On the flow shear instability driven by Reversed Flow Events in the polar ionosphere

Master Thesis

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Abstract

The Kelvin-Helmholtz instability (KHI) is known as one of the two main drivers of ionospheric irregularities at high-latitudes, the other being the Gradient Drift instability (GDI). This thesis quantifies the growth rate of the Kelvin-Helmholtz instability in the shear regions of Reversed Flow Events using a multi-instrument dataset consisting of coherent and incoherent scatter radar data, as well as in-situ rocket measurements. Other properties of these flow channels are also investigated. A quantification of the growth rate is important to understand the significance of KHI, which has broad implications to ionospheric space weather research, which is the main research focus of the University of Oslo Investigation of Cusp Irregularities project.

The main quantification of the growth rate is done by applying a statistical method on a dataset from the EISCAT Svalbard Radar (ESR) from 2001. Using the ESR to quantify the KHI growth rate, we find that the distribution of the growth time resembles a skewed normal distribution with a peak at 40 seconds and a long tail to about 400 seconds.

Presented in this thesis is a clear example of an RFE using a combination of high-resolution rocket data and lower resolution radar putting the rocket data in a larger plasma context. To this the SuperDARN radar network is a great addition providing data about the large-scale plasma convection of the polar cap. This is a case study. Using this high-resolution sounding rocket data, we find that two shears in the RFE in December, 2011 had a KHI growth rate of 38.4 and 79 seconds.

The results of this thesis match the growth rate expected for the KHI to GDI mechanism suggested for decameter scale irregularity creation. The growth rate also shows clearly that KHI itself is important for GNSS scintillation disturbances. We show that there is cases where HF radars show enhanced backscatter within the two minute resolution of the radar, just as an RFE appear in the ESR data at the same location.
Acknowledgment

I wish to thank my two great supervisors Yvonne Dåbakk and Jøran Moen. They have, while I have been working on the thesis, provided me with not only help, but great support and enthusiasm of the really interesting results I have found. I am really greatful to Jøran for letting me use the dataset from the ICI-3 rocket. Working with these two primary datasets (the 2011 ESR data and the ICI-3 rocket/radar data) have given me plenty of energy as I have seen that this is new and important knowledge the science community should know about. I also thank Jøran for letting me go to conferences to present the thesis results. Kjellmar Oksavik have also contributed with discussion, which I also are gratefull for.

I also wish to thank Tore Andre Bekkeng and Espen Trondsen for important technical discussion of the ICI-3 rocket and other instruments. A thanks go to Bjørn Lybekk for helping me with all my computer questions and problems.

My family and friends have been important when I need a break and to discuss anything else than space physics, so thank you for that. You know who you are.

Christoffer Stausland
Blindern, Oslo, March 2014
# Contents

Abstract

Acknowledgment

Acronyms and abbreviations

1 Introduction and motivation

2 Background

2.1 Coordinate systems

2.2 Plasma and the plasma motion

2.2.1 Space plasma

2.2.2 Single-particle motion

2.2.3 Magnetohydrodynamics (MHD)

2.3 The Sun, the solar wind and its magnetic field

2.4 The Magnetosphere

2.4.1 Bow shock, magnetosheath, and magnetopause

2.5 Solar wind-magnetosphere coupling

2.5.1 Dayside magnetic reconnection

2.5.2 The Dungey cycle

2.5.3 Transient reconnection

2.6 The ionosphere

2.6.1 The creation of the ionosphere

2.6.2 Altitude layers/regions

2.6.3 Boundary layers/precipitation regions

2.6.4 Ionospheric currents

2.7 Magnetosphere-ionosphere coupling

2.8 The aurora

2.9 High-latitude ionospheric instabilities

2.9.1 The Rayleigh-Taylor instability

2.9.2 Gradient drift instability

2.9.3 Kelvin-Helmholtz instability

2.10 Flow channel events

2.10.1 Enhanced Flow Events

2.10.2 Flow structures and Reversed Flow Events
3 Instrumentation

3.1 EISCAT Svalbard radar and incoherent scatter

3.1.1 Incoherent scatter radar

3.1.2 ESR and its unique location

3.1.3 The ESR SP-NO-FASM mode

3.2 SuperDARN chain of radars and coherent scatter

3.2.1 Coherent scattering

3.2.2 The SuperDARN radars

3.2.3 The use of SuperDARN

3.3 ICI-3 rocket

3.3.1 Physical dimensions and flight path

3.3.2 Electric field measurements

3.4 DMSP spacecrafts

3.4.1 SSJ/4

3.5 NOAA spacecrafts

3.5.1 Total Energy Detector (TED)

3.5.2 Medium Energy Proton and Electron Detector (MEPED)

3.6 ACE satellite

3.6.1 L1 Lagrange point

3.6.2 MAG and SWEPAM instruments

4 KHI growth rates of RFE velocity shears

4.1 The statistical approach to growth rates

4.1.1 A common ESR reference system

4.1.2 Range gate velocity fitting

4.1.3 KHI growth time result and distribution

4.2 Using high-resolution data from the ICI-3 sounding rocket

4.2.1 The velocity dataset

4.2.2 KHI growth rate from the ICI-3 RFE

4.3 Discussion

5 On the location, HF backscatter and density enhancements of RFEs

5.1 Source region of RFEs

5.1.1 RFEs in relation to the OCB

5.1.2 RFE location in the dayside ionosphere

5.2 Case study: 20th December, 2001

5.2.1 Electron density enhancements

5.2.2 RFEs in relation to HF backscatter by the CUTLASS radars

5.3 Discussion

6 Summary and future work

A Keskinen equations from CGS to SI units
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>E\times B drift</td>
<td>6</td>
</tr>
<tr>
<td>2.2</td>
<td>Plasma bouncing motion</td>
<td>6</td>
</tr>
<tr>
<td>2.3</td>
<td>Layers of the Sun</td>
<td>9</td>
</tr>
<tr>
<td>2.4</td>
<td>Solar wind spiral structure</td>
<td>10</td>
</tr>
<tr>
<td>2.5</td>
<td>Heliospheric current sheet</td>
<td>11</td>
</tr>
<tr>
<td>2.6</td>
<td>The magnetosphere</td>
<td>12</td>
</tr>
<tr>
<td>2.7</td>
<td>Solar wind-magnetosphere coupling field topology</td>
<td>13</td>
</tr>
<tr>
<td>2.8</td>
<td>Magnetospheric movement of field lines and ionospheric flows</td>
<td>14</td>
</tr>
<tr>
<td>2.9</td>
<td>Polar cap potential vs. IMF clock angle</td>
<td>15</td>
</tr>
<tr>
<td>2.10</td>
<td>Chapman profile and electron densities of the ionosphere</td>
<td>17</td>
</tr>
<tr>
<td>2.11</td>
<td>The dayside ionospheric precipitation regions</td>
<td>19</td>
</tr>
<tr>
<td>2.12</td>
<td>Birkeland currents</td>
<td>21</td>
</tr>
<tr>
<td>2.13</td>
<td>O2 energy bands resulting in aurora</td>
<td>22</td>
</tr>
<tr>
<td>2.14</td>
<td>Rayleigh-Taylor setup</td>
<td>24</td>
</tr>
<tr>
<td>2.15</td>
<td>Gradient drift setup</td>
<td>25</td>
</tr>
<tr>
<td>2.16</td>
<td>Setup of the Keskinen et al. [1988] KHI model</td>
<td>26</td>
</tr>
<tr>
<td>2.17</td>
<td>Development of the Kelvin-Helmholtz instability</td>
<td>27</td>
</tr>
<tr>
<td>2.18</td>
<td>Growth rates from Keskinen et al. [1988]</td>
<td>29</td>
</tr>
<tr>
<td>2.19</td>
<td>Suggestions of FTEs</td>
<td>32</td>
</tr>
<tr>
<td>2.20</td>
<td>Flow channel on old-open flux</td>
<td>33</td>
</tr>
<tr>
<td>2.21</td>
<td>Flow reversal by change of $B_y$ polarity</td>
<td>34</td>
</tr>
<tr>
<td>2.22</td>
<td>An RFE</td>
<td>35</td>
</tr>
<tr>
<td>2.23</td>
<td>Moen et al. RFE Current system</td>
<td>36</td>
</tr>
<tr>
<td>2.24</td>
<td>Measurements of forward enhanced flow channels</td>
<td>37</td>
</tr>
<tr>
<td>2.25</td>
<td>Oksavik Reversed Flow Events</td>
<td>38</td>
</tr>
<tr>
<td>3.1</td>
<td>Incoherent scatter radar returns</td>
<td>40</td>
</tr>
<tr>
<td>3.2</td>
<td>EISCAT Svalbard Radar</td>
<td>41</td>
</tr>
<tr>
<td>3.3</td>
<td>The SP-NO-FASM ESR scan mode</td>
<td>42</td>
</tr>
<tr>
<td>3.4</td>
<td>SP-NO-FASM ESR map projection</td>
<td>43</td>
</tr>
<tr>
<td>3.5</td>
<td>SuperDARN ionospheric scattering and true velocity vector</td>
<td>44</td>
</tr>
<tr>
<td>3.6</td>
<td>The Saskatoon SuperDARN radar</td>
<td>45</td>
</tr>
<tr>
<td>3.7</td>
<td>SuperDARN single radar power example</td>
<td>47</td>
</tr>
<tr>
<td>3.8</td>
<td>SuperDARN convection example</td>
<td>48</td>
</tr>
<tr>
<td>3.9</td>
<td>The ICI-3 rocket</td>
<td>49</td>
</tr>
<tr>
<td>3.10</td>
<td>The physical measurements of the ICI-3 rocket</td>
<td>50</td>
</tr>
</tbody>
</table>
4.1 ESR example plot .............................................. 57
4.2 Velocity shear data fit ........................................ 58
4.3 Distribution of KHI growth times ............................. 60
4.4 ICI-3 flight path overlaid the ESR velocity fan showing the RFE ............................... 61
4.5 Solar wind data from ACE and SuperDARN large-scale flow for the ICI-3 RFE ............................... 62
4.6 The ICI3 RFE as seen with ESR. Colors in units of m/s .......................................................... 63
4.7 Both components of the ICI-3 RFE velocity ................................. 65
4.8 ESR components ............................................. 66
4.9 ICI-3 velocity data parallel to the RFE with tanh-datafits .................................................... 67
4.10 Examples of ESR flow directions ................................ 68
4.11 KHI growth time with other works .................................. 69

5.1 ACE-data (OMNI) for 15-Dec-2001 .................................. 73
5.2 Large-scale convection around RFE #5 ......................... 74
5.3 Trajectory of NOAA-16 near RFE #5 ............................ 75
5.4 NOAA-data of RFE #5 ......................................... 76
5.5 DMSP F13 trajectory on 16-Dec-2001, near RFE #9 .................................................. 77
5.6 DMSP particle data around RFE #9 ............................ 78
5.7 DMSP flow data near RFE #9 .................................... 78
5.8 SuperDARN convection plot around RFE #18/#19, 20th December, 2001. ......................... 79
5.9 SuperDARN plot at the time of RFE #9 ............................ 80
5.10 Solar wind data on 20th December ............................ 80
5.11 ESR ion velocity and electron density of RFE #18/#19, scan 1-3 .................. 81
5.12 ESR ion velocity and electron density of RFE #18/#19, scan 4-6 .................. 82
5.13 ESR ion velocity and electron density of RFE #18/#19, scan 7-9 .................. 83
5.14 ESR ion velocity and electron density of RFE #18/#19, scan 10 .................. 84
5.15 A closer look at RFE density enhancements ...................... 85
5.16 SuperDARN backscatter before RFE #18 ...................... 87
5.17 SuperDARN backscatter before RFE #18 ...................... 87
5.18 ESR with borders, scan 1 ..................................... 88
5.19 SuperDARN backscatter with RFE borders, scan 1 .................. 88
5.20 ESR with borders, scan 2 ..................................... 88
5.21 SuperDARN backscatter with RFE borders, scan 2 .................. 88
5.22 ESR with borders, scan 3 ..................................... 88
5.23 SuperDARN backscatter with RFE borders, scan 3 .................. 88
5.24 ESR with borders, scan 4 ..................................... 89
5.25 SuperDARN backscatter with RFE borders, scan 4 .................. 89
5.26 ESR with borders, scan 6 ..................................... 89
5.27 SuperDARN backscatter with RFE borders, scan 6 .................. 89
5.28 ESR with borders, scan 5 ..................................... 89
5.29 SuperDARN backscatter with RFE borders, scan 5 .................. 89
5.30 ESR with borders, scan 7 ..................................... 90
5.31 SuperDARN backscatter with RFE borders, scan 7 .................. 90
5.32 ESR with borders, scan 8 ..................................... 90
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.33 SuperDARN backscatter with RFE borders, scan 8</td>
<td>90</td>
</tr>
<tr>
<td>5.34 ESR with borders, scan 9</td>
<td>90</td>
</tr>
<tr>
<td>5.35 SuperDARN backscatter with RFE borders, scan 9</td>
<td>90</td>
</tr>
<tr>
<td>5.36 RFE velocity and electric field</td>
<td>91</td>
</tr>
<tr>
<td>5.37 The Moen et al. [2008] RFE current/electric field system</td>
<td>92</td>
</tr>
<tr>
<td>5.38 Post-RFE #18 SuperDARN backscatter evolution</td>
<td>94</td>
</tr>
<tr>
<td>5.39 Post-RFE #18 SuperDARN backscatter evolution</td>
<td>94</td>
</tr>
<tr>
<td>5.40 Post-RFE #18 SuperDARN backscatter evolution</td>
<td>95</td>
</tr>
<tr>
<td>5.41 Post-RFE #18 SuperDARN backscatter evolution</td>
<td>95</td>
</tr>
</tbody>
</table>
## Acronyms and abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AU</td>
<td>Astronomical Unit</td>
<td></td>
</tr>
<tr>
<td>BPS</td>
<td>Boundary Plasma Sheet</td>
<td></td>
</tr>
<tr>
<td>CPS</td>
<td>Central Plasms Sheet</td>
<td></td>
</tr>
<tr>
<td>CSR</td>
<td>Coherent Scatter Radar</td>
<td></td>
</tr>
<tr>
<td>ESR</td>
<td>EISCAT Svalbard Radar</td>
<td></td>
</tr>
<tr>
<td>eV</td>
<td>Electron Volts</td>
<td></td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
<td></td>
</tr>
<tr>
<td>FOV</td>
<td>Field of View</td>
<td></td>
</tr>
<tr>
<td>FS</td>
<td>Flow Structure</td>
<td></td>
</tr>
<tr>
<td>FTE</td>
<td>Flux Transfer Event</td>
<td></td>
</tr>
<tr>
<td>GDI</td>
<td>Gradient-Drift Instability</td>
<td></td>
</tr>
<tr>
<td>GEO</td>
<td>Geographic coordinate system</td>
<td></td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
<td></td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
<td></td>
</tr>
<tr>
<td>GSM</td>
<td>Geocentric Solar Magnetospheric coordinate system</td>
<td></td>
</tr>
<tr>
<td>HF</td>
<td>High Frequency</td>
<td></td>
</tr>
<tr>
<td>HLBL</td>
<td>High-Latitude Boundary Layer</td>
<td></td>
</tr>
<tr>
<td>IMF</td>
<td>Interplanetary Magnetic Field</td>
<td></td>
</tr>
<tr>
<td>ISR</td>
<td>Incoherent Scatter Radar</td>
<td></td>
</tr>
<tr>
<td>KHI</td>
<td>Kelvin-Helmholtz Instability</td>
<td></td>
</tr>
<tr>
<td>LLBL</td>
<td>Low-Latitude Boundary Layer</td>
<td></td>
</tr>
<tr>
<td>MAG</td>
<td>Geomagnetic coordinate system</td>
<td></td>
</tr>
<tr>
<td>MHD</td>
<td>Magnetohydrodynamics</td>
<td></td>
</tr>
<tr>
<td>MLAT</td>
<td>Magnetic Latitude</td>
<td></td>
</tr>
<tr>
<td>MLT</td>
<td>Magnetic Local Time</td>
<td></td>
</tr>
<tr>
<td>OCB</td>
<td>Open-Closed Boundary</td>
<td></td>
</tr>
<tr>
<td>PIF</td>
<td>Pulsed Ionospheric Flow</td>
<td></td>
</tr>
<tr>
<td>PMAF</td>
<td>Poleward Moving Auroral Form</td>
<td></td>
</tr>
<tr>
<td>TOI</td>
<td>Tounge of Ionization</td>
<td></td>
</tr>
<tr>
<td>VHF</td>
<td>Very High Frequency</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 1

