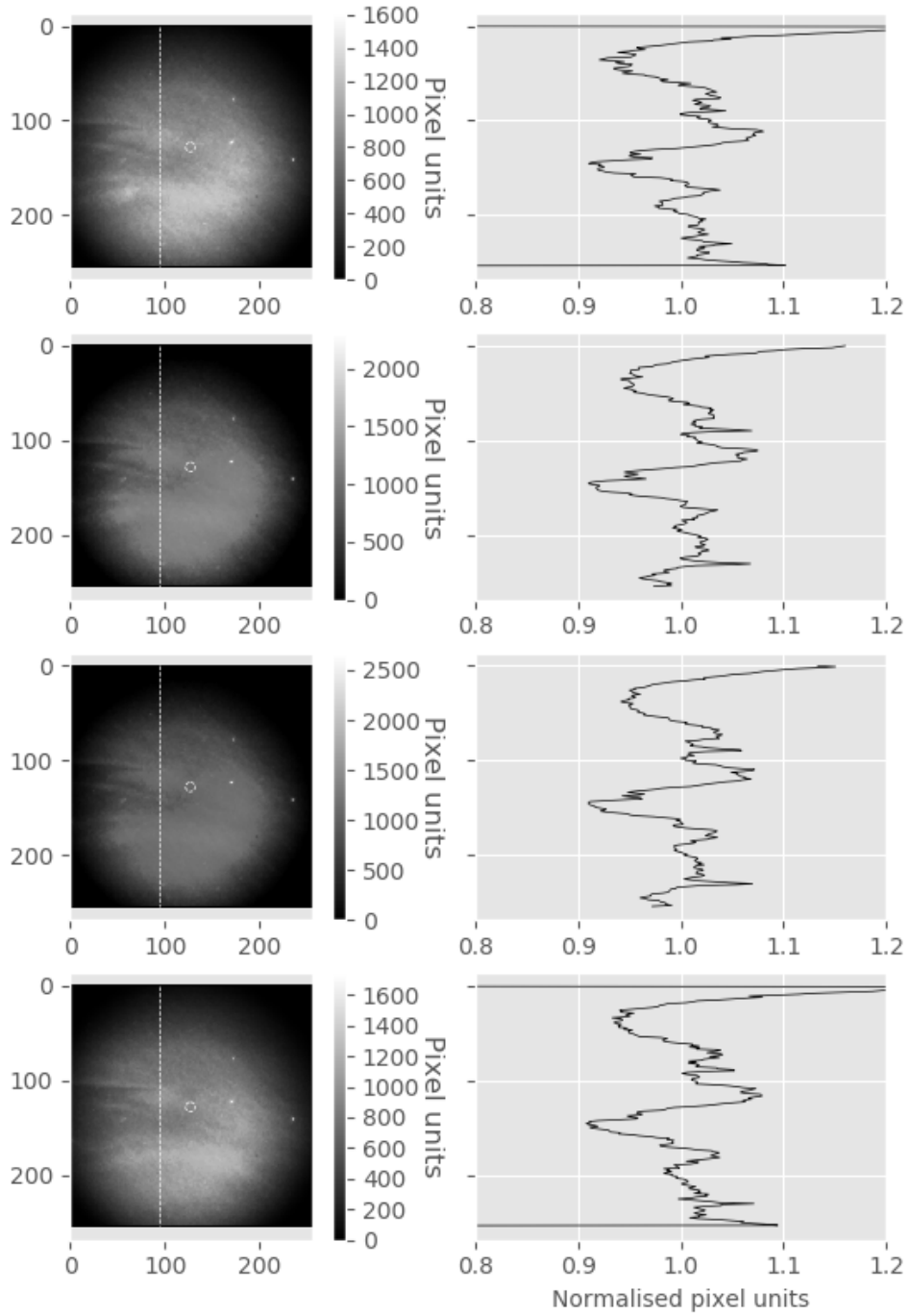


Figure A.4: Select frames from 427.8 nm event 5A on 2016-03-12 in the same format as Figure 4.9. Times were 21:56:01 , 21:56:04 , 21:56:07 , 21:56:10 UT from top to bottom panel.

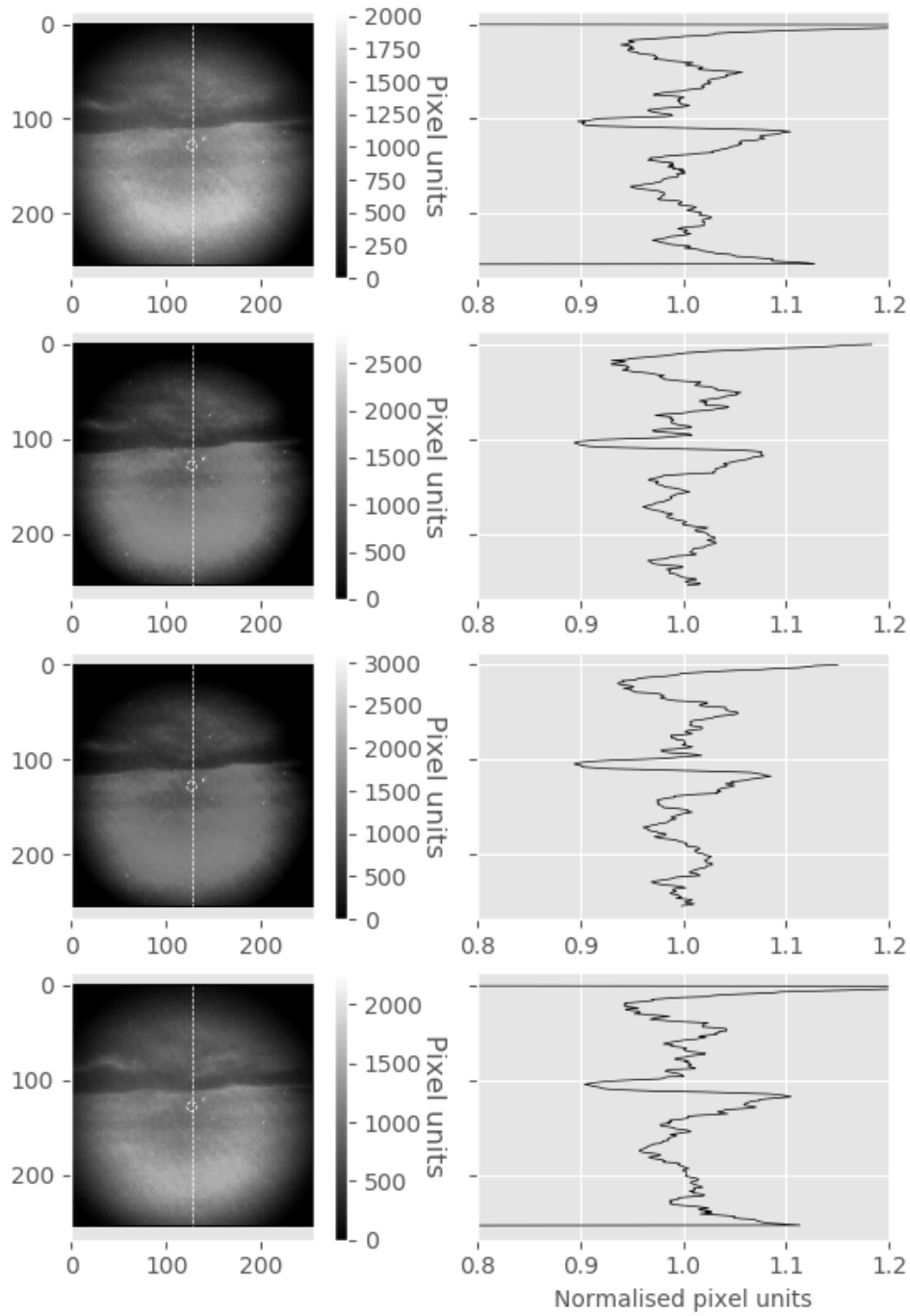


Figure A.5: Select frames from 427.8 nm event 5C on 2016-03-12 in the same format as Figure 4.9. Times were 22:12:04 , 22:12:07 , 22:12:10 , 22:12:13 UT from top to bottom panel.

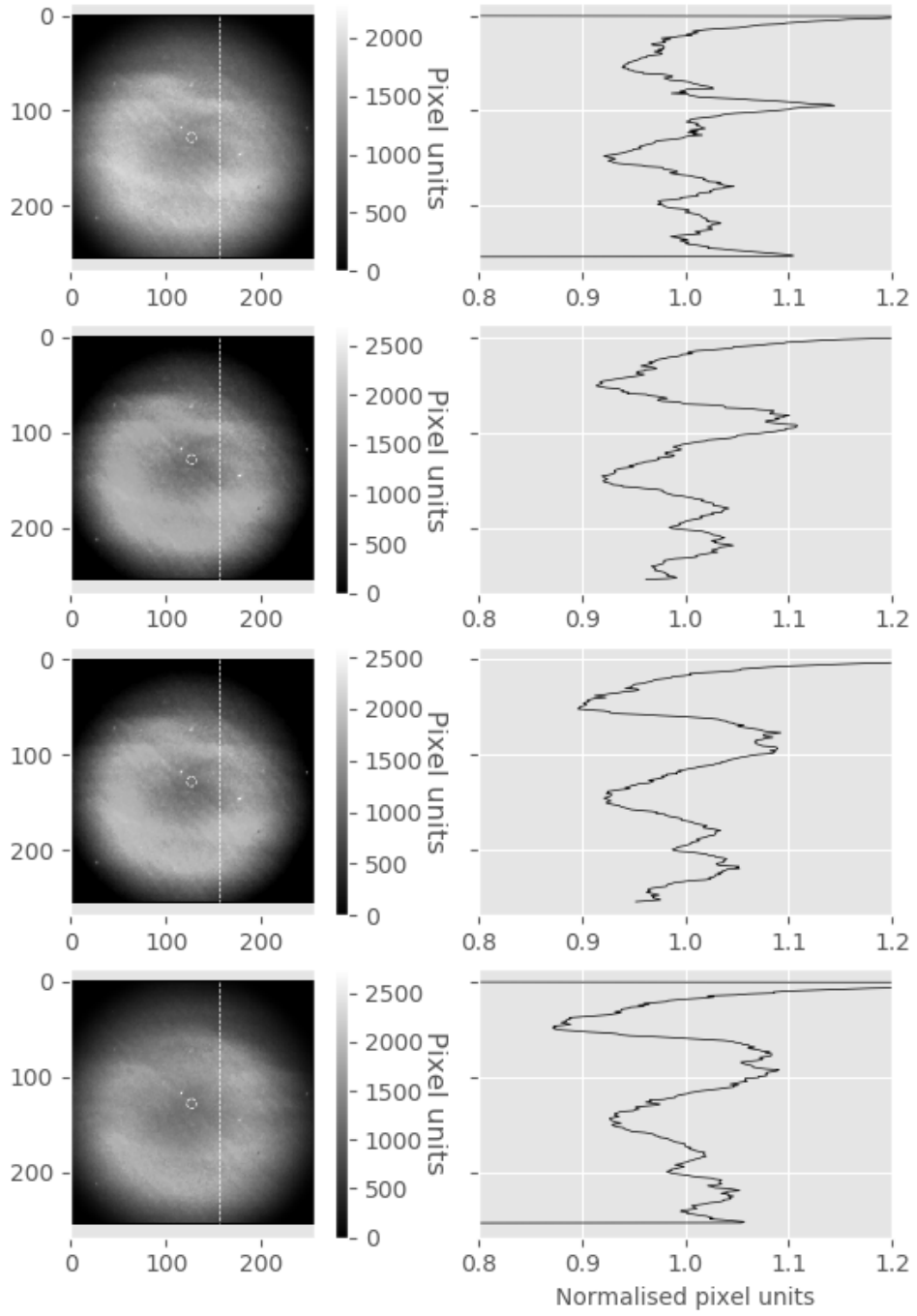


Figure A.6: Select frames from 427.8 nm event 5D on 2016-03-12 in the same format as Figure 4.9. Times were 22:32:19 , 22:32:22 , 22:32:25 , 22:32:28 UT from top to bottom panel.