Introduction and motivation

Space weather is increasingly important for the community at large since we are heavily dependent on satellite communication and navigation. The near-Earth space environment, stretching from the sun to the top of our atmosphere is very complex and involves a variety of different phenomena, making the results challenging to predict.

Irregularities are a common feature in the polar cap ionosphere, but they are not easily detected by ground-based instruments. However, some instruments such as HF backscatter radars and GPS scintillation are capable of detecting them indirectly. When decameter scale irregularities appear, the HF communication for airplanes crossing the polar cap can for example be disrupted, in some cases for longer time periods, which obviously can be challenging or even dangerous. [Moen et al., 2013] Similarly, during large geomagnetic storms the GNSS inaccuracy can be significant, and coverage even drop out at mid to high latitudes.

At high latitudes, two important irregularity creation mechanisms are the flow shear instability/Kelvin Helmholtz instability (KHI) and the gradient drift instability (GDI). A search for important drivers for irregularity creation are ongoing, [Moen et al., 2001, 2002, 2012; Oksavik et al., 2006, 2011, 2012; Carlson et al., 2002, 2007, 2008; Carlson, 2012] and this thesis is an advancement on this topic.

The thesis is divided in a background chapter followed by an introduction to the instruments used. Then the main work is presented in two result chapters, and a summary chapter with suggested future research follows last. The two result chapters are closely related to one another, with the first one being a case analysis of a dataset combination of in-situ sounding rocket and a ground-based radar and statistical approach to a radar dataset described by [Rinne et al., 2007] (referred to as the [Rinne et al., 2007] database) for a quantification of how fast the flow shear instability develops. The last result chapter is a further analysis on the radar database to extract more important features of the mentioned instability in the dayside high-latitude ionosphere.
Chapter 2

Background

Space physics can be divided into two time periods: the time before year 1957 and then the time of modern space physics after 1957, the transition being the space race between the Americans and Russians which led to an important tool for space scientists: satellites providing in-situ measurements of the ionosphere, magnetosphere and even the solar wind. The near-earth space was believed to be completely empty except in some extreme conditions with eruptions from the Sun. Satellites proved this to be wrong and a new theory and models of the near-earth space had to be developed.

The reader of this thesis is assumed to have passed introductory courses in space physics and electromagnetism. This chapter gives the reader a basic introduction to this exciting and important field to our modern satellite-based community. The reader is referred to Kallenrode [2004] or Kivelson and Russell [1995] for an extended introduction.

2.1 Coordinate systems

At first, we need to discuss two different coordinate systems: the geocentric solar magnetospheric (GSM) and the geomagnetic (MAG) coordinate systems. Most people are familiar with the geographic coordinate system (GEO), with \( x \) axis of the intersection of the Greenwich meridian and equator, and \( z \) axis at the geographic north poles (spin axis of the earth). The \( y \) axis is given by the right-hand rule.

The geocentric solar magnetospheric (GSM) coordinate system is defined as the \( x \) axis is along the Sun-Earth line and the \( z \) axis is the magnetic dipole axis. [Hapgood 1992] In this thesis, this will be used in presenting solar wind satellite data.

For near-Earth observations we use Magnetic Earth coordinates, termed MAG for short. [Hapgood 1992] The \( y \) axis is given by the intersection between the geographic equator and the geographic meridian 90° East of the meridian containing the dipole axis, and the \( z \) axis is again the magnetic dipole axis. [Hapgood 1992] Again, the third axis is defined from the right-hand rule. Using the magnetic dipole axis is a natural reference in space physics, as phenomena in the ionosphere and magnetosphere are organized by the magnetic field. We divide this coordinate system in a special way using MLT and MLAT. The longitude component is given in magnetic local time (MLT) where magnetic noon (MLT = 12h) is the meridian line of Earth pointing towards the
Sun. MLT is divided in 24 hours, making MLT = 12h pointing from the Sun on the Sun-Earth line, often referred to as magnetic noon. 1 hour of MLT is $360^\circ / 24 = 15^\circ$.

The other component is magnetic latitude (MLAT), defined as geographic latitudes with the dipole axis as reference instead of the geographic north pole.

### 2.2 Plasma and the plasma motion

There are four fundamental states of matter: gas, liquid, solid and plasma. Gases, liquids and solids are familiar to all of us in everyday life. Plasma on the other hand, is not so well known to the general public. In space physics however, this is the most essential state of matter, and it is essential to have an understanding of what space plasma is and how it behaves. Outside our planet’s atmosphere, almost everything exist as plasma: the Sun (and every living star), the solar wind, the heliosphere. First we will have a short look at plasma, and then explain two approaches to how the space plasma behaves: single particle motion and plasma motion as a fluid.

#### 2.2.1 Space plasma

A plasma is a gas of charged ions and electrons, often with a strong neutral component present. It is quasi-neutral, meaning that on larger volumes appear as neutral, but on smaller scales this does not necessarily need to be true. The neutral atoms of the gas have been ionized so one or more electrons are not bound to any certain atom. There can be several reasons for the ionization within the plasma, one reason is extreme temperatures as often seen in nature, as for example within every star. The temperature of a substance is is measured by the mean velocity/energy of the atoms within it. In an extremely hot star the helium and hydrogen atoms have a very high velocity and due to the high material density they collide frequently with each other. These collisions knock of electrons from the atom, which is the ionization process, creating an ion-electron pair. A plasma consist of many such pairs, and can be regarded as a gas consisting of ion-electron pairs making it highly conductive. It is this conductivity that makes it a distinct state of matter. Contrary to the impression we get on the surface of the Earth, plasma is actually the state that 99% of the (visible) matter in the universe is in!

In Sections 2.3-2.6 we will describe plasma regions: inside the Sun, the solar atmosphere, the magnetosphere (the outermost part of the terrestrial atmosphere), and then at last the ionosphere.

#### 2.2.2 Single-particle motion

The governing equation for space plasma single-particle motion is the Lorentz force

$$\mathbf{F} = m \frac{\partial \mathbf{v}}{\partial t} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}),$$

which acts on any charged particle, and where $q$ is the charge of the particle, $\mathbf{E}$, $\mathbf{v}$ and $\mathbf{B}$ the vector electric field, velocity and magnetic field respectively.
There are two terms in this equation: one term in the direction of the electric field and one perpendicular to both velocity and the magnetic field. If we for one moment assume no electric field, the Lorentz equation can be rewritten

\[ ma = m \cdot \frac{\partial v}{\partial t} = qv \times B \quad \text{if } E=0. \]  

(2.2)

The acceleration is perpendicular to the velocity, which means that the speed of the particle will never change and the particle will move in a circle where the acceleration is into the center of the circle. Since the particle is gyrating in a circle the acceleration is \( a = \frac{v_{\perp}^2}{r} \), we can combine this with equation (2.2) and get (where \( v_{\perp} \) is perpendicular to the magnetic field \( B \))

\[ r = \frac{mv_{\perp}}{qB} \quad \text{(gyroradius).} \]  

(2.3)

If we use the equation for speed around a circle, given by \( v_{\perp} = \frac{s}{T} = \frac{2\pi r}{T} \) where \( T \) is the gyroperiod and apply it to (2.3), we get

\[ T = \frac{2\pi m}{qB}, \]

which finally gives the gyrofrequency in revolutions/second (using \( f_g = 1/T \))

\[ f_g = \frac{qB}{2\pi m}. \]  

(2.4)

We see here that for an electron or an ion the gyrofrequency and gyroradius are determined by the mass of the particle and the magnetic field. If we assume constant magnetic field strength, the gyroradius is bigger with increasing mass. An ion has, for the same velocity, about a thousand times larger radius than an electron because of the factor of a thousand in mass.

Gyrating particles have zero net motion, as they gyrate around a fixed point. However, if we now take the electric field into account as well, the net motion of both the electrons and the ions is in the same direction, which is called the E-cross-B drift. This is demonstrated in Figure 2.1.

In the low altitude ionosphere D and E layer the densities are high enough for collisions between ions and neutrals to be significant, and the ions will no longer follow the E-cross-B drift, whereas the electrons still do. In the ionosphere above about 200 km the neutral density is so low that the effect of ion-neutral collisions vanish, and both the ions and electrons follow the E-cross-B drift. When we average (2.1) one get zero order drift, and the terms on the left side is zero \( (\partial v/\partial t = 0) \). Then

\[ E = -u \times B, \]

(2.5)

that is, the electric field is perpendicular to both the magnetic field and the drift of the ions and electrons. One can rewrite this equation to get

\[ u = \frac{E \times B}{B^2}, \]  

(2.6)

5
Figure 2.1: $E \times B$ drift as seen in the F-layer high-latitude ionosphere. From Kivelson and Russell [1995].

Figure 2.2: Plasma bouncing motion. Figure on the right shows the mirror point, where the particles change their direction of motion along the magnetic field lines. We also see how this mirror point depends upon the angle of motion to the magnetic field line.

which is the E-cross-B drift explained above. This confirms the direction of motion of the electrons and ions in Figure 2.1, and there will be no net currents. In the above derivation, a uniform magnetic field is assumed.

**Bouncing motion** There is one other particle motion which is important for this thesis, created by the mirror force which leads to the bouncing motion along the magnetic field lines. In space physics,

$$\mu = \frac{1}{2} \frac{mv^2}{B}$$

is called the first adiabatic invariant. If the magnetic field changes slowly enough, meaning that it is approximately constant over one gyration orbit, this invariant can be considered constant. It can be viewed as a magnetic moment, and the force along the
magnetic field line of the gyrating particle is \( F = -\mu dB/dz \) where \( z \) is along the magnetic field. As the particle move closer and closer to a positive magnetic field gradient, the parallel velocity component decreases, and as the magnetic gradient increases, the particle will eventually stop and move in the opposite direction. The point where the particle shifts its direction is called the mirror point, see Figure 2.2. This means that when a particle in the magnetosphere is stuck on a magnetic field line, it will in principle oscillate or bounce along that field line forever. The exception is for particles with a certain angle to the field lines (see Figure 2.2 for the angles \( \alpha_1 \) and \( \alpha_2 \)), will get close enough to the Earth’s atmosphere to collide with the plasma or neutral particles. If the mirror point is close to the atmosphere, there is a probability that collisions will take place and the bouncing particle will be lost the atmosphere. The altitude of the mirror point is a function of the angle to the magnetic field line.

Below some separation angle the probability for the particles to be lost is high, and this is called the loss cone. Particles within the loss cone have a high probability to get lost, and the particles outside will most likely not be lost. As we will see again in the instrument chapter, instrument measuring particle precipitation must take this loss cone into account. For a satellite in the ionosphere measuring precipitating particles it is important to know if the particle is in or outside inside the loss cone or not. The lost particles can create aurora and otherwise contribute to other ionospheric phenomena.