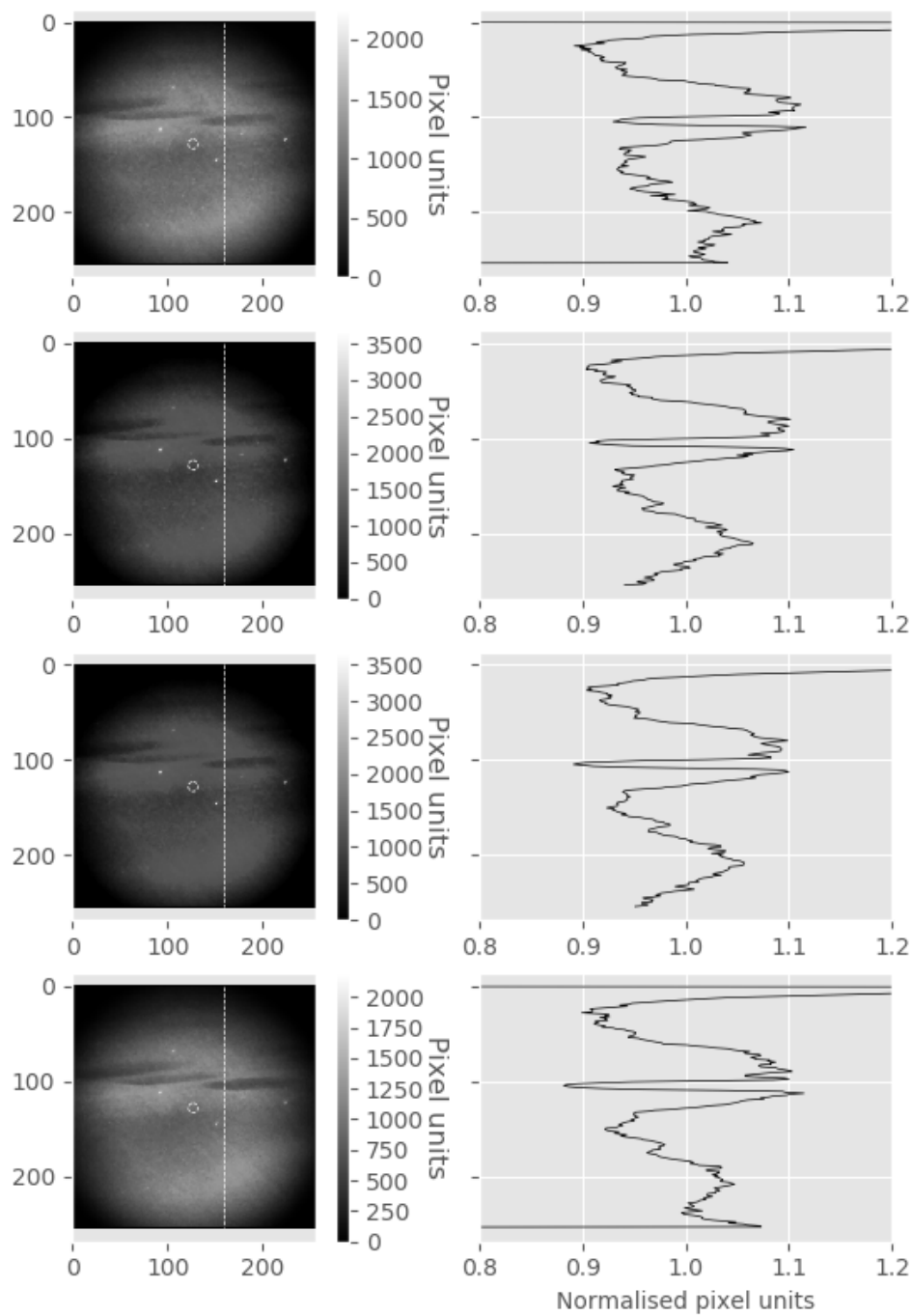


Figure A.7: Select frames from 427.8 nm event 5E on 2016-03-12 in the same format as Figure 4.9. Times were 22:52:34 , 22:52:37 , 22:52:40 , 22:52:43 UT from top to bottom panel.

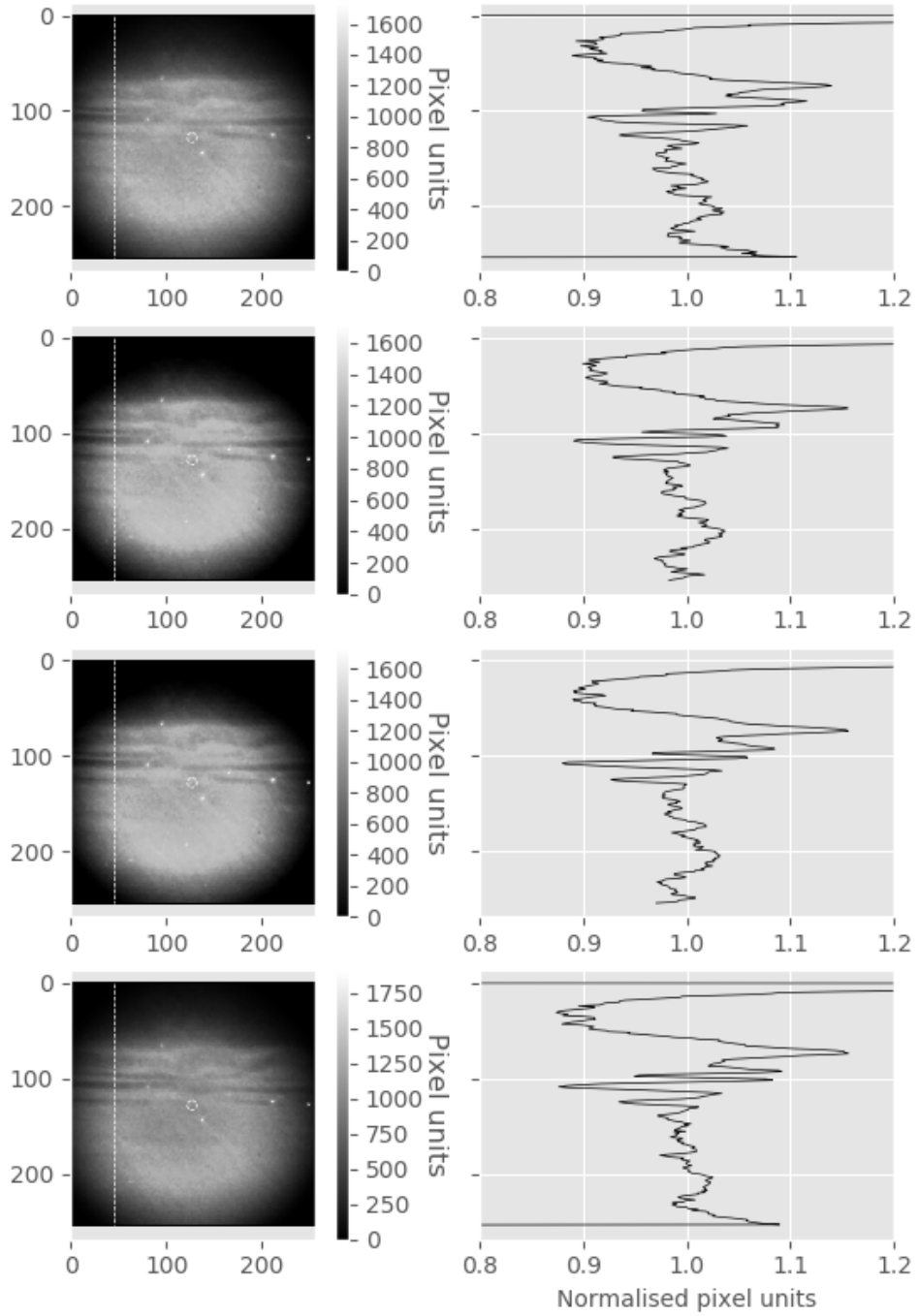


Figure A.8: Select frames from 427.8 nm event 5G on 2016-03-12 in the same format as Figure 4.9. Times were 23:03:13 , 23:03:16 , 23:03:19 , 23:03:22 UT from top to bottom panel.

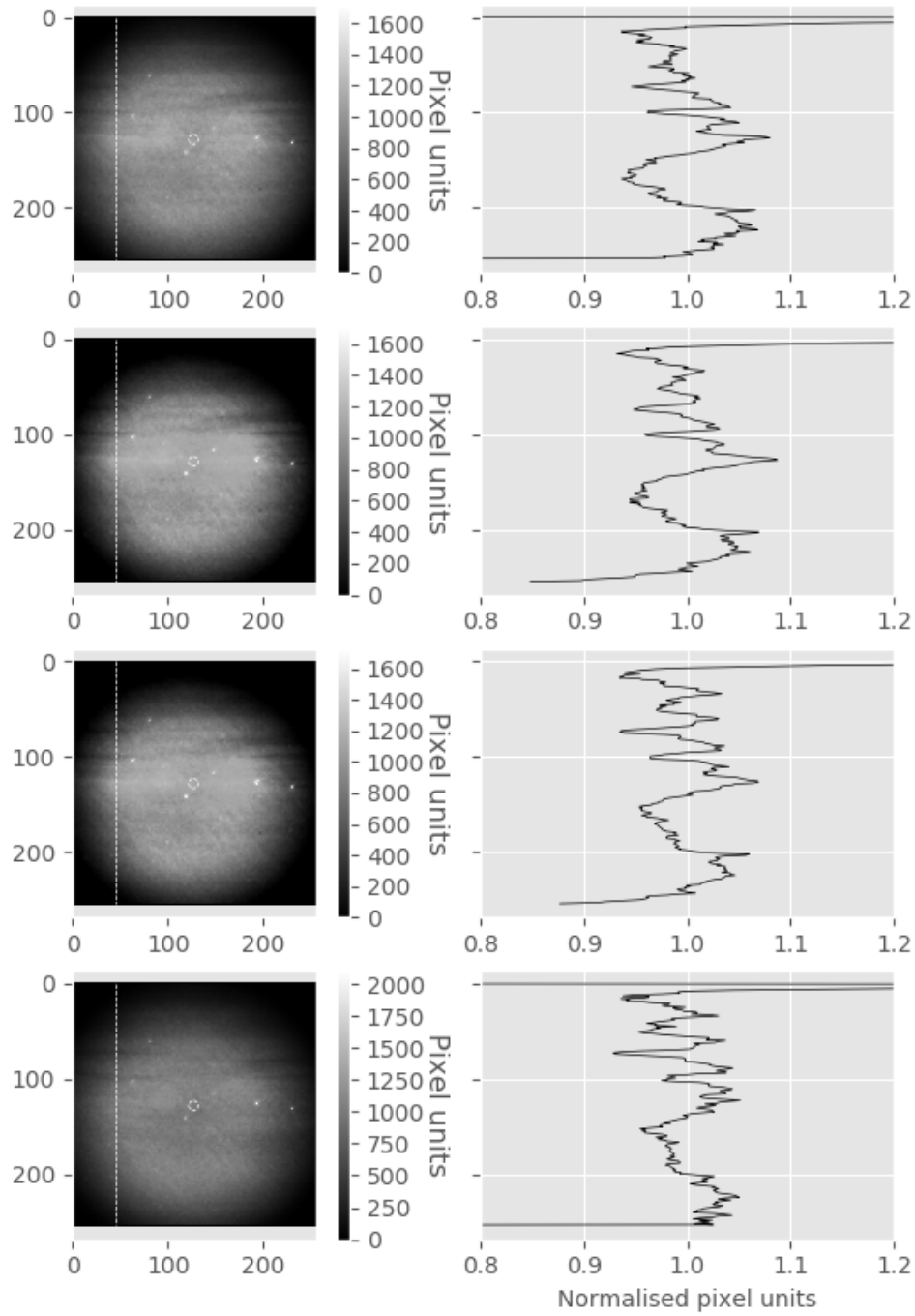


Figure A.9: Select frames from 427.8 nm event 5I on 2016-03-12 in the same format as Figure 4.9. Times were 23:18:28 , 23:18:31 , 23:18:34 , 23:18:37 UT from top to bottom panel.

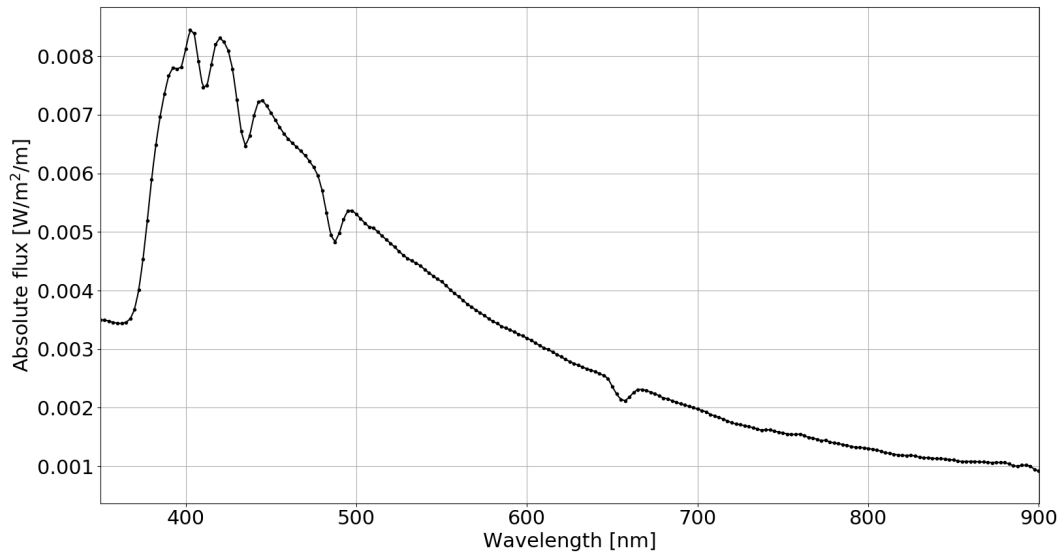


Figure A.10: The spectral photon flux range in nanometers for UMa Beta, taken from the Pulkovo spectrophotometric catalog [Alekseeva *et al.*, 1996].

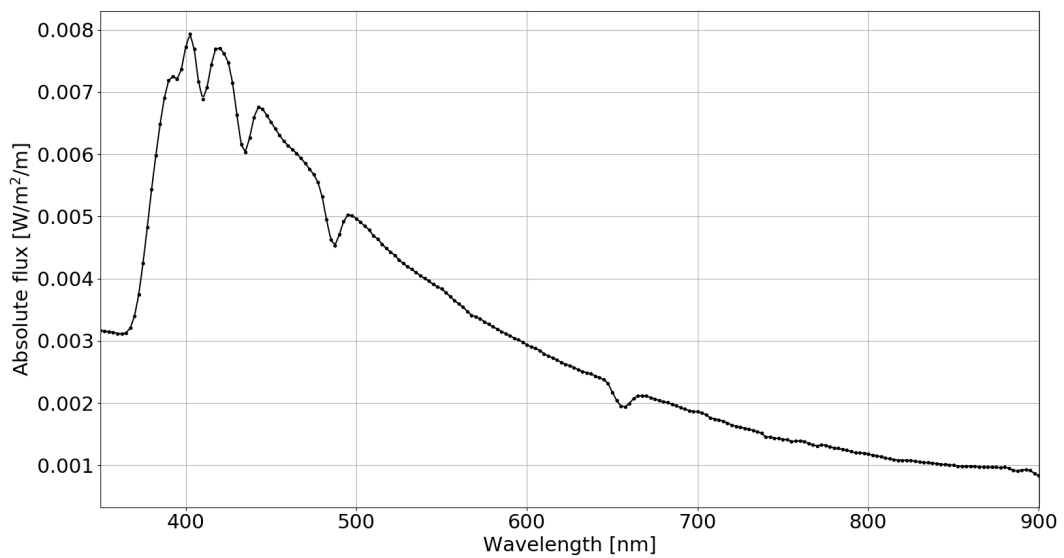


Figure A.11: The spectral photon flux range in nanometers for UMa Gamma, taken from the Pulkovo spectrophotometric catalog [Alekseeva *et al.*, 1996].

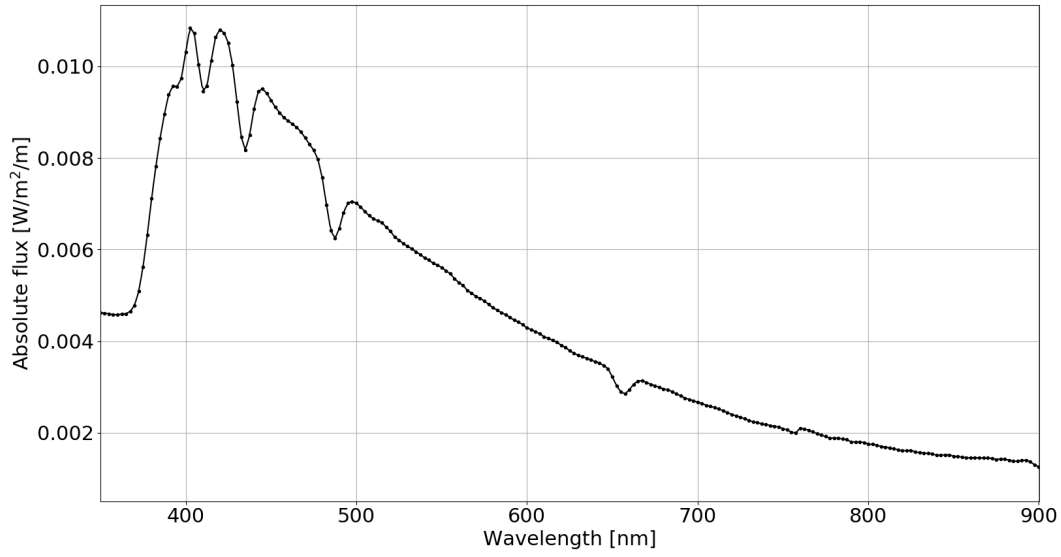


Figure A.12: The spectral photon flux range in nanometers for UMa Zeta, taken from the Pulkovo spectrophotometric catalog [Alekseeva et al., 1996].

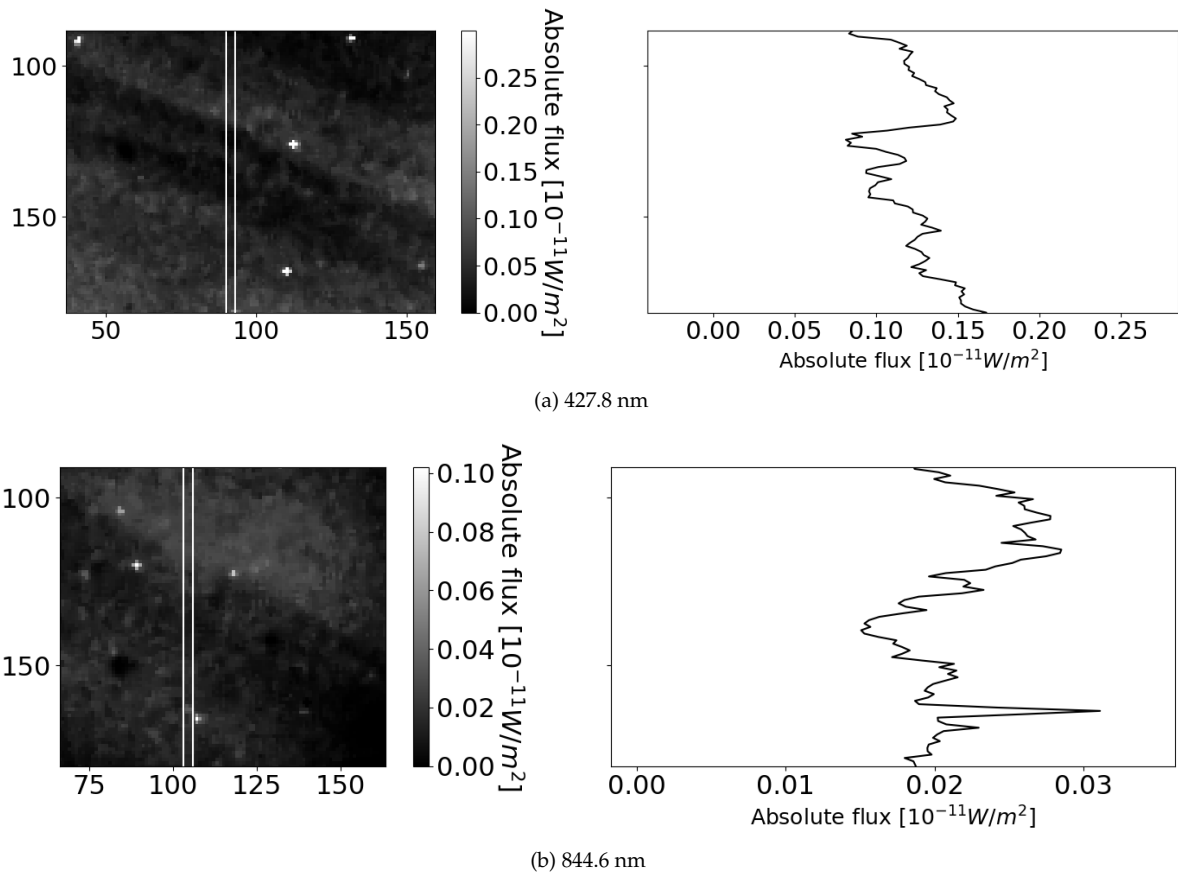


Figure A.13: Event 2A intensities for both 427.8 nm and 844.6 nm with their respective brightness profiles averaged between the solid white lines.