### 2.2.3 Magnetohydrodynamics (MHD)

In classical hydrodynamics the governing equations is the Navier-Stokes equations. This is a system of equations that explain the behavior of neutral liquids. Combining these with the Maxwell’s equations for electromagnetism yields the equations for magnetohydrodynamics (MHD) which explain the behavior of plasma as a macroscale fluid. In the upper parts of the ionosphere, the neutral density is low enough to assume that ion-neutral collision is negligible. We can then assume infinite conductivity, and the limit of MHD where that is true is called ideal MHD.

The MHD equations is

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0 \\
\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} &= \mathbf{j} \times \mathbf{B} - \nabla p \\
\mathbf{j} \times \mathbf{B} &= \frac{\left( \mathbf{B} \cdot \nabla \right) \mathbf{B}}{\mu_0} - \nabla \left( \frac{B^2}{2\mu_0} \right) \\
\mathbf{E} &= -\mathbf{v} \times \mathbf{B} \\
\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E} \\
\mu_0 \mathbf{j} &= \nabla \times \mathbf{B} \\
\frac{D}{Dt} \left( \frac{p}{\rho^2} \right) &= 0 \\
\nabla \cdot \mathbf{B} &= 0.
\end{align*}
\]
(2.7) is the continuity equation, (2.8) is the momentum equation, (2.9) the expansion of the Lorentz force term, (2.10) the ideal Ohm’s law (the same as seen in the last subsection), (2.11) Faraday’s law, (2.12) a variant of the Ampere’s law. (2.13) is the energy equation and (2.14) is the constraint of the magnetic field, as there is no magnetic monopoles.

Here $\rho$ is the plasma density, $v$ is the velocity, $j$ is the current density, $B$ the magnetic field, $E$ the electric field, $p$ the plasma pressure, and $\gamma = 5/3$ is the adiabatic index. Note that we here assume one single plasma species.

A current in MHD is given by $j = \sigma (E + v \times B)$ and since we assume $\sigma = \infty$, we have $E + v \times B$. There is one important result of this: frozen-in field. The plasma can be viewed as bound to the magnetic field lines, and the motion of the plasma in the ionosphere, which is measurable by e.g. radars, can be used to track how the magnetic field lines move in the magnetosphere. The large-scale movement of the plasma is elaborated later in this chapter.

There are some restrictions to ideal MHD, and certain places the approximation breaks down. We will return to this in Section 2.5.1.

### 2.3 The Sun, the solar wind and its magnetic field

The Sun is an average class 2G-star with a mass of $m_\odot = 2 \times 10^{30}$ kg. With an average distance between the Sun and the Earth of $d = 1.5 \times 10^{11}$ m (1 astronomical unit, AU) and the light speed of $c = 3 \times 10^8$ m/s, light uses $t = d/c = 500$ seconds, a little over 8 minutes, to reach Earth. In Figure 2.3 we see the different layers of the Sun. Starting from the core where the nuclear fusion of hydrogen to helium generate the energy, the next layer is the radiative layer where the cores energy moves by thermal photons radiating out to the next layer: the convecting zone. Hot solar material that is not dense enough to support radiation of the energy now starts a convection process that rises to the cooler photosphere (the surface for visible light) and then convects back into the Sun. The core of the Sun has a temperature of 16 million degrees Kelvin, but at the visible surface of the photosphere this is cooled to 5700 Kelvin.

The lowest layer of the Sun’s atmosphere, the chromosphere, has a low density of about $10^{-8}$ of the atmosphere of Earth. From there the temperature keeps increasing up in the outer corona. A clear outer boundary of the corona can not be seen, but rather mixes into the solar wind.

The Sun’s atmosphere, commonly known as the corona, consists of plasma. Because of the extreme temperatures (and additional unknown mechanisms) and the associated high kinetic energy of some of the particles, single particles with favorable properties can escape Sun’s gravitational field. These particles from the corona make up the so-called solar wind streaming out from the Sun in our solar system, further beyond the planets and eventually hits the heliopause. The heliopause is the boundary between the solar wind and the interstellar wind, and this boundary is probably the farthest our solar system reaches.

The Sun’s rotational period is 26 days and since the Earth rotates around the Sun
during this time, the rotational period seen from the Earth is 27 days. The magnetic field will, due to the rotation as seen in Figure 2.4, appear as spiraled like a garden hose. One can show that the spiral is an Archimedian spiral \( r = a + b\theta \), and is described by the equation [Kallenrode, 2004]

\[
r = u_{s.w.}\frac{\varphi - \varphi_0}{\omega_{\odot}} + r_0.
\]

At Earth the solar wind has a bulk velocity normally spanning 350-700 km/s (with extremes in either directions, from about 250 and up to 1000 km/s). With a mean velocity of 400 km/s, the time the solar wind uses to travel from the Sun to the Earth is \( t_{\text{ave}} = \frac{d}{400 \text{ km/s}} \approx 4.5 \text{ days} \). The particles will be slowed down somewhat because of Sun’s gravitational pull shortening the travel time to about 4 days [Kivelson and Russell, 1995]. Pressure differences near the Sun and farther away contributes to increase the velocity.

The magnetic field is frozen into the solar wind. The average magnetic field strength at 1 AU is 5.5 nT [Lepping et al., 2003]. The solar wind consist mainly of protons and electrons, with a smaller amount of heavier ions. The ion density and temperature is about 5-10 cm\(^{-3}\) and \( 7.5 - 8 \times 10^4 \) K.

2.4 The Magnetosphere

The magnetosphere acts as an important shield for the terrestrial body from solar wind particles. Some planets do not have a magnetic field, and hence no shielding magne-
t0
t1
t2
t3
t4
tosphere, making them a very harsh environment.

Figure 2.6 shows the structure of the magnetosphere. The magnetopause is shown in pink as a "shell" around the magnetosphere, and is the main divider of the solar wind and the magnetosphere. The solar wind generator is a current sheet at the magnetopause at the interaction between the magnetosphere and the solar wind, where energy from the solar wind is transferred from the solar wind.

2.4.1 Bow shock, magnetosheat, and magnetopause

As shown in Figure 2.8, a bow shock is the outermost boundary between the solar wind and magnetosphere, where the solar wind speed changes abruptly. The bow shock is not a part of the magnetosphere itself. Between the bow shock and the magnetopause is the magnetosheat, with shocked solar wind particles. The position of the magnetopause can be found where the pressure from the solar wind is equal to that of the magnetosphere:

\[ \rho_{\text{sw}} v_{\text{sw}}^2 = \frac{2 B_{\text{MS}}^2}{\mu_0}. \]

[Kivelson and Russell, 1995] Using that the magnetic field falls off with a factor \(1/r^3\) we get

\[ \rho_{\text{sw}} v_{\text{sw}}^2 = \frac{2 B_0^2}{r_{\text{MP}}^3 \mu_0} \]

and when solved for \(r\) we get the distance [Kallenrode, 2004]

\[ r_{\text{SO}} = \sqrt[3]{\frac{2 B_0^2}{\mu_0 \rho_{\text{sw}} v_{\text{sw}}^2}}. \]

The most important parameters determining the location of the magnetopause are the solar wind density and speed, where the terrestrial magnetic ground field strength is considered constant. The typical distance, called stand-off distance, is 10 Earth radii, but may vary between 4.5 to 20 Earth radii. [Kallenrode, 2004]

2.5 Solar wind-magnetosphere coupling

The solar wind-magnetosphere coupling is the important driver for space physics. Particles and energy from the solar wind is injected into the magnetosphere-ionosphere...
Figure 2.5: The Sun’s heliospheric current sheet. A ballerina skirt like current sheet is clearly visible in the figure on the left. The surface showing the current sheet also show the reversal of the open magnetic field (which is creating the current from Ampere’s law).

2.5.1 Dayside magnetic reconnection

In Figure 2.7 we see the dayside magnetic field topology with the interplanetary magnetic field (IMF) on the Sun side and the terrestrial magnetic field on the Earth side. Where two oppositely directed magnetic fields are close to each other, Amperes law \( \mu \mathbf{j} = \nabla \times \mathbf{B} \) requires a current sheet between them. Where these fields are close enough, as is the case when the solar wind with the IMF approaches the magnetopause, these two magnetic fields merge together. This merging of magnetic field lines is called magnetic reconnection, a process in which two different magnetic field domains mixes.

2.5.2 The Dungey cycle

Open field lines are connected to both the Earth and the solar wind. The Earth connection can be seen as fixed from a given point in the middle of the Earth. The other line, though, is not fixed in space but is dragged along with the moving solar wind away from the Sun. This will force a movement of open flux from the dayside to the nightside inside the open magnetosphere. When the field lines are closed again in the nightside magnetotail, continuity will force the field lines to convect back to the dayside on lower latitudes, and they will once again be opened at the dayside. This cycle is called the Dungey cycle, and was initially described by Dungey [1961].

The movement of field lines from the dayside, over the polar cap to the nightside, with return on lower latitudes creates a distinct two-cell flow pattern in the ionosphere. In the left part of Figure 2.8 we see a cut of the Earth with north pole to the top, south pole in the bottom and the Sun towards the left. Here the solid lines are magnetic.
field lines, with blue for IMF, green for closed and red for open field lines. The bow shock and magnetopause are shown as dashed lines. The field lines are marked with numbers, and 1 is at a time $t_1$ just at a reconnection event happens. At time $t_2$ through $t_5$ the field line is dragged over the poles as the solar wind travel past the Earth. At time $t_6$ the open field line is closed by reconnection and one part of the field line is then closed to the terrestrial body and the other is freed to the IMF. At time $t_7, t_8$ and $t_9$ the closed field lines is pushed back to the dayside again, and the cycle is complete, as the field line is once again ready for dayside reconnection.

On the right side, the ionospheric footprint of the same field line is shown with the same colored numbers. The line on which the field line move is the corresponding plasma line, and we see the dusk part of the north pole. The same flow pattern is mirrored on the dawn part of the pole. This creates a two-cell structure, which can be measured by radars and other instruments. The auroral oval is colored by light green and also extends around the pole to the dawn side.

Figure 2.8 is for simplification only correct for IMF $B_y \approx 0$. The $B_y$ component of the
Figure 2.7: Solar wind-magnetosphere coupling field topology. The IMF is shown in blue, and Earth's magnetic field is shown in green. Currents in red. Ampère's law \( \mathbf{\mu j} = \nabla \times \mathbf{B} \) explains how a current sheet is developed at the magnetosphere, because of the magnetic field topology with the IMF on one side and the terrestrial magnetic field on the other. This explains the main coupling between the solar wind and the magnetosphere, which drives energy from the solar wind into the magnetosphere. Note that pink arrow explains the magnetic field curl \( \nabla \times \mathbf{B} \), and not the direction of the curl itself.

IMF will drag the two-cell structure to an asymmetric banana-orange style structure towards either dusk or dawn, dependent on the polarity of the component.

Figure 2.9 shows 8 spherical harmonic fits from satellite passes binned to 45° of IMF clock angle (the Y-Z component plane). The two fits horizontally in the middle show the polar cap potential for \( \pm B_y \) and \( B_z \approx 0 \), while the two fits vertically in the middle show for \( \pm B_z \) and \( B_y \approx 0 \). Since the potential \( \Phi \) is given from the E-field by the relation \( \mathbf{E} = \nabla \Phi \) and the E-field is given by the MHD ohms law \( \mathbf{E} = -\mathbf{v} \times \mathbf{B} \) the potential levels (shown as solid lines for fixed potential values) will also be the plasma streamlines, that is, the path the plasma and magnetic field line will follow through the Dungey cycle at the ionosphere. For strong \( B_y \) the potential, most easily seen when \( B_z \approx 0 \), has a dawn-dusk asymmetry. We also see from the figure that the total polar cap potential decreases with increasing IMF \( B_z \).

2.5.3 Transient reconnection

Dungey [1961] suggested a quasi-steady reconnection model at the two diffusive domains, meaning that reconnection is present at all times, but the reconnection rate, the amount of magnetic flux that opens (day) and closes (night), varies with time. Later satellite measurements indicated that this could not be correct at all times (see e.g. Lockwood [1995] and Davis and Lockwood [1997]). Solar wind ions, seen on open field lines given by low energy ions and electrons, were seen with a clear low-energy cut-off, as reported in many papers (e.g. Escoubet et al. [1992, Figure 1], Farrugia et al. [1998, Plate 1], Yeoman et al. [1997] and Newell and Meng [1998]). These ionospheric signatures are indication of a so-called stepped cusp. This is a clear violation of what to expect from quasi-steady reconnection, and the reason for this is that there should
Figure 2.8: Magnetospheric field line movement and the corresponding ionospheric flow. Blue field lines is the IMF, green is closed and red is opened field lines. The magnetopause and bow shock is clearly marked with dashed lines, and the numbers are marked for time, 1 (first, at reconnection) through 9 (end of Dungey cycle). From Kivelson and Russell [1995], edited.

always be all solar wind particle energies present on newly-opened flux, and only the flux of such particle will vary.

The stepped cusp is an indication of pulsed reconnection, with sudden burst of reconnection between quiet periods with no reconnection at all. The closed field line at time $t_0$ is not containing any solar wind particles. At time $t_1$ reconnection happens on that field line and solar wind particles are propagating down that field line from the dayside magnetopause towards the ionosphere. Since the ions contain more or less all energies within a certain interval the more energetic particles will arrive at the ionosphere first since they have larger velocities (and they all travel approximately the same distance). This is the key to explain pulsed reconnection from the stepped cusp empirically measured by satellites. They have also been associated with other phenomenon, as PMAFs in optics [Farrugia et al., 1998].