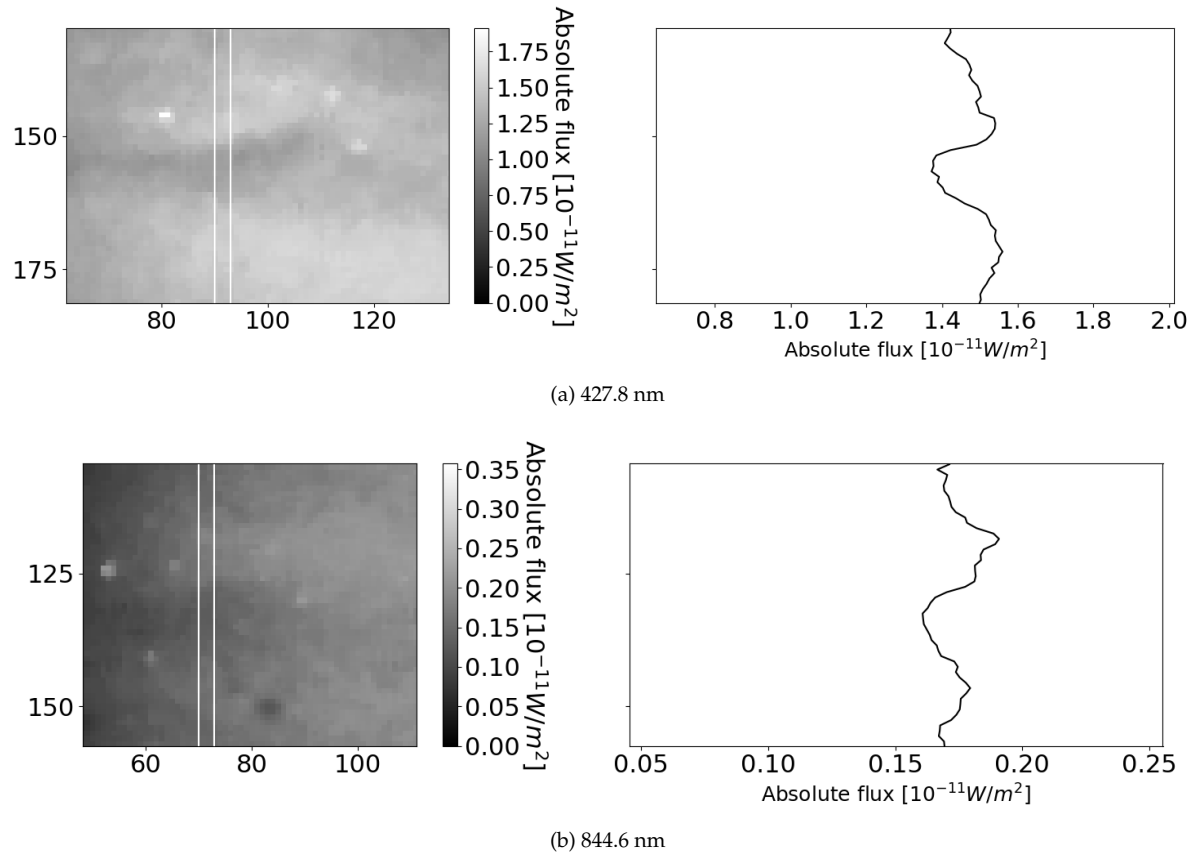


Figure A.14: Event 2B intensities for both 427.8 nm and 844.6 nm with their respective brightness profiles averaged between the solid white lines.

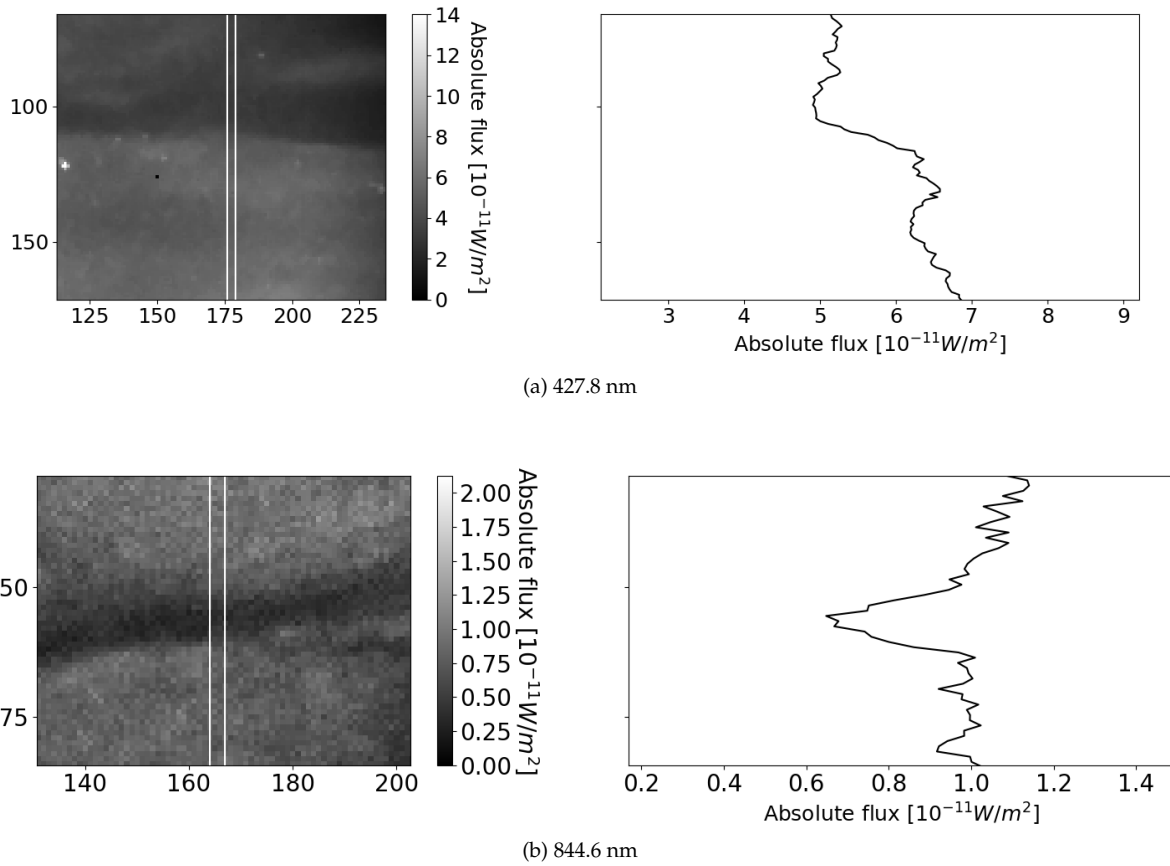


Figure A.15: Event 5C intensities for both 427.8 nm and 844.6 nm with their respective brightness profiles averaged between the solid white lines.

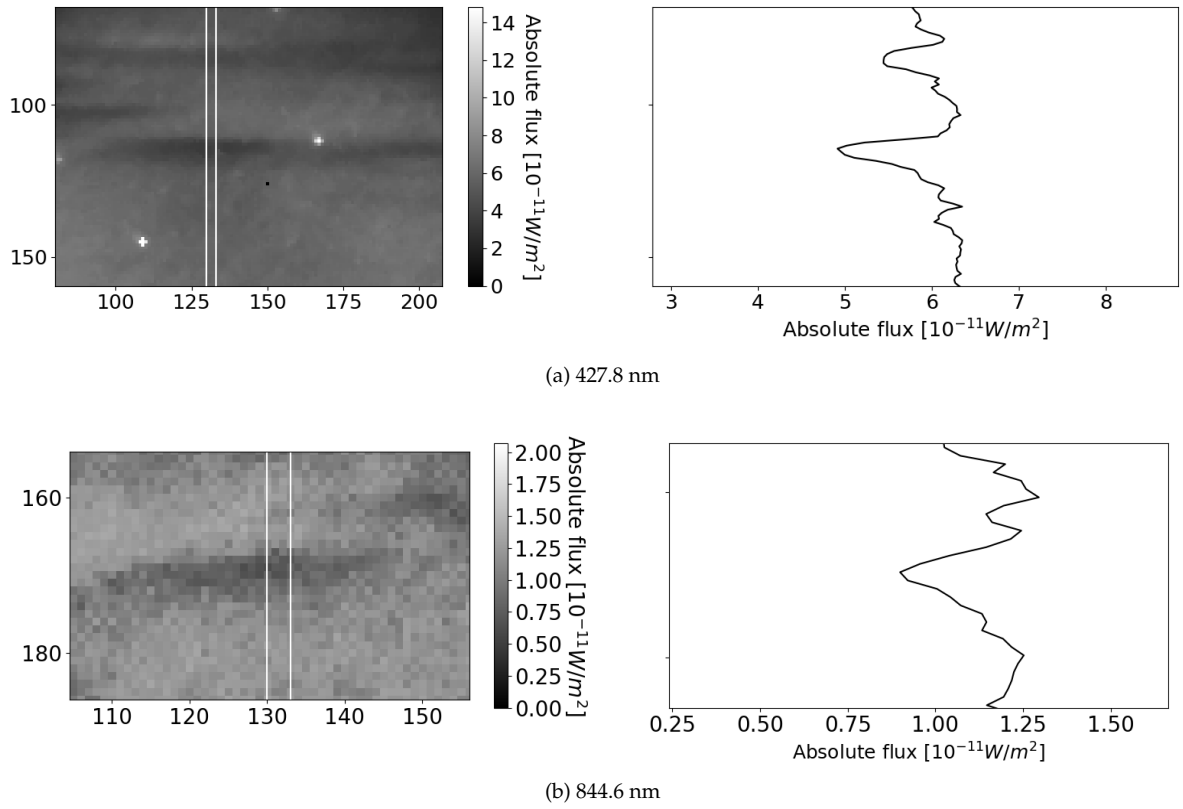


Figure A.16: Event 5F intensities for both 427.8 nm and 844.6 nm with their respective brightness profiles averaged between the solid white lines.

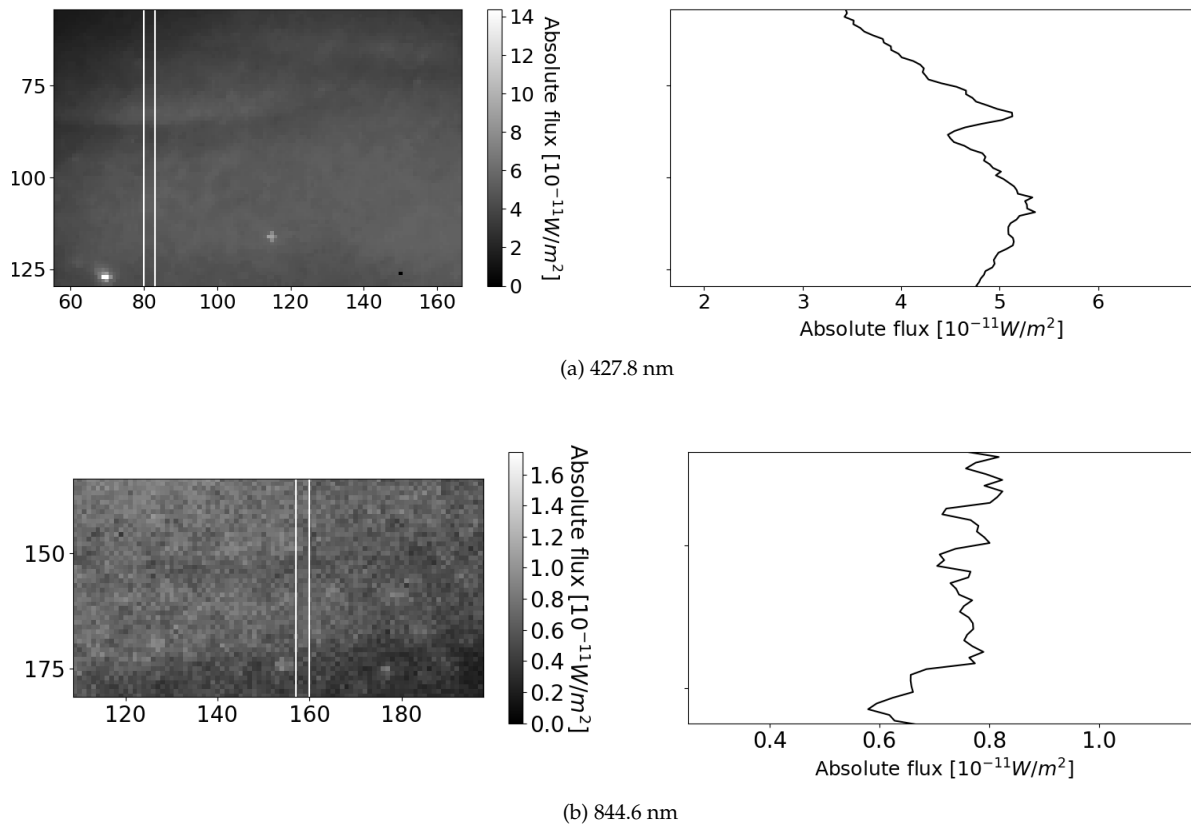


Figure A.17: Event 5J intensities for both 427.8 nm and 844.6 nm with their respective brightness profiles averaged between the solid white lines.

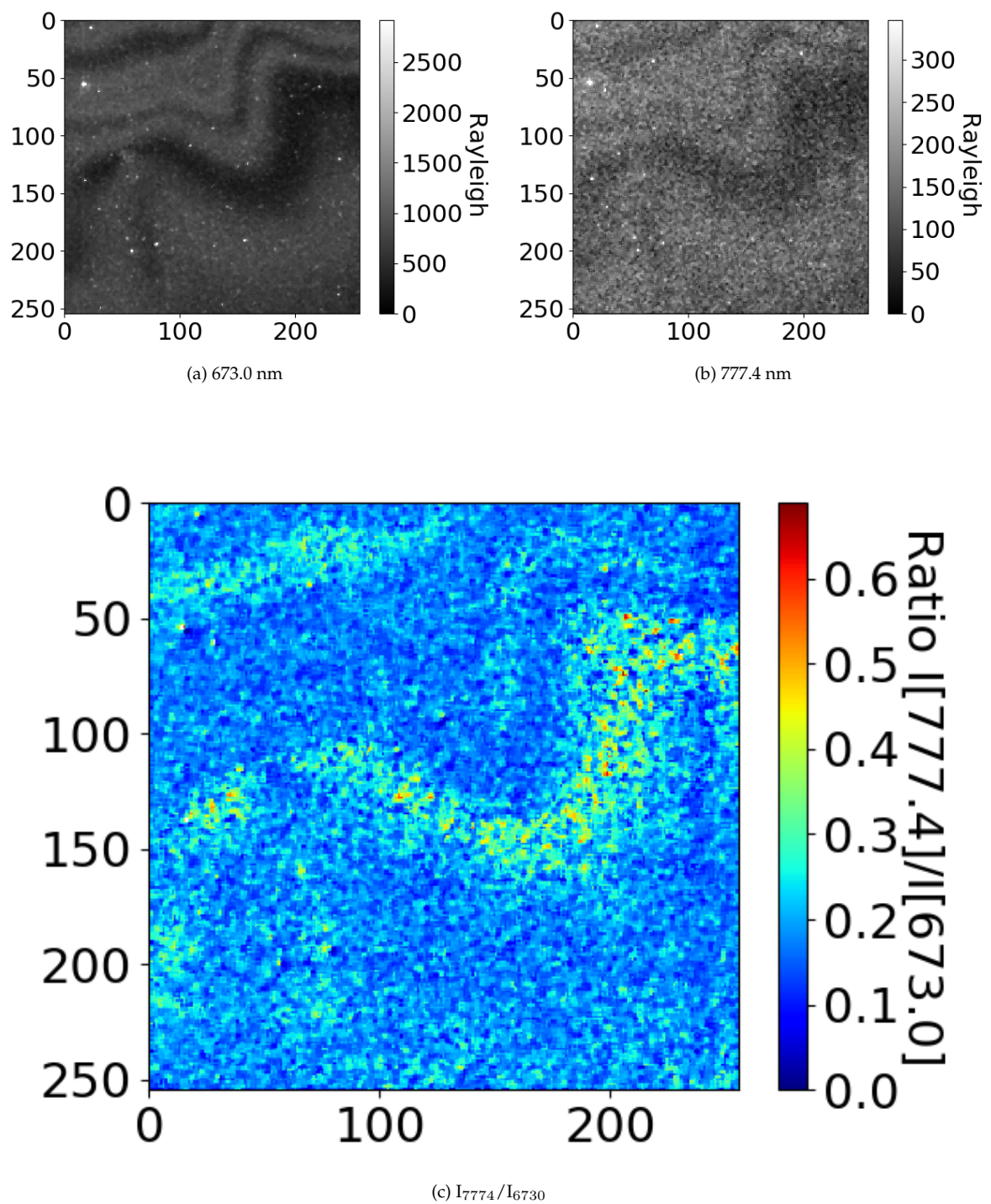


Figure A.18: Images from event 1B given in Rayleighs with filters 673.0 nm, 777.4 nm, and their ratio.

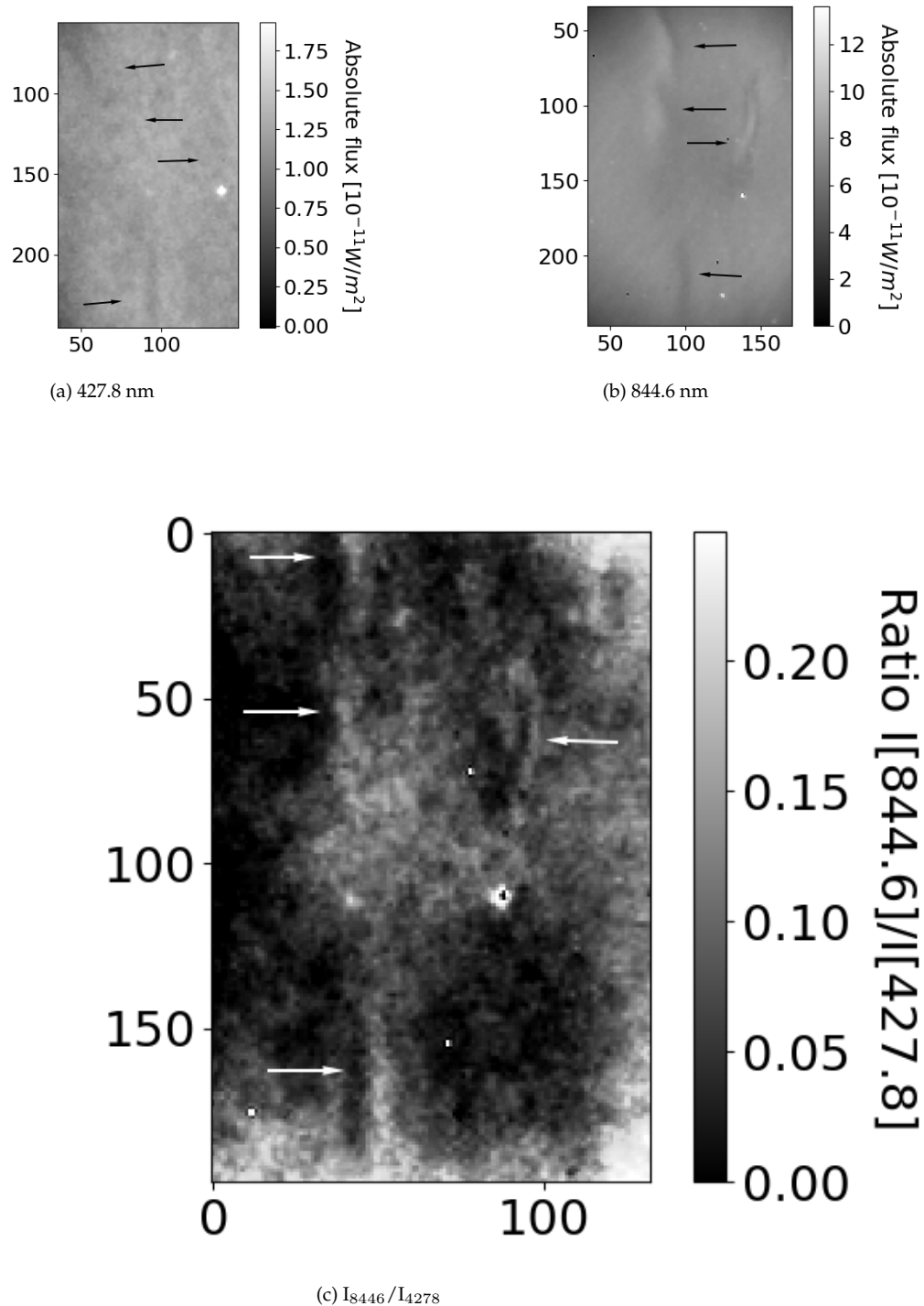


Figure A.19: Images from event 5B given in W/m^2 with filters 427.8 nm, 844.6 nm, and their ratio. Four anti-black auroras are visible, three at the top of the image, and the other close to the bottom indicated by arrows.

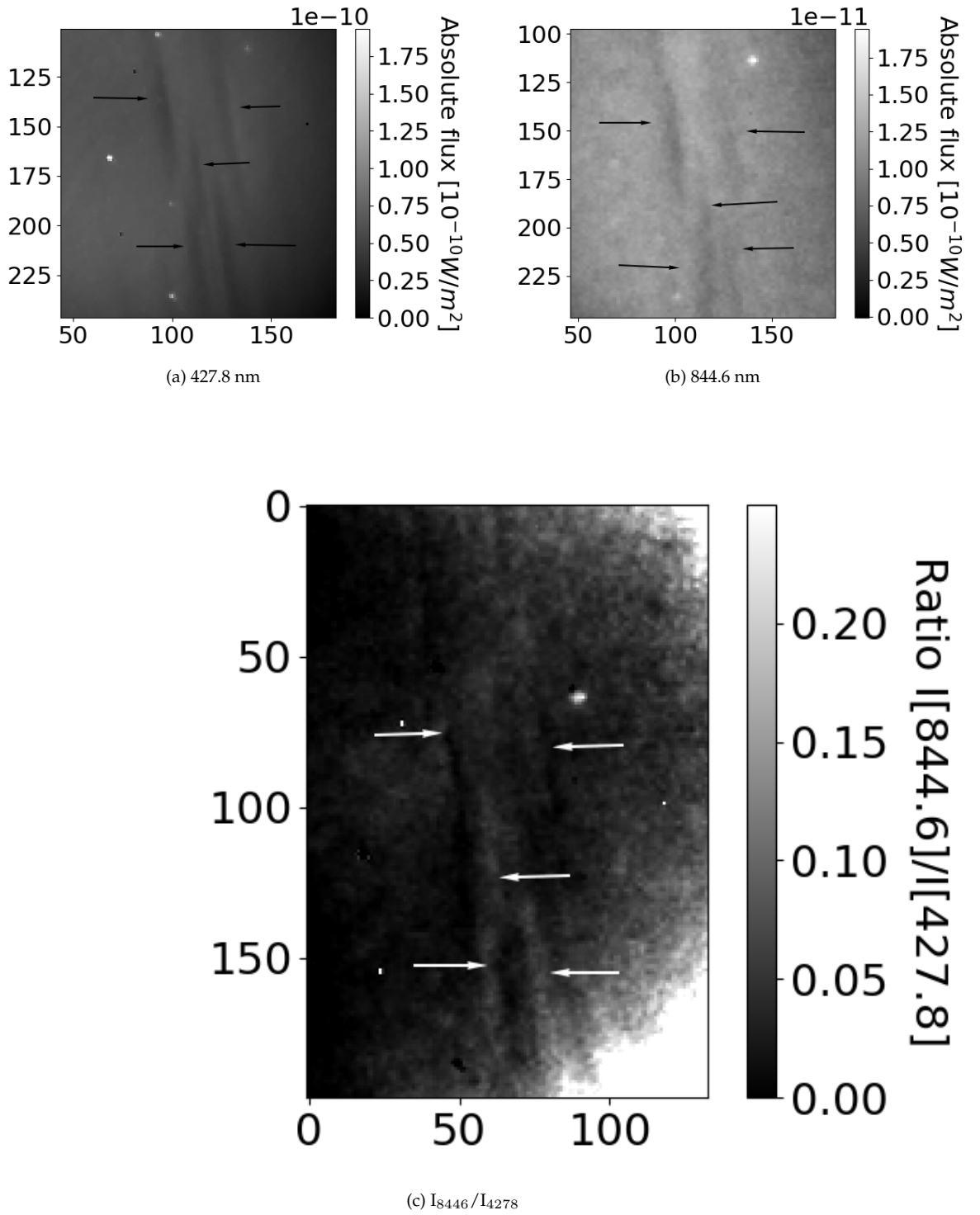


Figure A.20: Images from event 5F given in W/m^2 with filters 427.8 nm, 844.6 nm, and their ratio. A cluster of four arc segments are seen here and on the right-hand side an anti-black aurora is visible, indicated by arrows.