2.6 The ionosphere

The ionosphere is a region of the upper atmosphere, and consists of both neutral and charged components, as already discussed. The ionosphere starts at about 85-90 kilometers and extends to about 500-1000 kilometers. The density in ionosphere is very low compared to the atmosphere as we know it, but is much denser than the average magnetosphere. Due to the presence of plasma, electromechanical processes dominates the conductive, high-latitude ionosphere.
Figure 2.9: Polar cap potential vs. IMF clock angle, for $B_T > 7.25 \text{ nT}$. Seen is 8 spherical harmonic fits to a series of Dynamics Explorer-2 satellite passes. From Weimer [1995].

2.6.1 The creation of the ionosphere

An ionosphere is created from a neutral atmosphere and a source of ionization. At the height of the ionosphere there are two primary sources of ionization: photo-ionization and impact ionization.

The density of the atmosphere can be approximated by

$$n(z) = n_0 \exp \left( -\frac{z}{H} \right),$$  \hspace{1cm} (2.15)
where $z$ is the given height and $H = kT/mg$ is the scale height of the atmosphere ($m$ is the weight of the average atmospheric particles and $T$ is the temperature). Bouger-Lambert-Beer’s law give a relation between the absorption of light to a material, and is given by

$$A = \frac{dI}{dz} = -I_\infty \sigma_a n$$

(2.16)

where $A = dI/dz$ is the absorption rate, $n$ is the number density, $\sigma_a$ is the absorption cross-section and $I_\infty$ is the intensity at the top of the ionosphere. Integrate 2.16 over height and get

$$I(z) = I_\infty \exp\left(-\frac{\tau}{\cos \theta}\right)$$

(2.17)

where $\tau = \int_z^\infty \sigma_a n(z) \, dz$ is the optical depth and $\theta$ is the angle of the Sun to zenith. Electromagnetic radiation have a height-dependent ionization rate given by

$$q(z) = n \sigma_i I(z)$$

where $\sigma_i$ is the ionization cross-section. Combining these equations gives us the charge density

$$q(z) = \sigma_i n_0 I_\infty \exp\left(-\frac{\tau}{\cos \theta} - \frac{z}{H}\right).$$

(2.18)

The above equation describes how the charge density varies in the ionosphere, and is called the Chapman profile, as shown in Figure 2.10a. This equation has a maximum at a certain height $z_{\text{max}}$ which is dependent of the zenith angle.

Note here that this derivation which is based on Kallenrode [2004, section 8.3.2] only takes photo-ionization into account. At lower latitude with Sun closer to zenith, this is the main driver for ionization, and as the latitude increases, particle precipitation becomes increasingly important for ionization, and at the polar cap impact ionization is the main driver, as the Sun is very low on the horizon if present at all.

There is also loss of ions by recombination, and the rate of change of ions is given by [Hargreaves, 1992]

$$\frac{dN}{dt} = q - L - \nabla \cdot (Nv),$$

where $L$ is the rate of recombination to neutrals and $\nabla \cdot (Nv)$ is loss by motion of particles from one place to another. The most important loss processes is dissociative recombination of molecular ions, charge density, then radiative recombination of atomic ions. [Prolss, 2004] The dissociative recombination is given by the reaction

$$XY^+ + e^- \rightarrow X^{(*)} + Y^{(*)},$$

where the asterisk denotes possible exited states. Radiative recombination is given by the reaction

$$X^+ + e^- \rightarrow X^{(*)} + \text{photon}.$$

A more important process than radiative recombination is charge exchange, that keeps the total charge but change the ion species, and is given by

$$X^+ + Y \rightarrow X^{(*)} + Y^+. $$

16
In the E-region, the loss processes are proportional to the squared of the density, \( L_E(h) = \alpha n^2(h) \), and in the F region proportional to the density, \( L_F(h) = \beta(h) n(h) \). The loss coefficient \( \alpha \) is weakly dependent of height (can be approximated to a constant), but \( \beta \) is height-dependent and varies more than the density. \[ \text{Prolss, 2004} \]

See Figure 2.10b for the true electron density for solar minimum and maximum and for day and night.

### 2.6.2 Altitude layers/regions

Figure 2.10b shows the layers of the ionosphere, namely D, E, F1 and F2. They are defined from the dayside solar max curve. As we see in the figure, these layers vary, and for example the distinction between the F1 and F2 layers is not always possible. Often different phenomena exist in the different layers, as we will now discuss very briefly.

**D layer** The D layer extends up to about 90 kilometers (with lower limits at about 60-70 kilometers). The electron density is very low, commonly around \( 10^9 \) m\(^{-3} \) and the neutral density are very low as compared to the rest of the atmosphere below. This layer is not important for this thesis.
In the E layer, the electron density is high, often above $10^{11}$ m$^{-3}$ on the dayside, and the plasma behavior is important. The neutral density is high enough to make ion-neutral collisions important, and in this layer the ideal MHD approximation is not valid. The ion-neutral collisions happen so frequently compared to the electron-neutral collisions that a current develops as ions and electrons do not move at the same velocity, as being discussed further in Section 2.6.4. It was this layer of the ionosphere that was first found when radio waves were reflected of it and back to the Earth. The layer extends from 90 kilometers to about 150 kilometers. The most important neutral species are molecular nitrogen as well as atomic and molecular oxygen. The most important ion species are NO$^+$ and O$_2^+$. [Kallenrode, 2004, Figure 8.18]

The F layer is sometimes divided into two parts: F1 as the lower part and F2 as the upper part. For most phenomena, the F layer as a whole is used. The layer extends from about 150 kilometers and upwards, and a clear upper limit is hard to find, but one often set its upper limit between 500 and 1000 km. The most important neutral species are atomic oxygen and molecular nitrogen, while the most important ion species is O$^+$. [Kallenrode, 2004] The number density of the neutral species is orders of magnitude larger than for the ions and electrons, but the difference is smaller than in the E region, where the factor difference between the ion density and neutral density is in the order of millions. The density here is so low that the ion-neutral collision frequency is not dominant and the MHD approximation is valid, as already discussed in subsection 2.2.3. As the ideal MHD limit is valid, there is no significant horizontal currents, as were the case for the E layer.

2.6.3 Boundary layers/precipitation regions

In Figure 2.11 the dayside and nightside ionospheric boundary layers are shown, based on a statistical study by Newell et al. [2004] on particle precipitation as measured by DMSP satellites. Each layer has distinct particle precipitation, and is what defines the different layers. The dayside layers are described below, and is based on the work by Newell, Meng and others (Newell et al. [1991a,b, 2004], Lockwood and Smith [1993], Newell and Meng [1992, 1993, 1995, 1998]).

Central and Boundary Plasma Sheet The central (CPS) and boundary plasma sheet (BPS) is on closed field lines, and the field lines is located equatorward of the open-closed boundary on the dayside in the ionosphere and, as the name suggests, at the plasma sheet in the magnetosphere. In Figure 2.6 the plasma sheet in the tail is shown, not at the dayside extension to this sheet. The precipitation definition of these regions used by the earlier cited work is based on Winningham et al. [1975]. CPS precipitation is high-energy plasma with little spatial and spectral structure, and BPS with fewer high-energy ions and more low-energy electrons.

Low-Latitude Boundary Layer The Low-Latitude Boundary Layer (LLBL) is the boundary layer at and near the magnetopause at the equatorial plane. [Prolss, 2004] The LLBL has been seen to be on both closed field lines (mostly off noon) and open field lines
Figure 2.11: The dayside ionospheric precipitation regions, here for negative IMF $B_y$ and $B_z$. Convection patterns is overlaid in solid lines. From Newell et al. [2004]. The dayside (upper part) parts with the cusp (cleft), LLBL, BPS and mantle is precipitation from direct entry as can be seen in Figure 2.6 (often near noon). The plasma is a mix of magnetosheath and magnetospheric plasma, and the ion energies is at the range between a few hundred to a few thousands electronvolt. LLBL is distinguished from the cusp by that it is hotter and with slower bulk velocity, as well as lower density (a factor of around 5) and lower flux. The ion energy is usually between a couple of hundred eV (electron volts) and 3 keV.

**Polar cusp** Kallenrode [2004] defines the polar cusp as singularities where the magnetic field vanishes and plasma can freely penetrate into the ionosphere. In practice, it has a small latitudinal extension and broader longitudinal extension of about 3h MLT around noon. The polar cusp is characterized by high fluxes (compared to the rest of the high-latitude ionosphere), and ion energy peak at about 1 keV, and electrons has a temperature of about 30-100 eV. The densities are about $10^6$ – $10^7$ particles pr. m$^3$.

**High-Latitude Boundary Layer or Mantle** As the field lines move further over the polar cap, the precipitation is characterized by less energy and less flux, as is the case for the plasma mantle. It exists of decelerated, shocked solar wind particles, with ion energy below 1 keV. Also, there is not any low-energy cutoff seen in the mantle (which is the case in the cusp) as all particles have the time to reach the ionosphere after
a (pulsed) reconnection event on the open field lines. The temperature is typically around 100 eV, with densities of around $10^4 - 10^5$ particles pr. m$^3$.

**Polar rain** Polar rain is identified by Winningham and Heikkila [1974] as a near-background, structureless, low-energy electron population that precipitates over the ’unperturbed’ polar caps. In the polar cap on old-open field lines three different, but somewhat similar electron precipitation regions are found: polar rain, polar showers and polar cap arcs. [Gussenhoven, 1989] These are similar in number flux, but the energies is a bit larger for the two latter cases (with polar cap arcs as the highest). Note that a background precipitation is found across the high-latitude ionosphere, which is similar to polar rain.

### 2.6.4 Ionospheric currents

In space physics, there are three different types of currents: Pedersen currents parallel to the electric field and perpendicular to the magnetic field, Hall currents perpendicular to both the electric and magnetic field, and Birkeland currents perpendicular to the electric field and parallel to the magnetic field. Both the Pedersen and Hall currents are horizontal and are therefore purely ionospheric. As already noted, these currents exist mainly in the D and E regions.

A simple equation for an electric current is given by

$$ j = n e (v_i - v_e) $$  \hspace{2cm} (2.19)

where $v$ is the velocity (of ions and electrons respectively), $n$ the ion and electron density and $e$ is the elementary charge. This expression, however, assumes zero conductivity perpendicular to the electric field (hence, zero Hall and Birkeland currents). Generally an electric current is given by

$$ j = \sigma \cdot E $$

where $j$ is the current density vector and $E$ is the electric field vector. $\sigma$ is the conductivity tensor given by

$$ \sigma = \begin{pmatrix} \sigma_P & -\sigma_H & 0 \\ \sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_\parallel \end{pmatrix} , $$

where $\sigma_P$ is the Pedersen conductivity in the direction of the Pedersen current, $\sigma_H$ is the Hall conductivity, and $\sigma_\parallel$ is the Birkeland conductivity. We see that if $\sigma_H$ is zero, we have only Pedersen conductivity in the horizontal plane and hence we get back the simplified expression for the horizontal current in (2.19). The field-aligned Birkeland current comes from particle precipitation and is not taken into account in the simplified current expression. Note that the tensor $\sigma$ is nothing but a rotation matrix around the z-axis with a certain strength dependent on the conductivity (again with Birkeland conductivity not taken into account). Note that this is only valid for the D, E and lower F region.
2.7 Magnetosphere-ionosphere coupling

The main coupling between the magnetosphere and ionosphere takes place on field-aligned currents, called Birkeland currents after the Norwegian scientist that did pioneering work on these currents. In Figure 2.12, the Birkeland currents is clearly seen marked as region 1 and region 2, and is closed in the ionosphere with Pedersen currents. Region 1 currents are the poleward currents on field lines to the LLBL close to the magnetopause on the dusk/dawn flanks. Region 2 currents on somewhat lower latitudes are closed in the ring current discussed in the previous section. In the midnight, the Birkeland current overlap without a clear separation. [Kallenrode, 2004]

When taking a closer look at the right part of the figure, we see that Region 1 is closed over the polar cap from dusk to dawn by Pedersen currents. On the dawn side, Birkeland currents go upward/outward into the magnetosphere and close in the LLBL in the equatorial plane at the magnetopause. From there, a current flows over the High-Latitude Boundary Layer (HLBL) along the magnetopause over the polar cap, and around to the Region 1 dusk-side current back to the ionosphere. From there the Pedersen current goes again over the polar cap. There is another current system where the dusk-side Region 1 current is directed as Pedersen currents equatorward towards lower latitudes and upwards/outwards along the Region 2 current, which is closed to the ring current seen in Figure 2.6. Through the ring current, the system closes to the field-aligned Region 1 dawnside currents to the ionosphere, which again goes poleward though a Pedersen current, and the two electric current systems is then closed.

Electrons are the major current carrier. [Hoffman et al., 1985] An upward current is often associated with precipitating electrons, which can be further associated with aurora.
As we have seen, solar wind particles precipitate along magnetic field lines. These particles are the energy source of the aurora, but they only indirectly cause the aurora. The solar wind particles precipitate along the magnetic field lines, into the ionosphere where they excite neutral molecules and atoms. When an excited molecule relaxes to its ground state it gives off a photon at a certain wavelength, corresponding to the energy level of the excitation.

Figure 2.13 shows two of the excited energy levels for the atomic oxygen O. We will look at two cases: excitement to 1.96 eV and 4.17 eV. The ground level is 0 eV. When the molecule is excited to 4.17 eV, it will first relax to the 1.96 level and then further to the ground level. The average time it takes between excitement and relaxation is called the relaxation time $\tau$. The relaxation time for the green line is $\tau(4.17 \text{ eV} \rightarrow 1.96 \text{ eV}) = 0.8 \text{ s}$ and for the red line $\tau(1.96 \text{ eV} \rightarrow 0 \text{ eV}) = 110 \text{ s}$. These are the two most common emission lines in auroral physics research, and is hence the focus in this discussion. The molecule can also make the jump from 4.17 to the ground level, and will then give off a photon at 297.2 nm. In the lower ionosphere, the green jump is likely to happen before a collision occur because of the short relaxation time. For the red line, however, the relaxation time is so long that an excited molecule probably will collide with another particle and return to its ground state before emitting a photon. This is the reason why the red 630.0 nm line is not seen below 200 km where the density is too high for the red transition to happen.
2.9 High-latitude ionospheric instabilities

The high-latitude ionosphere is highly structured with irregularities spanning many different scale sizes from hundreds of kilometers down to meters. It is commonly distinguished between two types of plasma instabilities: micro and macro. Microinstabilities work on scales on the order of or less than the ion gyroradius (~10m at the F region), while macroinstabilities work on much larger scale sizes, and can be considered as fluid-like instabilities. [Keskinen and Ossakow, 1983] Different instabilities appear at and close to the polar cap, and we will briefly discuss two different instability mechanisms to provide the background and intuition, following the approach of Spicher [2013]. After that we will discuss the Kelvin-Helmholtz instability in-depth.

The wavenumber is \( k = \frac{2\pi}{\lambda} \), where \( \lambda \) is the wavelength. That is, \( k \) is a spatial frequency. The wave vector is a combination of the wave numbers in each spatial dimension: \( \mathbf{k} = k_x \mathbf{e}_x + k_y \mathbf{e}_y + k_z \mathbf{e}_z \). The wave vector points in the direction of the phase velocity of the wave, which is not necessarily the same direction as the group velocity.

2.9.1 The Rayleigh-Taylor instability

The Rayleigh-Taylor instability (RTI) exists mostly at low- and mid-latitudes, but it is intuitive to understand and good to use as a background.

The main idea of this instability is that a dense medium is accelerated into a less dense medium. Examples of this instability include water on top of oil accelerated by the gravity field and supernovae explosion of dense core medium accelerated by the explosion itself into a less dense shell medium. In this discussion we will use a simplification which is shown in Figure 2.14a: a medium with a certain density \( n_1 \) on top of a vacuum \( (n_2 = 0) \). The magnetic field \( \mathbf{B} \) is horizontally directed into the paper, and we assume we are at the equator in this case. The gravity is directed downward (negative \( z \) direction) and the density gradient at the interface in positive \( z \) direction (upwards). An electric field with an electric current is in positive \( y \) direction (also horizontal). We follow here the derivation of Kelley [2009].

In a collisionless plasma with spatially uniform temperatures of the species, with a density gradient and a gravitational component, in a reference frame of the neutral wind velocity denoted with "\(^\prime\)" the velocity of the species \( (j \) is either \( i \) or \( e \)), the velocity is \( \mathbf{u}_j^\prime = \mathbf{u}_j - \mathbf{u} \), where \( \mathbf{u}_j \) and \( \mathbf{u} \) is the species velocity and neutral velocity in the rest frame. The velocity perpendicular to the magnetic field for each species is

\[
\mathbf{u}_{j,\perp} = \left[ \mathbf{E} - \frac{k_j T_j \nabla n}{q_j} + \frac{M_j}{q_j} \mathbf{g} \right] \times \mathbf{B}. \tag{2.20}
\]

The parallel velocity component is given in equation (2.36a) in Kelley [2009].

A small perturbation is introduced at the interface as seen in the figure. The plasma is approximately as collision free, as is true for the F region. The gravitational term in (2.20) give a current with a magnitude \( J_x = nMg/B \) in the direction of \( x \), which is the
same direction as $\mathbf{g} \times \mathbf{B}$. Since the current is proportional to the density $n$, the current in the medium on the top will have a magnitude $J_{x,1} = n_1 M g / B$ and in the vacuum under will have no current, $J_{x,2} = n_2 M g / B = 0$.

This strictly horizontal current will, in the presence of a small perturbation as seen in the figure, lead to the build up of charges on the upper side of the interface which yield small perturbation electric fields $\delta E$. These electric fields will cause a force on the plasma by $\delta E \times \mathbf{B}$ which will further increase the build-up of charges, which again give an increase in the $\delta E$ field and $\delta E \times \mathbf{B}$ force, and an irregularity is clearly present. Note that this is only the case when $\nabla n$ and $\mathbf{g}$ are oppositely directed as is the case when the density of the medium on the top is larger than on the bottom. The opposite case is stable.

The typical development of the instability is shown in Figure 2.14b. The result is typically fingers in the mixed part of the two mediums, which is clearly seen in the case for $t_2$ on the right part of the figure.
2.9.2 Gradient drift instability

The gradient drift instability (GDI) is similar to RTI in some aspects as seen in Figure 2.15. The difference between these two is that GDI is seen at high-latitudes. Contrary to RTI, the gravity force is approximately in the same direction as the magnetic field, and will have little effect on plasma structuring. Here $x$ is in the western direction, $y$ is towards the closest pole and $z$ is in the vertical direction of the magnetic field.

We have an ambient electric field $E_0$ in the negative $x$-direction and a density gradient towards the pole (positive $y$). A perturbation with wave vector $k$ in the direction of the background electric field is introduced. With this perturbation in the F region ionosphere, the ions will drift in the direction of Pedersen current, and we will get a charge separation between the ions and the electrons. As in the case of RTI, this will generate a perturbation electric field $\delta E$ which again results in a $\delta E \times B$-drift, which again increase the separation. This is an unstable situation, and we have an irregularity.

The linear growth rate of this instability is for the F region

$$\gamma_{\text{GDI}} = \frac{V_0}{L} \quad \text{where} \quad L = \left[ \frac{1}{N_{e,0}} \frac{\Delta N}{\Delta x} \right]^{-1}$$

$L$ is called the gradient scale length and the drift $V_0$ in respect to the neutral gas [Tsunoda 1988; Moen et al. 2012].

2.9.3 Kelvin-Helmholtz instability

Another important instability for the high-latitude ionosphere is the Kelvin-Helmholtz instability (KHI), also called flow shear instability. Results of KHI are seen many places. Possibly the most well-known effect is surface waves on water: the two media water and air with breaking waves stabilized by the water tension along the direction of the wave vector. With increasing air speed the stabilizing effect will decrease, and
Figure 2.16: Setup of the Keskinen et al. [1988] KHI model. Flow velocities is in dark blue, electric field in light red, currents in magenta (pink), magnetic fields in dark green, neutral flow in light green, wave vector $k$ in cyan (light blue) and density in dark red.

The water waves will break with increasing $\Delta v$. The ionospheric magnetic field will have a stabilizing effect if it is directed along the wave vector $k$, which is not the case at high latitudes. The first work in this instability was performed by von Helmholtz [1868] and Thomson [1871], from whom the instability was named (William Thomson was also known as Lord Kelvin).

The theory for KHI is more complicated in a plasma than in a neutral medium. Important work for this discussion is the work of Keskinen and Ossakow [1983], and especially Keskinen et al. [1988], which did modeling work assuming electrostatic plasma.

To analyze the Kelvin-Helmholtz instability, Keskinen et al. [1988] starts with a simple model of the ionosphere and its coupling to the magnetosphere. The setup with different fields (electric and magnetic), velocities and currents is shown in Figure 2.16. The model assumes an electrostatic ionosphere, where the electric field is either stationary or slow-moving (low frequencies) which is the case in the F-layer. The electrostatic approximation is much used in modeling, often in large-scale potential studies (as the convection modeling using SuperDARN radars, explained by Shepherd and Ruohoniemi [2000] and many others), and also in turbulence studies (see Lagoutte et al. [1992] and the review by Kintner and Seyler [1985] and references therein). In the electrostatic limit, the magnetic field from currents is so small it can be neglected, and any currents come from the charge distribution of the ion layer seen in Figure 2.16a [Nishikawa and Wakatani, 2000].

The electrons follow the $\mathbf{E} \times \mathbf{B}$-drift, but not necessarily the ions, as they might deviate by a small amount as we will see in this section. As the process takes place in the F layer of the ionosphere, they assume that the ion gyrofrequency is large com-
Figure 2.17: Development of the density in Kelvin-Helmholtz instability from a numerical simulation. The time is shown in equally-spaced simulation steps. The boundary in horizontal direction is periodic. A small sinusoidal perturbation is seen at the interface in the first time step. This is not a MHD simulation, and is used to show how KHI development looks in general. Source: Wikimedia (user: Bdubb12).

pared to ion-neutral collision frequency and the characteristic frequency of the Kelvin-Helmholtz instability. Keskinen et al. [1988] perform the simulations with and without Pedersen and polarization currents, which implies that the ions follow closely, but not fully, the $\mathbf{E} \times \mathbf{B}$-drift. The ion drift is therefore the electron drift in addition to smaller terms from the Pedersen and polarization currents.

The electrons and ions are affected by recombination (see section 2.6.1), but since this does not have an effect on the structuring of the ion layer, recombination is neglected in the model.

It should be noted that the equations in Keskinen et al. [1988] are in CGS units, whereas this thesis uses SI units. The conversion of these equations from CGS to SI units is found in the appendix chapter A on page 99.
The ion continuity equation is
\[ \frac{\partial n_i}{\partial t} + \nabla \cdot n_i v_i = 0 \quad (2.21) \]
and the ion momentum equation is
\[ \left( \frac{\partial}{\partial t} + v_i \cdot \nabla \right) v_i = \frac{q_i}{m_i} (E + v_i \times B) + v_i (v_n - v_i). \quad (2.22) \]

Combining these two equations in the F-layer approximation give the ion velocity
\[ v_i = V + \frac{m_i}{q_i B^2} v_i (E + v_n \times B) + \frac{m_i}{q_i B^2} \left( \frac{\partial}{\partial t} + v_i \cdot \nabla \right) E \quad (2.23) \]
which consist of the large term \( V = E \times B / B^2 \) (which is the drift of the electrons) along with smaller terms for the Pedersen and polarization drift.

As already discussed a simple expression for current density is given as \( j = ne(v_i - v_e) \) and combining this with equation (2.23) and \( v_e = V = E \times B / B^2 \) makes the horizontal current (from the Pedersen and polarization currents)
\[ j = \sigma_p (E + v_n \times B) + c_M \left( \frac{\partial}{\partial t} + v_i \cdot \nabla \right) E. \quad (2.24) \]

Pedersen currents tend to reduce potential over the shear, while the polarization current slows that decay. The Pedersen conductivity is \( \sigma_p = \frac{n_i e m_i v_i}{q_i B^2} \) and \( c_M = \frac{n_i e m_i}{q_i B^2} \) is the inertial capacitance. They assume that all currents must close inside the model, which gives
\[ \nabla \cdot (J_{\text{Ped}} + J_{\text{pol}}) = \nabla \cdot \left[ \Sigma_p (E + v_n \times B) + C_M \left( \frac{\partial}{\partial t} + v_i \cdot \nabla \right) E \right] = 0 \quad (2.25) \]
for the field aligned divergence of the current. Here \( v_n = \frac{1}{\Sigma_p} \int \sigma_p v_n dz \) is the conductivity-weighted average neutral field line-integrated velocity. The strength of these currents are given by the field-line integrated Pedersen conductivity \( \Sigma_p = \int \sigma_p dz \) and the field-aligned integrated inertial capacitance (for the polarization current) \( C_m = \int c_m dz \). The relation between these two, \( \nu = \Sigma_p / C_m \), is the inertial relaxation rate. This rate affects the growth rate of the instability. Pedersen currents are mainly driven in the ionosphere, and the inertial capacitance effect is mainly in the magnetosphere.

In the electrostatic limit, the E-field is given as \( E = -\nabla \phi \), and then the ion continuity equation for each layer is given as (when using that \( A \times B = -B \times A \))
\[ \frac{\partial n}{\partial t} + \nabla \cdot n \frac{B \times \nabla \phi}{B^2} = 0. \quad (2.26) \]
Substituting the new E-field in equation (2.25), we get
\[ 0 = \nabla \left[ \Sigma_p (\nabla \phi - v_n \times B) + C_M \left( \frac{\partial}{\partial t} + \frac{1}{B^2} B \times \nabla \phi \cdot \nabla \right) \nabla \phi \right]. \quad (2.27) \]
They assume further that the source of the instability is the magnetosphere, which is consistent with the RFE creation hypothesis of Moen et al. [2008] for the source of the RFEs. They also assume a density gradient, as is the case over the magnetopause. The field-line integrated density is \( N = \int n \, dz \), from which it follows that \( \Sigma_p \) and \( C_M \) are proportional to \( N \). In that case, the relaxation rate \( \nu \) is a constant for each simulation run. The development of the instability is dependent on the relationship between the growth rate \( \gamma \) and \( \nu \). We can use this to modify equation (2.26) and (2.27) to

\[
\left[ \frac{\partial}{\partial t} + \frac{1}{B^2} (B \times \nabla \phi) \cdot \nabla \right] N = 0
\]

(2.28)

and

\[
0 = \nabla \cdot \left[ \nu N (\nabla \phi - V_n \times B) + N \left( \frac{\partial}{\partial t} + \frac{1}{B^2} (B \times \nabla \phi) \cdot \nabla \right) \nabla \phi \right].
\]

(2.29)

Equation (2.28) and (2.29) simulate the electric potential \( \phi \) and the density \( N \). In the electrostatic limit in the F region, \( V_n \) and \( B \) are constant.