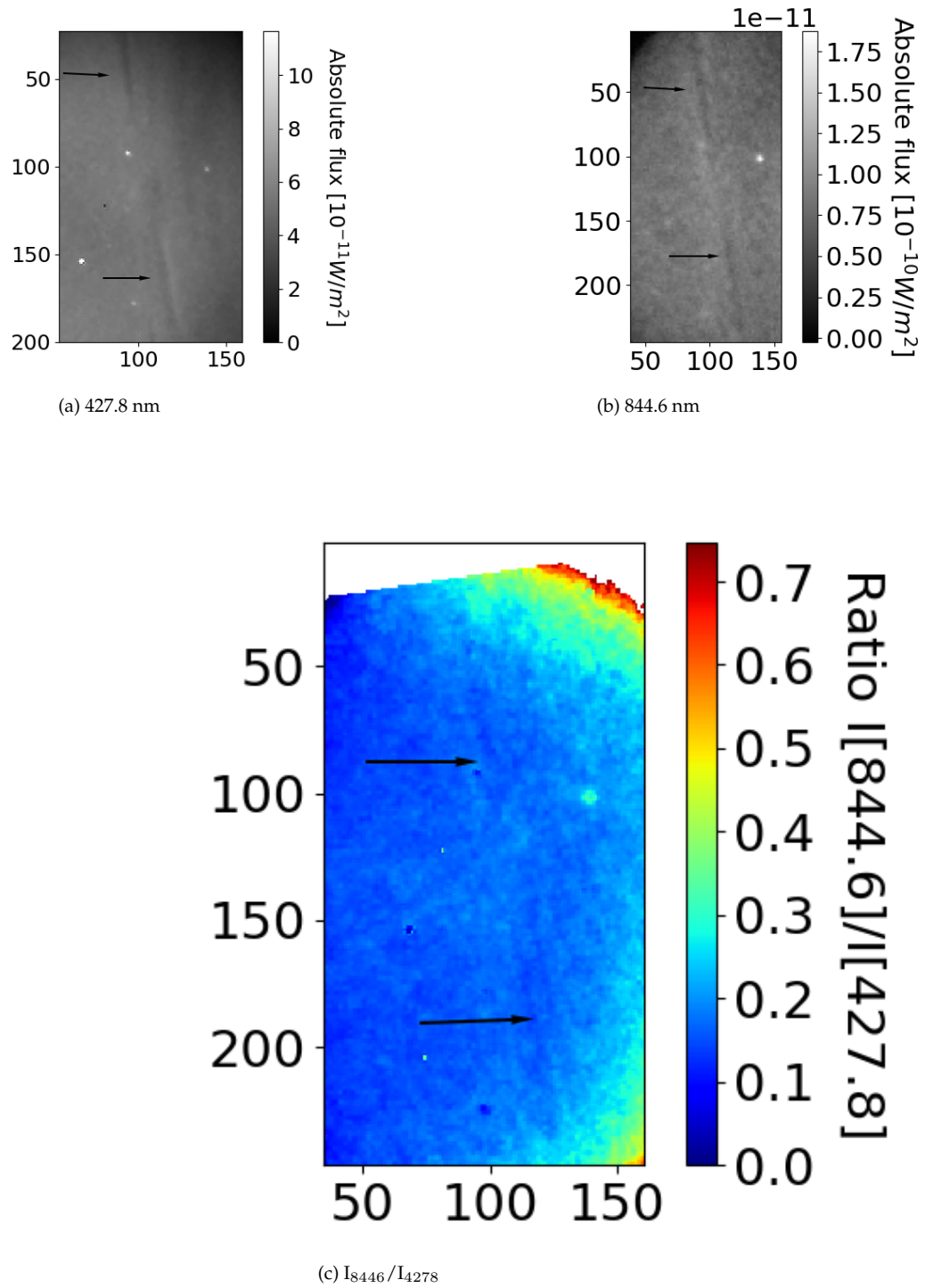


Figure A.21: Images from event 5H given in W/m^2 with filters 427.8 nm, 844.6 nm, and their ratio.

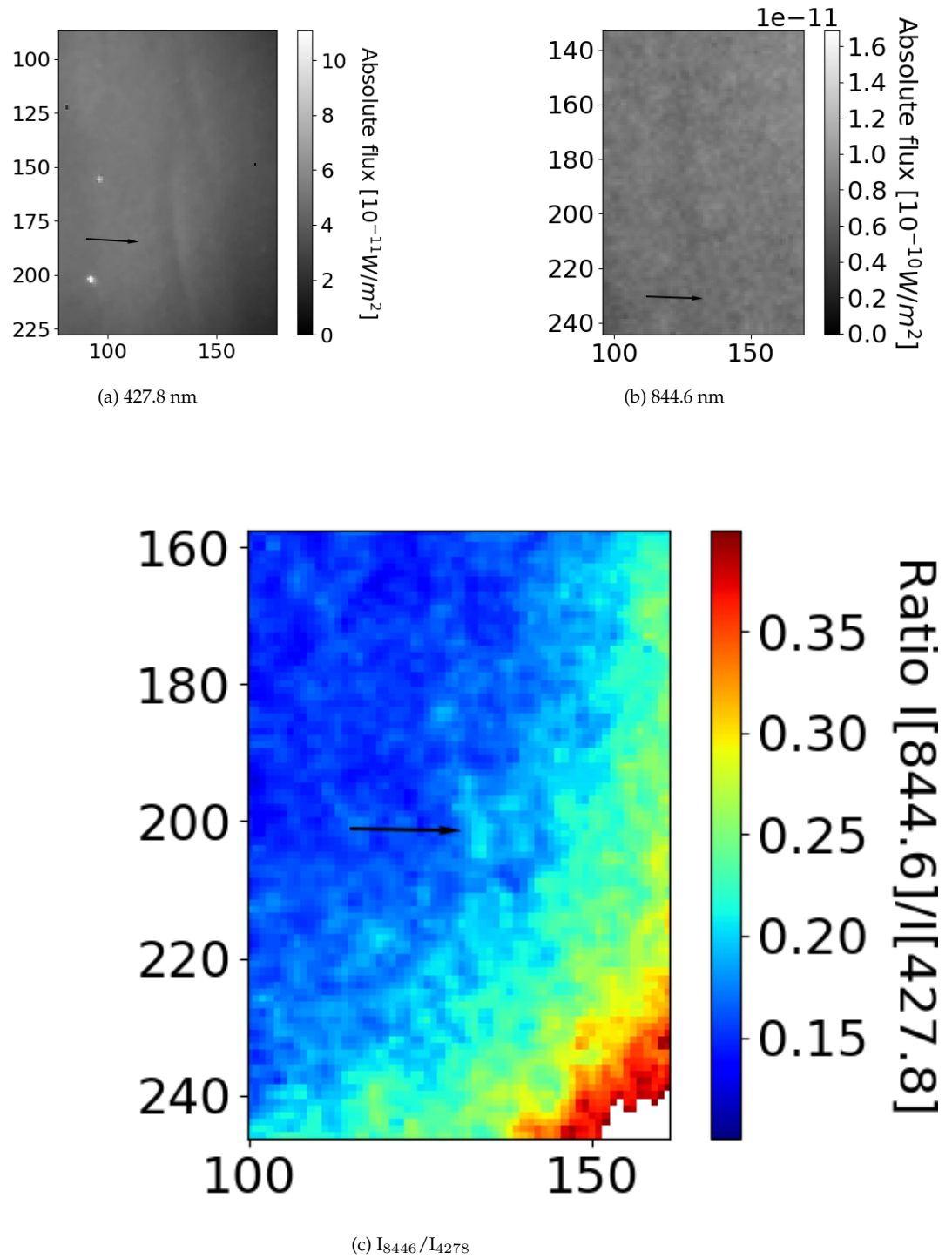


Figure A.22: Images from event 5J given in W/m^2 with filters 427.8 nm, 844.6 nm, and their ratio.

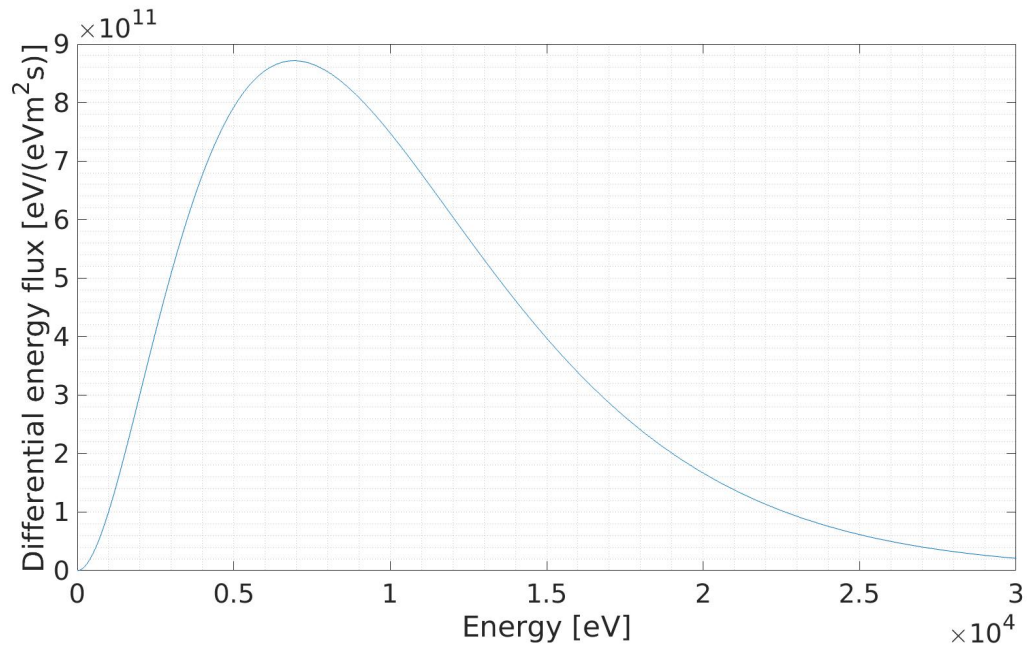


Figure A.23: Energy [eV] versus differential number flux [$\text{eV}/(\text{eVm}^2\text{s})$] for event 1B. The characteristic energy is 7.0 keV.