We will now shift to the linear growth theory of KHI. The perturbations introduced have a wave vector along the x axis with a frequency \( \omega \), hence giving

\[
N(x, y, t) = N(y) + \delta N(y) \exp \left[ i(kx - \omega t) \right]
\]

(2.30)

and

\[
\phi(x, y, t) = \phi(y) + \delta \phi(y) \exp \left[ i(kx - \omega t) \right].
\]

(2.31)
Using this in Equation (2.28) and (2.29) yields
\[
(\omega - kV_x)\delta N = \frac{k}{B} \frac{\partial N}{\partial y} \delta \phi,
\]
(2.32)
where we have used that \( V = E \times B / B^2 = -\nabla \phi \times B / B^2 \) which gives \( V_x = (\partial \phi / \partial y) / B \), and further
\[
(\omega - i\nu - kV_x) \left( \frac{\partial}{\partial y} \left( N \frac{\partial \delta \phi}{\partial y} \right) - N k^2 \delta \phi \right) = -k\delta \phi \frac{\partial}{\partial y} \left( N \frac{\partial V_x}{\partial y} \right) - i\nu B N (V_n - V_x) \frac{\partial}{\partial y} \frac{\delta N}{N}.
\]
(2.33)
Substituting one of these into the other, one arrives at the equation
\[
\frac{\partial}{\partial y} \left[ A \frac{\partial}{\partial y} \left( \frac{\delta \phi}{\omega - kV_x} \right) \right] = k^2 A \left( \frac{\delta \phi}{\omega - kV_x} \right),
\]
(2.34)
where
\[
A = \frac{(\omega - kV_x)(\omega + i\nu - kV_x)}{V_n - V_x}.
\]
The solution for this equation is given for five different values of \( \nu^* = \nu / (V_0 / L) \) in Figure 2.18. The maximum growth rate when assuming no density gradient is
\[
\gamma_{\text{max}} = 0.19 \frac{V_0}{L}
\]
(2.35)
at 0.44kl. We will use this equation in Chapter 4. With a density gradient and non-negligible Pedersen current, \( \nu \neq 0 \), the growth rate decreases.
2.10 Flow channel events

Flow channels are a frequently occurring phenomena at high-latitudes. There are principally three classes of flow channels: the enhanced flow channels that have increased velocity in the direction of the surrounding background convection velocity, reduced flow channels with lower velocity compared to the background flow but still in the same direction as the background and the reversed flow channels where the flow velocity is in the opposite direction of the background. It is believed that reduced flow is a special case of reversed flow channels, and that they belong to the same category. We will discuss these three categories in detail in the following sections.

2.10.1 Enhanced Flow Events

There are potentially many different causes for flow channels in the high-latitude ionosphere. Sandholt et al. [2004] found three different types flow channels in the dayside ionosphere on (i) closed, (ii) newly opened and (iii) old-open field lines. They chose two days of semi-stable (December 3th, 1997) and very stable (December 12th, 1999) solar wind conditions, both for \( B_z < 0 \) and \( B_y > 0 \). For these days, they used all-sky camera and meridian scanning photometer in Ny-Ålesund over several local hours as Svalbard passed magnetic noon from dawn to dusk. They found different types of aurora, and compared these with current systems found with DMSP satellites.

(i) Moen et al. [1995] used the Tromsø EISCAT radar to locate several flow channels on closed field lines of sunward return flow. Using two beams with slightly different azimuth angles pointing north, a vector of flow velocity is given when assuming the velocity is constant over the two beams (SP-UK-CONV mode of EISCAT). An example of one of these flow channels is shown here in Figure 2.24a. See also their Plate 3. They did not have any direct solar wind data, but the flow measurements from several passes of DMSP satellites suggests \( B_z \approx 0 \) and \( B_y < 0 \). Lockwood et al. [1993] also did similar work on such flow channels using EISCAT, see their Figure 4 for another case of this. Both Moen et al. [1995] and Lockwood et al. [1993] attributes these enhancements to pulsed reconnection at the magnetopause.

(ii) Another type of flow channel is located on newly opened flux. Transient reconnection suggests a kind of flux tube (a qualitative sketch of a flux tube from Russell and Elphic [1979] is shown in Figure 2.19a, their Figure 2) that transfer magnetic flux from the magnetopause to the ionosphere. These transfer events are called Flux Transfer Events (FTE). The flux tube have an upward Birkeland current on one side and downward on the other side, [Southwood, 1987] which will cause a distinct meso-scale footprint flow with locally enhanced flow inside and return flow on the outside of the tube with Pedersen currents closing the current system of the Birkeland currents. This is the Southwood [1987] model of the footprint of an FTE, shown in Figure 2.19b. Search of such signatures has been ongoing (e.g. Pinnock et al. [1993], Rodger and Pinnock [1997] and McWilliams et al. [2001]), but the limited field of view of ground based radars and the one-dimensionality of satellites make the search challenging. Moen et al. [1995] comment that the flow enhancement in Figure 2.24a could not been a part of an FTE footprint because the flow does not turn, as would be the case for the elliptic flow in such footprints.
(a) A qualitative sketch of a flux tube at the magnetopause. Suggested by and taken from [Russell and Elphic 1979].

(b) The Southwood model of the ionospheric footprint of an FTE. Taken from [Southwood 1987].

Figure 2.19: Suggested forms of Flux Transfer Events, at the magnetopause (left) and the ionosphere (right).

[Pinnock et al. 1993] showed an enhanced flow channel without weak return flow, and interpreted this as an FTE footprint. Figure 2.24b show one of the scans (the weak return flow is seen only in the overlaid satellite pass) from the PACE radar containing the flow channel. They called this a Flow Channel Event (FCE). They believed that the actual flow channel extended across the whole backscatter area as enhancements was seen in both ends of the scan, and points out that the radar only measures line-of-sight velocity. The flow channel was approximately 900 km long. [Provan et al. 1998] called the flow enhancements on newly open flux pulsed ionospheric flows (PIFs) to distinguish these from other flow channels (e.g. (i) and (iii)), though with slightly different characteristics [Oksavik et al. 2011]. [Provan et al. 2002] showed data of PIFs from the SuperDARN Hankasalmi radar, as seen in Figure 2.24c. The radar data clearly show poleward enhancements, and the repetition rate of the enhancements resembles the repetition rate of the transient reconnection. The motion of PIFs (as in in [Pinnock et al. 1993] and [Provan et al. 2002]) is a result of the magnetic tension force on the flux tubes of the $B_y$ IMF component. $|B_y| \gg 0$ results in motion more equatorward then the poleward convection of IMF $B_y \approx 0$. For the data in [Pinnock et al. 1993] $B_y$ was negative and positive (+4 nT) in [Provan et al. 2002]. $B_z$ was negative in both cases.

(iii) The flux tube in case (ii) will convect tailward and the flux far into the polar cap is called old-open. On old-open flux, work by Sandholt and Farrugia have shown that the HLBL dynamo set up Birkeland currents and Pedersen currents at the ionosphere give closure of the current system. These Pedersen currents give (forward) flow enhancements tailward. [Sandholt et al. 2010] call the Birkeland currents the C1
(downward) and C2 (upward) currents. This is to relate them to the R1 and R2 regions that map to the LLBL and the ring current respectively more equatorward of the C1 and C2. DMSP data from one of the flow channel is shown in Figure 2.24d. A sketch of a typical current setup suggested in Sandholt et al. [2010] is shown in Figure 2.20.

### 2.10.2 Flow structures and Reversed Flow Events

The Special Norwegian Fast Azimuth Scan Mode (SP-NO-FASM) of EISCAT (see Section 3.1.3) used in the studies gave a new view of the ionosphere. Oksavik et al. [2004, 2005] found two clear channels of reversed flow compared to the background flow, with a narrow channel of flow in the direction of the background with similar speed. They also found poleward moving auroral forms (PMAFs) in the poleward most flow channel that moved along with the flow channels also convecting poleward, and as we will come back to, this seemed to be clear evidence of an FTE footprint as suggested by Southwood [1987] (see Figure 2.25 for the location of PMAF in relation to the RFE). A train of such events was found, see Oksavik et al. [2005, Figure 3] (as Figure 2.25a is cropped from).

Rinne et al. [2007] termed this type of flow channel Reversed Flow Events (RFE), and did a statistical study of the phenomenon using the EISCAT Radar in Longyear-
byen. The RFE criteria were:

1.: It must be present in more than one consecutive radar scan.
2.: The background line-of-sight flow must be larger than 250 m/s and the reversed flow larger than 250 m/s in the opposite direction. This makes a velocity shear of at least 500 m/s of line-of-sight velocity. If the channel is not parallel to the radar beam, this makes the real velocity larger by $v_{\text{real}} = \frac{v_{\text{l-o-s}}}{\cos(\theta)}$.
3.: The longitudinal extent must be larger than 400 km.
4.: The flow channel must be in clear contrast to the background flow, and the background must be uniform.
5.: The RFE must be embedded within the background flow for at least one scan, to avoid $B_y$ changes (see under).

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3.: The longitudinal extent must be larger than 400 km.
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5.: The RFE must be embedded within the background flow for at least one scan, to avoid $B_y$ changes (see under).

Rinne et al. [2010] showed several flow reversals that first looked like RFEs (see Figure 2.21), but the reversals grew in width and it was shown that this was because of two changes in $B_y$ polarity. They attributed this flow reversal to the magnetic tension. This show that caution must be used in identifying RFEs by radars.

Rinne et al. [2007] located 21 unique RFEs in a total of 767 radar scans with RFEs in 16% of the scans and average lifetime of ~19 minutes, and these where approximately normally distributed around 11:45 MLT with very few found before 11:00 MLT and later than 12:45 MLT (steep decrease at 12:45 MLT). It is to be noted here the fact that the distribution is skewed slightly towards postnoon could be because of the EISCAT data is biased towards positive $B_y$ and there is few measurements after 12:45 MLT. It could seem like that the real distribution is normally around 12:00 MLT with a half-width at about 11:00-11:30 and 12:30-13:00, but with only 21 observations this is to be considered only speculations.

One important observation by Rinne et al. [2007] is that RFEs never appear in pairs. They found coexistence in only three cases, and the time delay between the RFEs was in those cases 13, 17 and 36 minutes. The Southwood model of FTEs used by Oksavik et al. [2004, 2005] requires two return flows that develop simultaneous, not with the observed delay. The Southwood FTE explanation cannot be correct in the RFE case.
Rinne et al. [2007] suggested that with a strong $B_y$-component an FTE could develop with a single return flow, not the twin cells seen in Figure 2.19b. See their Figure 6 and its text.

Also reduced flow speeds was found in the ESR data. This is plasma that is slowed down compared to the background convection, but not reversed. These events have been termed Flow Structures (FS) in Rinne et al. [2007]. Moen et al. [2008] speculates that the RFEs might only be the "top of the iceberg" of the RFE phenomena if these reduced flow channels is of the same cause and is principally underdeveloped RFEs [Rinne et al., 2007] and therefore belong to the same class of channels. FS' are observed 31 times compared to RFEs 21 times, and was observed in $\sim 7.8\%$ of the scans.

Moen et al. [2008] put forward two explanations of an RFE: two magnetosphere-ionosphere current loops and a coupling region of type inverted V. They suggested that the poleward part of the RFE is on newly opened flux in the cusp while the equatorward could be a subsequent flux transfer event or it could be on closed field lines (see their Figure 6). In the case of closed field lines the R1-R2 current system maps to the LLBL and ring current respectively. In the cusp area there is a different current system which was attributed to reconnection and driven by the solar wind. As Moen et al. [2008] pointed out, the voltage generators is different and independent, so it might be that there is a E-field discontinuity between them that could be the potential difference we see as flow driven the other way, see Figure 2.23 (the potential is given as the sum $\Sigma v \cdot B \, dl$ across a velocity shear). This means that there is a potential difference and hence an electric field, and it is likely that this potential would even itself out, thus
creating the flow seen. They explained that if there is no electron precipitation inside the shear and no sunlight, the height-integrated Pedersen conductivity would be very low yielding a strong E-field. They pointed out that if this is true, there must be a summer/winter asymmetry of RFEs, as the Pedersen conductance is large if the area is sunlit. The second explanation, that might be related to the current loop explanation, is inverted-V electron precipitation. There might be lack of electrons to close a current through the existing potential, and the inverted-V accelerated electrons might be the mechanism to feed this current. Inverted V should be easy to see in a satellite spectrogram (an example of a spectrogram is in Figure 2.24d from a DMSP satellite), where the shape is an inverted V [Paschmann et al., 2003, page 100].

Moen et al. [2008] also found that some, but not all RFEs follow a PMAF that is always present during the event. A PMAF is closely related to an upward FAC current [Sandholt and Farrugia, 2007]. In Moen et al. [2008, Figure 5], it is clearly seen that RFE #18 followed a PMAF, but RFE #19 did not follow a later PMAF (the numbers are RFE events in Rinne et al. [2007]).
(a) A forward enhanced flow channel on sunward return flow of closed field lines. Note that the horizontal axis is local time. Lower latitudes are a part of the background flow, and the enhanced flow is clearly visible on higher latitudes. From Moen et al. [1995]. (Type i.)

(b) Forward enhanced flow channel on newly opened field lines. Pinnock et al. [1993] suggests that the flow channel seen in yellow actually extend across the backscatter area (see the text for more). From Pinnock et al. [1993]. (Type ii.)

(c) A series of flow channels on newly opened flux in the cusp ionosphere. This show typical repetition periods of reconnetion pulses. From Provan et al. [2002]. (Type ii.)

(d) DMSP satellite measurements of a flow channel on old-open field lines, showing the C1 and C2 Birkeland currents. Taken from Sandholt et al. [2010], and its essential to compare this with their text. (Type iii.)