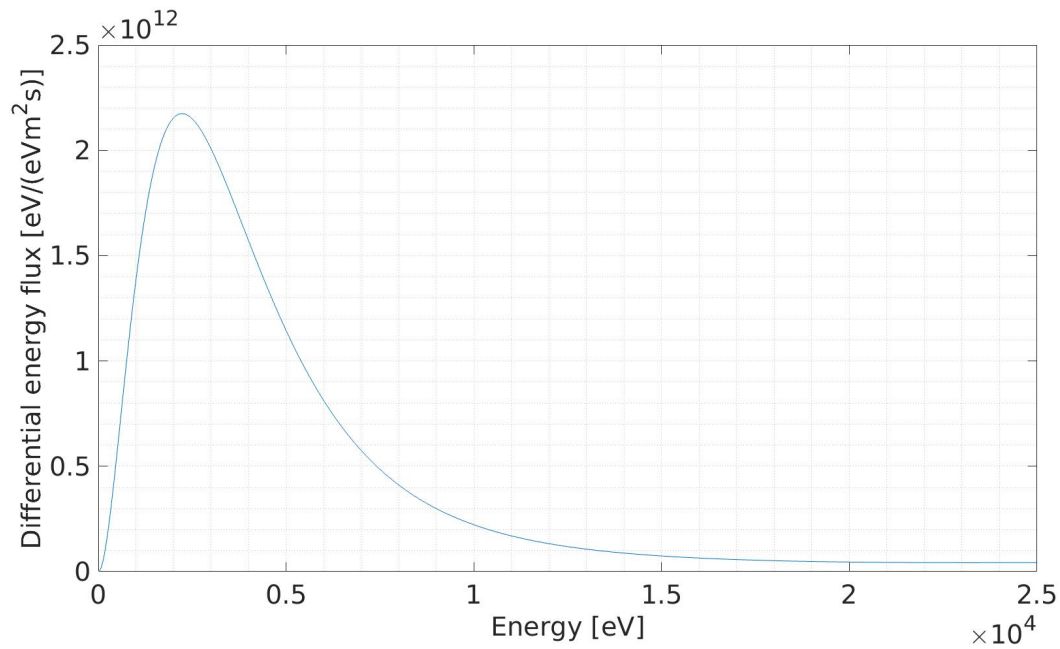


Figure A.24: Energy [eV] versus differential number flux [$\text{eV}/(\text{eVm}^2\text{s})$] for event 1C. The characteristic energy is 2.4 keV.

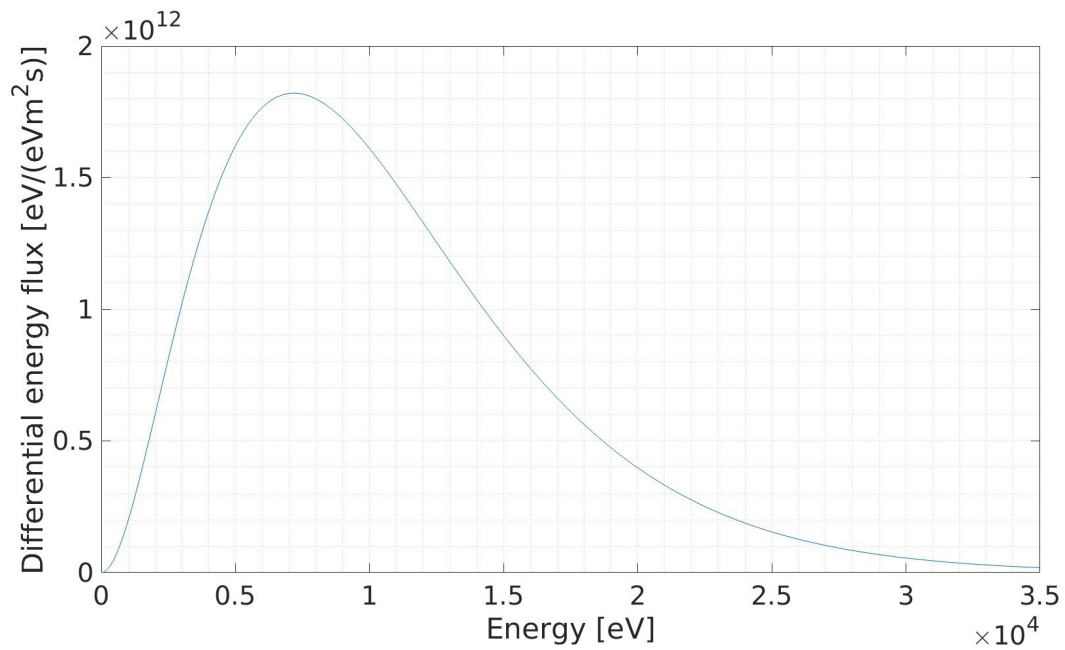


Figure A.25: Energy [eV] versus differential number flux [eV/(eVm²s)] for event 5B. The characteristic energy is 7.5 keV.

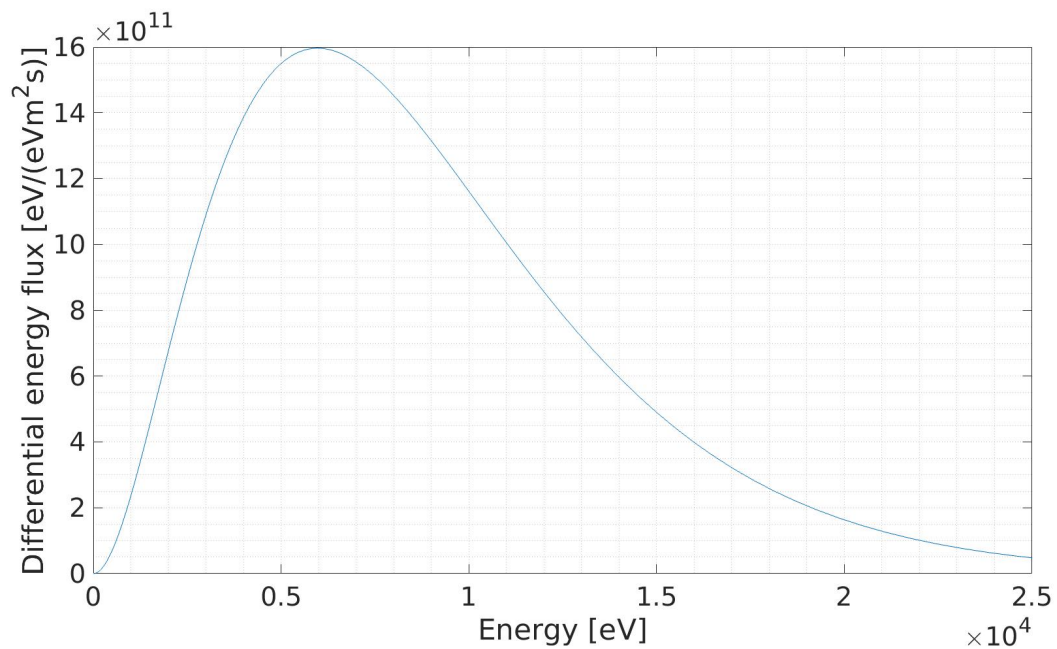


Figure A.26: Energy [eV] versus differential number flux [eV/(eVm²s)] for event 5F. The characteristic energy is 6.0 keV.

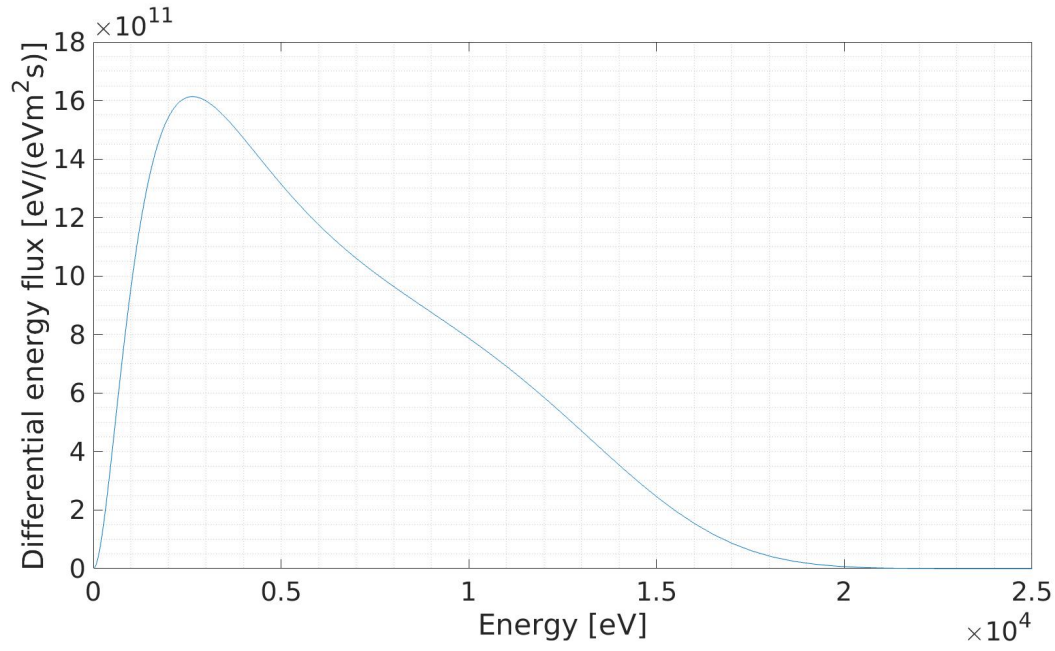


Figure A.27: Energy [eV] versus differential number flux [$\text{eV}/(\text{eVm}^2\text{s})$] for event 5H. The characteristic energy is 2.8 keV.

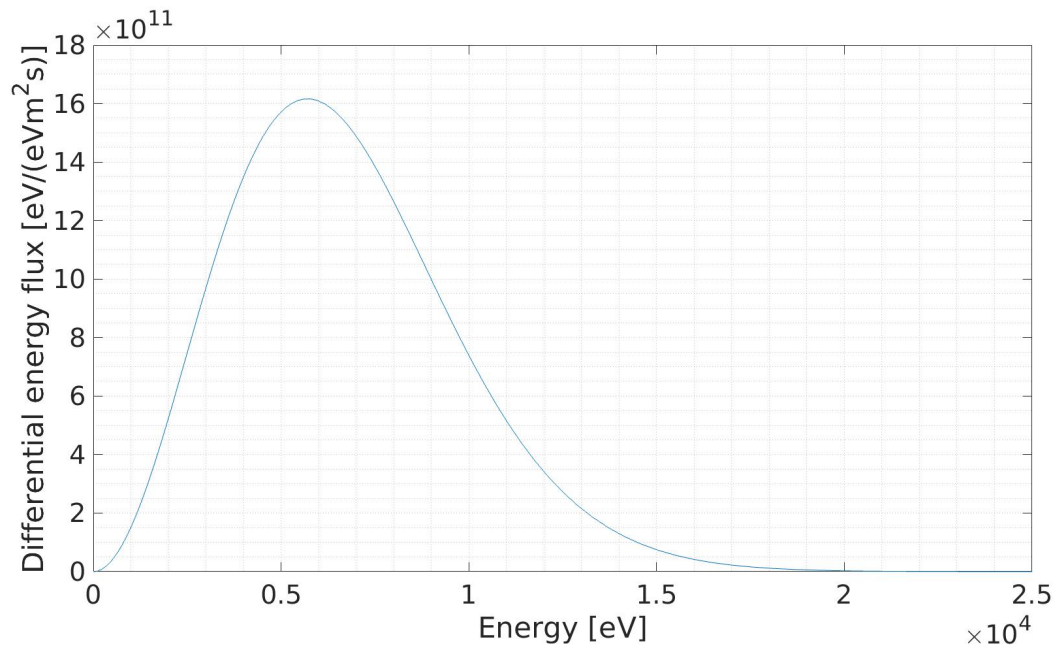


Figure A.28: Energy [eV] versus differential number flux [$\text{eV}/(\text{eVm}^2\text{s})$] for event 5J. The characteristic energy is 5.8 keV.