Figure 2.24: Measurements of forward enhanced flow channels

37
Figure 2.25: The reversed flow events found in Oksavik et al. [2005] in relationship to PMAFs. The sketch is derived from Southwood [1987] (see Figure 2.19b) by Oksavik et al. [2004] to show where they think the PMAF appears in an FTE.
Chapter 3

Instrumentation

This chapter presents the instrumentations used in this thesis. Two different kinds of radars, a sounding rocket, optics and three different spacecrafts are used, with the primary instruments being the steerable 32m dish of ESR and the ICI-3 sounding rocket. To correctly use and interpret data it is important to understand how the instruments work and, more importantly, their limitations.

3.1 EISCAT Svalbard radar and incoherent scatter

This section is based largely on the curriculum of the ISR Radar School 2007 from the EISCAT website.

The EISCAT Svalbard Radar (ESR), is located just outside Longyearbyen on the Svalbard archipelago. In this section we will discuss the incoherent scatter radar (ISR) technique.

3.1.1 Incoherent scatter radar

The ISR technique relies on the random thermal movement of the ions and electrons in a plasma. The coherence of any medium is given by how quickly density gradients changes in the medium, and in the case of incoherent scatter, the thermal movement of the plasma changes much faster than the radar measurements integration period. Any medium has thermal fluctuations, and the higher the temperature of the medium, the faster the thermal movement of the plasma ions and electrons.

ISR have large dishes and send high-powered electromagnetic pulses to the ionosphere. When the pulses reach the ionosphere, it’s electric field accelerates electrons in the plasma. When charged particles become accelerated they emit an electromagnetic pulse at the same energy/frequency as the pulse that accelerated it. The pulse is emitted at a random direction. This is what is called Thomson scattering. When looking at a large amount of such particles, the emitted pulse from a given volume is isotropic, that is, equal intensity in all directions. Since the radiation is isotropic, some of the radiation reaches back to the radar which can again be measured as the radar now works as a receiver rather than a transmitter. The received signal is very faint,
(a) Incoherent scatter radar return from the Millstone Hill Observatory radar. Return points in green, and the best-fit (approx.) model in red solid line.

(b) Theoretical incoherent scatter spectrum and the derived parameters. The electron density is proportional to the integral of this curve.

(c) Variation of the ISR parameters

Figure 3.1: The incoherent scatter radar returns. Experimental on the left and theory on the right. The x-axis is not true frequency, but the frequency shift from the transmitted signal. The derived parameters are electron and ion temperature, electron density and line-of-sight ion velocity. Remember that in the F region, the ion velocity equals the electron velocity, which is not true for the D and E region.

and a large high-gain antenna and a very sensitive receiver are required to make the measurements.

The velocity in reference to the ground of a single ion in the ionosphere is a sum consisting of the thermal velocity of the particle and the bulk velocity of the medium

\[ v_e = u_e + v_{th}, \]
where $v_{th}$ is the thermal velocity as described over and $u_i$ is the bulk ion speed. The radar can not measure the thermal velocity, but it can measure the collective temperature of it. The radar can also measure the bulk ion velocity.

Described here is a simplified case of the measuring technique. Two different overlapping Maxwellian-like distributions are received, centered on the bulk velocity. The theoretical distributions as well as a case of experimental data from the Millstone Hill-radar is shown in Figure 3.1. The received pulse is sampled at many times a second, and applying a Fourier transformation of the measured signal one moves from the time domain to the frequency domain. In the frequency domain the autocorrelation function is fitted a model, and a best-case of the model is found based on the measured frequencies. From this model one can measure the temperatures of the ions and electrons. The bulk ion velocity is measured from the red or blue-shift of the signal. The electron density is proportional to the integral of the model fit. With use of the Fast Fourier Transform (for a discretely measured signal) and new computers, this calculation can be done in near-real time, which is important during scientific campaigns.

### 3.1.2 ESR and its unique location

![The two ESR radar dishes. The steerable 32m dish in the left and the 42m fixed along magnetic zenith on the right. Photo by Yvonne Dåbakk.](image)

The EISCAT (European Incoherent Scatter) Scientific Association is a foundation shared between China, Japan, Norway, United Kingdom, Finland and Sweden, with other collaborating nations not part of the funding and operational cost. There are three different radars in use: Longyearbyen (as discussed), a VHF radar in Tromsø
and a tristatic radar with one transmitter in Tromsø and three receivers (in Tromsø, Kiruna and Sodankulä). In Tromsø there is also a ionospheric heater which can modify the ionosphere to create artificial aurora.

The location of ESR is quite unique in terms of scientific phenomena. Svalbard is perfect for studying the dayside ionosphere and the ionosphere-magnetosphere-solar wind connection. The location of the radar in relation to the Andøya Rocket Range (ARR) and SVALRAK (Svalbard Rocket Range, located at Ny-Ålesund) is important, as rockets can be launched into structures measured using ESR and other instruments. A lot of different instruments, most of them passive, are located in Longyearbyen and at Ny-Ålesund, which contributes to the success of Svalbard as a very important place for space physics research. For night time observations mainland Norway and Sweden are better places to do observations as the auroral oval is located more southward geographically.

3.1.3 The ESR SP-NO-FASM mode

![Figure 3.3: The SP-NO-FASM ESR scan mode. The azimuth direction used here is only an example, and other intervals is also used in the dataset.](image)

The way the steerable ESR antenna is used depends on the purpose of the measurements made. The transmitted pulse also varies with the height of the measurements. In 2001 a new mode was used for the first time, SP-NO-FASM, and was used to monitor polar cap patches by Carlson et al. [2002]. It was found, quite surprisingly, small velocity structures never seen before. These structures are discussed later in the thesis.

The mode is called a windshield wiper mode scanning from side to side in azimuth with a 30° elevation (the lowest possible for ESR). See Figure 3.3. The mode is often scanned 120° azimuth in direction dependent on the magnetic local time in direction with the background flow. Scans are done at a rate of 0.625°/s and using 192 seconds when scanning 120 degrees azimuth have shown to work well. 360 degrees have also been scanned. 120 degrees is used because it results in great spatial and temporal resolution with a relatively large field-of-view allowing observations of structures (density or others) passing by over the dayside polar cap.
The dataset used in this thesis is the SP-NO-FASM measured around magnetic noon (which is around 0900 UT at the ESR site) in January and December, 2001.

The map projection is important to understand while reading this thesis. Figure 3.4 shows an example of a SP-NO-FASM scan on the 18th of December, 2001. The scan shows plasma velocity, and no velocity structures can be seen. Since the ESR is scanning with a fixed elevation of 30° the measurements close to the radar are from a lower altitude than farther away from the radar. Marked on the top of the fan are some of the different heights. The closest measurement in this case is done at approx. 116 km, and as the distance from the radar increases, the altitude over the sea level increases and the measurement farthest away is at about 585 kilometers altitude. The 2-3 closest measurement points are from the E region where the ideal Ohms law does not apply. The 2-3 measurements at highest range gates are usually not very reliable and often not plotted as they are labeled by the integration software (GUISDAP) as not trustworthy. The main reason for this is that these measurements are done at an altitude where the density is too low to give a strong enough backscatter signal. The widths of the cells span from about 7.6 kilometers at the closest and 34.5 kilometers at the farthest cell. In the title of the figure the scans are labeled with either ‘cw’ or ‘ccw’ for clockwise or counter-clockwise, respectively. This means that two consecutive scans will done measurements on one of the sides close to each other in time, and the other sides farther away in time.

Also important when investigating these plots is that, as already stressed several times, when the ion velocity is shown, it is always the line-of-sight velocity that is shown, if not specified otherwise. Positive velocity is away from the radar, and negative values are towards the radar. The ESR location is shown with a pink asterisk.
Figure 3.5: SuperDARN ionospheric scatter and true velocity vector

and the gray solid line shown as a straight line is the approximate location of the magnetic noon, which was about 0907 UT in December, 2001 (taken from the SuperDARN software).

3.2 SuperDARN chain of radars and coherent scatter

This section is largely based on Greenwald et al. [1995].

SuperDARN radars are quite different from ISR. Both types of radars measures the same medium, but the technique and usages differs from one another.

3.2.1 Coherent scattering

In the last section we discussed incoherent scatter and the coherence of any medium. Incoherent scatter is dependent on the thermal fluctuations in the measured medium, which is always present. A signal will in principal always be possible to measure, but in practice this is dependent that the density is "high enough" that the medium returns a strong enough backscatter signal.

At high-latitudes the magnetic field is nearly perpendicular to the ground (vertical) and any plasma irregularities will be bound to the field lines. That means that the wavenumber vector is perpendicular to the field line, that is, (near) horizontal to the ground. CSR use the HF frequency band, as VHF will pass straight through the ionosphere when the field lines are directed vertically, as shown in Figure 3.5a. The
frequency band which is used is 8-22 MHz, which correspond to wavelengths of about 14 to 37 meters. Normally the operating frequencies is between 12-14 MHz, which correspond to wavelengths of 21-25 meters.

When the signal from the radar approaches the irregularities in the ionosphere, the density structures are in the direction perpendicular to the signal. The permittivity changes over the structure and the signal and constructive interference give strong backscatter received by the monostatic radar site. This is analogous to Bragg scattering in crystals. For constructive interference to happen, the wavelengths of the irregularity structure will have to be one half of the radar signal wavelength.

3.2.2 The SuperDARN radars

SuperDARN is an acronym for Super Dual Auroral Radar Network and is a network of radars in the high and middle latitudes in both northern and southern hemispheres. The network consists of 21 radars in the northern hemisphere, and 11 radars in the southern hemisphere.

As the name suggests, the radars work in a series of two radars with nearly perpendicular fields-of-view. When two measurements are taken at the same time in orthogonal directions, the two samples can be combined and a horizontal velocity vector obtained, see Figure 3.5b.

A picture of the Saskatoon SuperDARN radar in Canada is shown in Figure 3.6. The main antenna array is on the right, and is the transmitter of the radar signal. Such arrays of several fixed antennas are steered using electronically controlled phased delays. This makes it possible to cover large azimuthal directions in short time spans, as no moving parts are involved. The azimuthal resolution is dependent on the frequency which is used. For the normal frequency band this is about 4°. The antenna arrays consists of 16 log-periodic antennas at a height of 16 meters. This main antenna array is located 100 meters in front or behind of a second array consisting of four antenna sets which is used as a interferometer measuring the relative phases of the incoming signal, from which the elevation of the returning signal can be derived.
From this, one can get the range and the approximately altitude of the incoming return signal.

The three primary parameters measured by the radars are the line-of-sight plasma velocity, the backscattered echo power and the spectral widths. The spectral width is a measurement of the velocity activity. Moen et al. [2001, 2002] used spectral widths of 220 m/s as a discriminator for the cusp. Baker et al. [1995] and Rodger et al. [1995] used 250 m/s as a discriminator, and Rodger et al. [1995] found spectral widths up to ~500 m/s in the cusp region using the PACE HF radar at Antarctica.

The advantage of using CSRs compared to ISRs is that these are low-power radars using about 2 kilowatts and they are relatively cheap to build. The low power consumption enables for continuous operation. Another advantage of the technique is that the field of view covers a relatively large area of $4 \times 10^6 \text{ km}^2$. The normal range resolution is about 45 km (300 ms pulse signal), and 100 km width at a range of 1500 km. The range of the radar is about 3000 km, with an azimuthal angle of 52°. A typical common spatial area of a pair of radars spans $15^\circ$ – $20^\circ$ MLAT and 3h MLT. The azimuth interval is usually divided in 16 beams. Different operational modes exists, but the scans is usually done in either 1 or 2 minutes. Oksavik et al. [2011] found a RFE flow channel using the SuperDARN Hankasalmi CUTFASS radar. This shows that even smaller-scale structures like RFEs may in some cases be seen using HF radars.

A disadvantage of CSR is that, although the field-of-views are huge, the measurements itself are scarce, and if these irregularities is not there, the radar will not receive any backscatter. Ground scatter is often seen and marked by the software.

### 3.2.3 The use of SuperDARN

The combination of the radars as a network opens up for important research on large-scale ionosphere physics. The dual radars measure the true velocity vector, and with several such pair of radars spread around the poles, and approximation to the large-scale convection can be found. Ruohoniemi and Baker [1998] give an introduction to this technique. The measurements from the radar site are transferred to a central server in near real-time and the data is fitted to a spherical harmonics model, usually with the order of 8. If there are few real velocity measurements, the model is also combined with statistics from the IMF and other solar wind parameters. Using data fits, as shown in Figure 3.8, it is important to note the number of real data points. If it is low, the model is based mostly on statistics and might not be real. [Ruohoniemi and Baker, 1998]

### 3.3 ICI-3 rocket

This section is based partly on the Flight Requirements Plan, as prepared by the Andøya Rocket Range before the launch.

The Investigation of Cusp Irregularities (ICI) program is a part of the 4DSpace program at the University of Oslo, with Jørøn Moen as the Principal Investigator (PI).
Figure 3.7: An example of the two CUTLASS radar pair showing the backscatter power. The field-of-view is large compared to ESR (see for example Figure ), but the measurements scarce. The ESR site is marked by the pink asterisk. Ground scatter is shaded gray.

The primary scientific objective is to make in-situ measurements of the irregularities seen in or near the dayside cusp. The two primary irregularities investigated are GDI and KHI, which were discussed in Section 2.9. All rockets have been launched from Ny-Ålesund during winter time. The first rocket, ICI-1 failed before it got to do any scientific measurements. The second rocket, ICI-2, was launched in 2008 into a polar cap patch, and was a success. The third rocket, ICI-3, launched at 07:21:31 UT on 3rd of December, 2011 into a flow channel, and the data will be discussed further in Section 4.2. The rocket reached an apogee (maximum height) of 350 kilometers and the rocket flight lasted about 10 minutes.