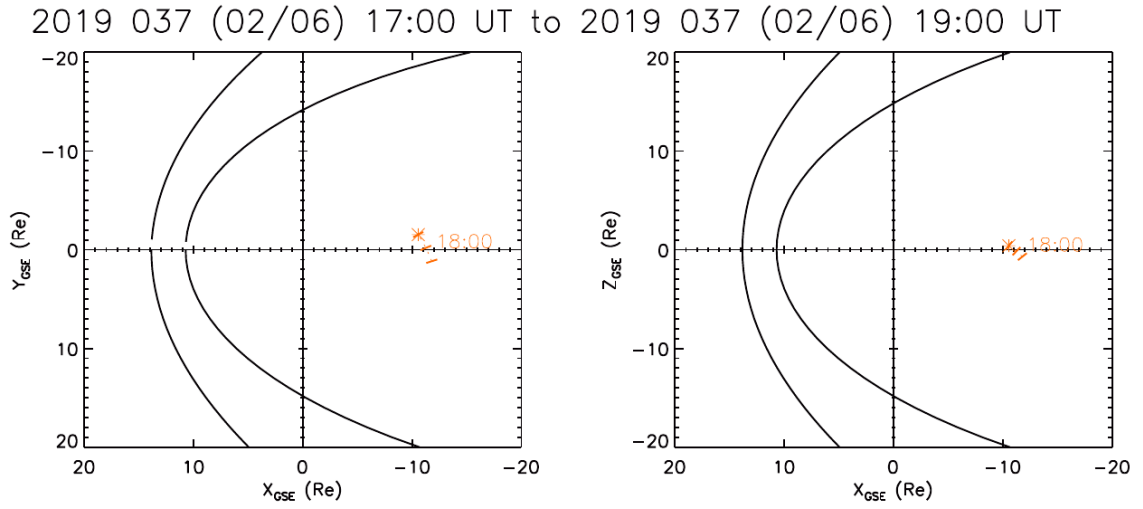


Figure A.29: Geotail orbit during 2019-02-06 from 17:00 - 19:00 UT. The X, Y, and Z axes in GSE coordinates are shown, The distance is measured in Earth radii. The red asterisk represents the end time.

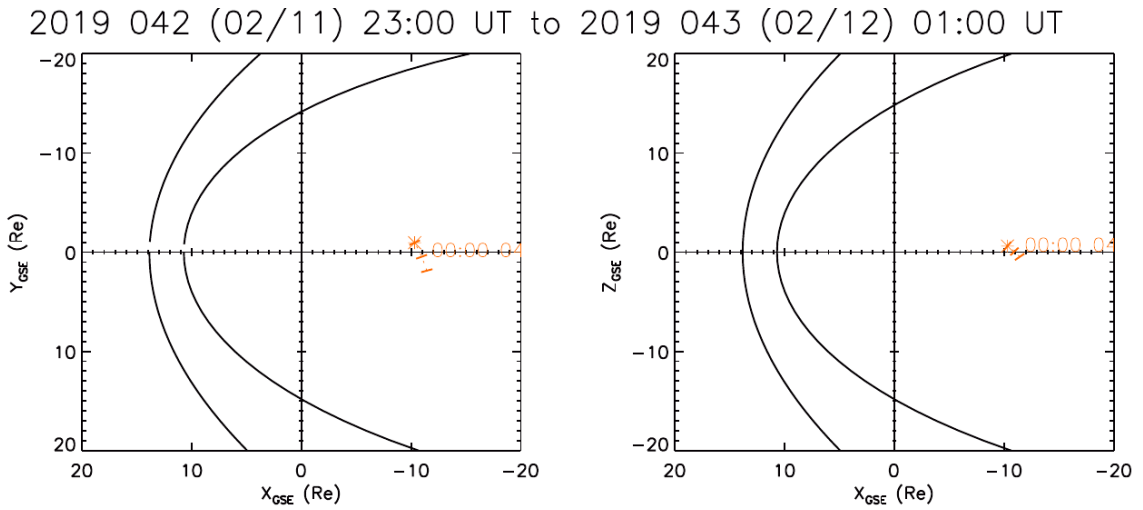


Figure A.30: Geotail orbit during 2019-02-11/12 from 23:00 - 01:00 UT. The X, Y, and Z axes in GSE coordinates are shown, The distance is measured in Earth radii. The red asterisk represents the end time.

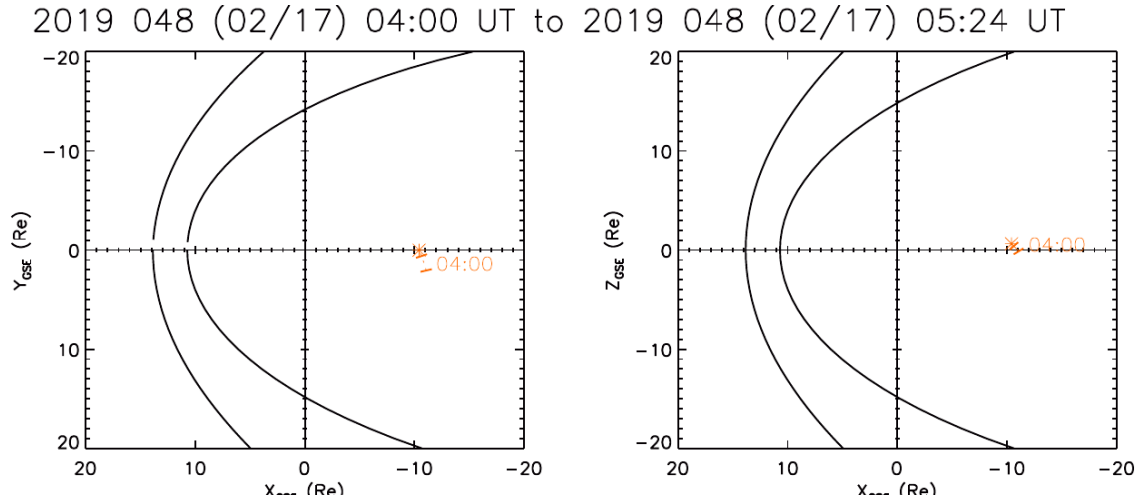


Figure A.31: Geotail orbit during 2019-02-17 from 04:00 - 05:30 UT. The X, Y, and Z axes in GSE coordinates are shown, The distance is measured in Earth radii. The red asterisk represents the end time.

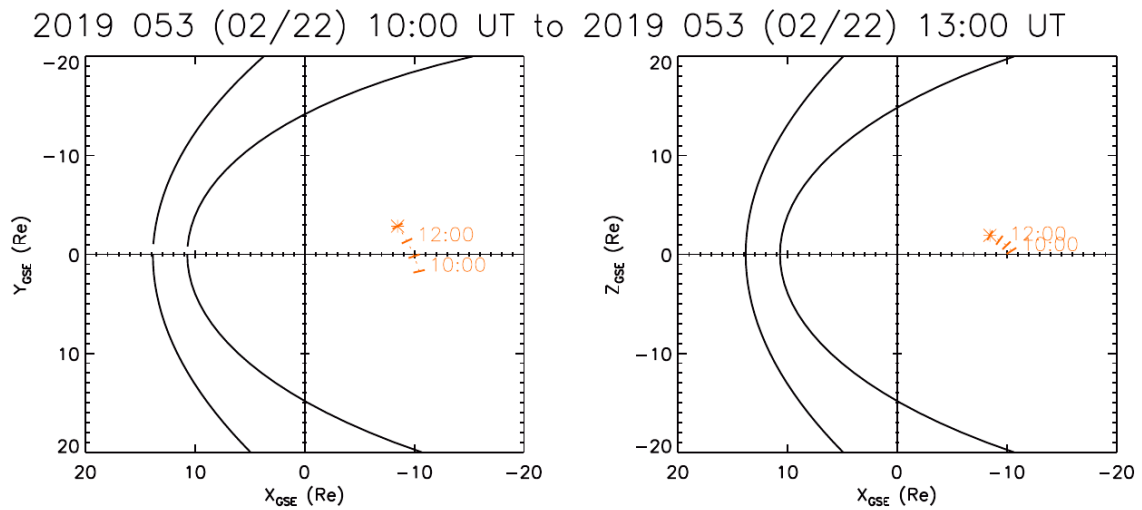


Figure A.32: Geotail orbit during 2019-02-22 from 10:00 - 13:00 UT. The X, Y, and Z axes in GSE coordinates are shown, The distance is measured in Earth radii. The red asterisk represents the end time.

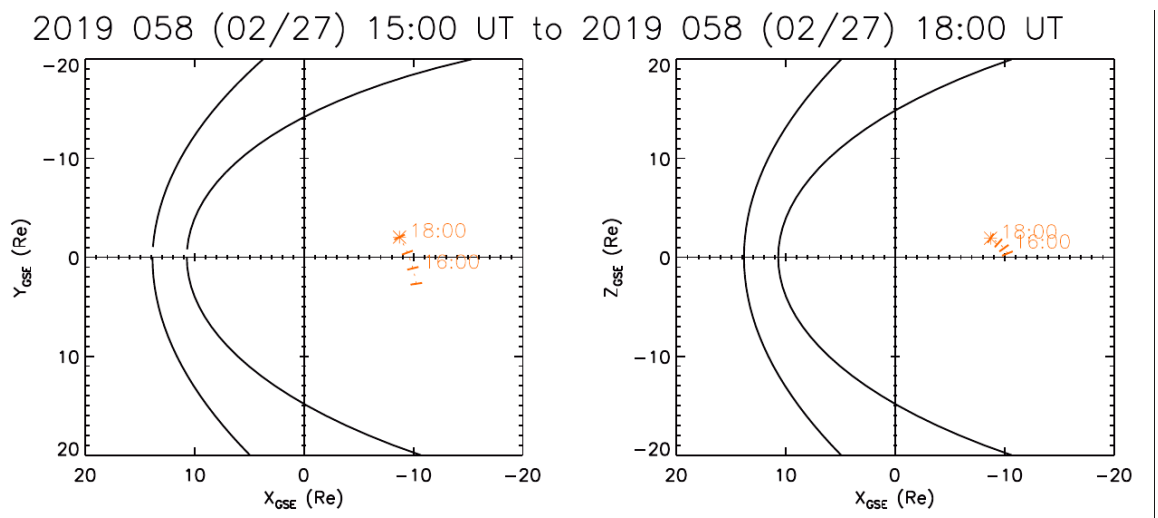


Figure A.33: Geotail orbit during 2019-02-27 from 15:00 - 18:00 UT. The X, Y, and Z axes in GSE coordinates are shown, The distance is measured in Earth radii. The red asterisk represents the end time.

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