3.3.1 Physical dimensions and flight path

Figure 3.10 shows a sketch of the ICI-3 rocket. On the top the payload section of the rocket is shown with the physical dimensions. The payload is made up of three sections: the electronic and nose cone section, the hotel section and the service section. Under the service section is the igniter and the motors. The scientific part of the rocket is the nose cone, the electronics and the hotel sections. In the nose cone and hotel sections the six booms of the rocket are mounted. These are an important part of the experiments, which we will return to when describing the different experiments. In the middle of these the electronic section is placed. The service section contains the technical part of the rocket, which are the responsible of the ARR. This is where the electronics gathers, convert and send the data through the four antennas.

As we see in the figure, the payload structure is 35.6 cm in diameter and almost 3
Figure 3.8: SuperDARN convection example plot, at the same time as Figure 3.5. The convection equipotential is shown as solid (negative) and dashed (positive) lines. A dot with a short line is the velocity vector, given by the location with a dot and length and color of the for the speed and direction. Note that the sun is upwards, as given by the noon MLT line and every 6 hours (0/24, 6, 12 and 18h).

For sounding rockets there are two different methods of stabilizing the rocket body: spin-stabilized and active stabilizing. Active stabilizing is used by controlling the attitude of the rocket by actively steer the engine nozzle to the opposite direction as to where one want to go. With this method one has the ability to maintain a certain height during a part of the rocket flight. This makes the technical solution more complicated and expensive. Spin-stabilization is a more reliable solution as there are less parts that can malfunction during the launch. The rocket is launched, and driven into a spin (about 4 Hz was used by the ICI-3 rocket). The spin is maintained throughout the
flight and ideally the coning of the rocket is small and negligible for the measurements.

The flight path of the rocket is shown in Figure 4.4 on page 61. From Ny-Ålesund, which is located at 78.9° N and 11.9° in geographic coordinates, the rocket was launched equatorwards and falls in the northern Atlantic ocean. The maximum velocity was 2480 m/s at 55.7 seconds and minimum speed at the maximum altitude was 889.9 m/s at 313 seconds.

3.3.2 Electric field measurements

In Section 2.2.3 ideal MHD was discussed as a valid fluid approximation in the F region ionosphere, where the ICI-3 spent most of its flight. The ideal Ohms law states that the plasma, both ion and electrons, have the velocity $v = E \times B / B^2$. Thus, when measuring both the magnetic and electric fields, one can approximate the velocity from this equation. Field measurements are easier to do, and high-frequency sampling is possible. The effective sampling frequency of the E-field measurements is 362 Hz, which correspond to a spatial resolution of 2.46 meters at the peak altitude when the speed is at its lowest. The Nyquist frequency is at half the sampling frequency, and the resolution will effectively be double of this.

As seen in Figure 3.9(b) and in Figure 3.10, the rocket has six booms which unfolds at a certain height. Four booms are located at the front of the rocket, inside the nose cone during launch, and additional two booms inside the hotel section in the middle of the payload section. One E-field probe is on each of the booms in front, and on one of the probes in the mid-section. This allows for three-dimensional measurements. Each probe measures an electric field potential, and the potential difference $\Delta \phi$ between these divided by the length between the probes gives the E-field, since the E-field is
Figure 3.10: The physical measurements of the ICI-3 rocket, along with the position of the different sensors. The entire payload is shown on the top, the three different parts on the low left and the rocket in flight with unfolded booms. The three different sections is the electronic section on the top, the hotel section in the middle and the service section on the bottom part, which is all mounted on top of the motors. Illustration by Andøya Rocket Range.

given by $E = \nabla \phi \approx \Delta \phi / L$. As there are five probes, two in each direction perpendicular to the rocket direction, and one behind these, the electric field in three dimensions are measured. The two double probes in the front are orthogonal. The diameter of the probes is 45 mm, which is much larger than the Debye length of the F region (~5-20 mm). The Debye length is dependent on the electron temperature and density, and with a electron temperature of 2000 K and density of $10^{11} \text{ m}^{-3}$ the length is 8.49 mm.

ICI-3 had a spin of 3.485 Hz. This is easily seen in the E-field data and need to be removed. The spin frequency and also some of its higher harmonics need to be removed, and we have done this in the data for this thesis. First, we start by doing a Fourier transform of the data using Fast Fourier Transform (FFT) which is for discrete signals like this. This transform the data from the time domain to the frequency domain. Then, a commonly used method for removal of unwanted frequencies is to just set the unwanted frequencies to 0. Doing so removes some of the physically correct background information, which is not desired. What we have done here is to set the frequency band around the unwanted frequency to the average of the frequency levels around it, which is then a best guess of the background signal. Manual inspection
of the frequency data showed that the spin frequency and the first three higher harmonics are dominant in this data, and were removed. Higher harmonics were not significant and is left in the data.

### 3.4 DMSP spacecrafts

The Defense Meteorological Satellite Project (DMSP) monitors the atmosphere and near-earth environment. The spacecrafts are in a 101 minutes sun-synchronous near polar orbit with a height of about 830 km. This is the uppermost region of the ionosphere. A number of spacecrafts have been launched during the years, and the current line of spacecrafts include seven scientific instruments, most of them to either image or measuring the atmosphere. One of them is a precipitation spectrometer called SSJ/4.

#### 3.4.1 SSJ/4

The particle precipitation instrument is the one which is used in this thesis. Every second particle fluxes in the 30 eV to 30 keV range for ions and electrons over 10 channels for low energies (centered on 34-960 eV) and high energies (centered on 1-29.5 keV) in logarithmic steps is measured. The instrument consists of electrostatic analyzers looking towards zenith where an electric field is set up between two plates, filtering out any particles outside the desired energy interval.

### 3.5 NOAA spacecrafts

NOAA-16 is a Polar Orbiting Environmental Satellites (POESS) spacecraft with orbit similar to the DMSP spacecrafts. It is sun-synchronous with an altitude of 850 km, inclination of 98° and an orbital period of 102 minutes. It has a number of instruments, but we will focus only on the Space Environment Monitor (SEM-2) instrument suite in this thesis. The SEM instrument package consists of two sensors: TED and MEPED, both measuring particle precipitation.

#### 3.5.1 Total Energy Detector (TED)

The TED instrument measures the flux of precipitating ions and electrons in the range from 50 eV to 20 keV. This is an electrostatic analyzer, suppressing particles with unwanted energies. The sensor measures in directions of 0° and 30° to zenith, but only the former is used in this thesis.

#### 3.5.2 Medium Energy Proton and Electron Detector (MEPED)

This sensor measures particle precipitation in the energy range of 30 - 1000 keV for electrons, and 30 - 6900 keV for protons and ions. This is a solid-state sensor. This type of sensor are degraded by the particle fluxes it measures[1][2][3][4][5][6][7][8][9][10], and the measured energy interval change over time. Work has been done to correct this,
e.g. Asikainen et al. [2012] and Glesnes Ødegaard et al. [2013], using different statistical approaches to find calibration coefficients. NOAA-16 was fairly new at the time of measurements used in this thesis, and the degradation is believed to be negligible for our use. Electrostatic analyzer (as in TED) is a different technology which is not degraded by particle flux. The detector measures in both parallel and perpendicular to zenith.

3.6 ACE satellite

The Advanced Composition Explorer (ACE) satellite is a NASA satellite used to monitor the solar wind and the interplanetary medium. It was launched in 1997 by a Delta II rocket, and is positioned between the Sun and the Earth orbiting the L1 point. In this thesis, data from the MAG and SWEPAM instrument suite is used.

3.6.1 L1 Lagrange point

In a three body system where two of the bodies have a large mass, and the third is of negligible mass compared to the other two, five stationary points exists. In this system the two larger bodies is the Sun and the Earth (other systems is e.g. the Earth and the Moon), and the third, smaller body is a satellite. A satellite can be positioned at any of these five points and use little fuel to maintain its orbit. The five solutions are found by comparing the gravity from the two bodies and the centrifugal force at the satellite.

One of these points are located between the sun and the Earth and is called L1 with a distance of the earth of 1/100 of 1 AU (the distance between the Sun and the Earth). L1 is about 1.500.000 km from the Earth. With normal speed of the solar wind, this is about 1 hour ahead of Earth, but can be as little as 15-20 minutes in some rare cases of ICMEs. The position of the ACE spacecraft make it excellent position for providing space weather forecasting for Earth.

Other spacecrafts are also located at the L1 (SOHO and WIND). This position is not a true, stable position for spacecrafts, so they are in a Lissajous orbit around L1, which is a quasi-periodic orbit around the L1 point itself. The other spacecrafts orbiting around L1, as SOHO, have a larger orbit. This makes ACE preferable for doing space weather forecasting. NASA provides a service through their OMNIWeb website, which combine data from the different spacecrafts around L1 to provide the most optimal data package for space science. Usually ACE data is used. The OMNI product approximates the measurements to the position of the bow shock. This is to provide a fixed reference when different spacecrafts are used. Moen et al. [1999] used 8 minutes as a timelag between the magnetosheat and the ionosphere. This depends on the solar wind speed at the time of measurements. In chapter 5 we use 6 minutes (for a solar wind speed of around 330 km/s), but for our purposes in this thesis a time lag difference of a couple of minutes make no difference.
3.6.2 MAG and SWEPAM instruments

Two magnetometers, each mounted on the tip of two booms on the spacecrafts, measures the IMF in three dimensions, and both are fluxgate magnetometers. The boom mounting makes it less prone to noise from the spacecraft itself. A fluxgate magnetometer consists of two coils of wires wrapped around a small, susceptible core. An alternating current is passed through one of the coils, which affects the other coil where a current can be measured. Note that the secondary coil has no internally driven current. If no magnetic field is present, the output of the secondary coil must match the primary current driven coil. With a magnetic field present, the output can be compared to the input and the external magnetic field can be measured. This is in one direction only, and on a triaxial magnetometer as the ones on ACE, three orthogonal fluxgate magnetometers are used to measure the different dimensions.

The Solar Wind Electron, Proton and Alpha Monitor (SWEPAM) instrument is used to measure the light-mass particles of the solar wind. The SWEPAM suite consists of two separate sensors, one for the positive particles (protons and alphas - alphas are helium nucleus particles) and the negative electrons. These sensors are electrostatic analyzers, the same as the TED instrument on the NOAA-16 satellite, and the sensors is not described further here. In the DMSP data plots the convention is to flip the energy axis of the ions (the y-axis), as seen in Figure 5.6 on page 78.
Chapter 4

KHI growth rates of RFE velocity shears

In this chapter, we will quantify the growth rates of KHI in the F-region ionospheric layer in the shears of the RFEs Rinne et al. [2007] identified in the SP-NO-FASM database.

This chapter is divided in two parts: a statistical approach to quantification of the growth rate using radar measurements, and a case of KHI using high-resolution rocket measurements.

4.1 The statistical approach to growth rates

In general, all flow shears will give rise to KHI, but due to the time limitation of this thesis data is limited to the 400 minutes of RFE observations seen in the Rinne et al. [2007] database (also called the RFE database). The summary of the RFE database is seen in Table 4.1. In this section, we will first introduce an ESR reference system to be able to discuss ESR data further, and then introduce the statistical approach. Then the data is presented.

4.1.1 A common ESR reference system

Before we discuss the ESR plots, we need to define a common reference for the plots. Figure 4.1 shows the ESR grid which is common to all the ESR parameters. Dimension 1 is in increasing distance from the radar in radial direction and is referred to as range gates. Dimension 2 is referred to as beams and is counted in clockwise direction as shown, that is, the cell coordinates are given as (range gate, beam number). On the last beam two of the cells are shown in coordinates: the closest to the radar as (1,12) and the farthest from the radar as (9,12). These two beams are on the 1st and 9th range gate from the radar respectively, both on the twelfth beam counted in clockwise direction from the first one, which is here the beam on the left hand side of the figure. This is a coarser grid than usual as an example, as the most commonly used grid consist of 16 range gates and 60 beams.

The title of each figure, as seen in Figure 4.1, states first the measured plasma parameter vi (ion velocity), ne (electron density), ti (ion temperature) or te (electron temperature), followed by the date, and the time of the start and end of the scan. Cw or
Table 4.1: The Rinne et al. [2007] RFE database. IMF conditions is referred to in polarity.

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<th>Start (UT)</th>
<th>End (UT)</th>
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Figure 4.1: Example of the ESR reference frame. First dimension is in distance from the radar, and second dimension is number of beams in clockwise direction, as shown.

ccw stands for clockwise or counterclockwise scan direction. The velocity data are not shown in this schematic figure.

4.1.2 Range gate velocity fitting

The equation for the maximum growth rate of KHI is given as [Keskinen et al., 1988]

\[ \gamma_{\text{KHI}} = 0.19 \frac{\Delta V}{L}. \]  

(Keskinen et al. [1988] did a numerical study of flow shears and found the factor 0.19 is a "best case" of rates, as discussed in Section 2.9. The initial condition they used were

\[ V(x) = V_0 \tanh \left( \frac{x}{L} \right). \]  

Note that \( \tanh(\pm \infty) = \pm 1 \), and \( \tanh(1) \approx 0.7616 \), which states that although \( \tanh \) goes towards 1 (in our case \( V_0 \)), it takes in practice an argument larger than 1 to get the maximum velocity difference. This is slightly different than in Carlson et al. [2007] and Oksavik et al. [2012], which used the whole minimum to maximum velocity as the length \( L \), yielding a smaller rate estimate. It is assumed here that the velocity distribution remains as \( \tanh \).
In each of the RFEs in the database analyzed by Rinne et al. [2007], the azimuthal position of the flow shears for each range gate in each ESR scan were manually noted and put in a database. Since the velocity measured is the line-of-sight component, the shear distribution is assumed to be perpendicular to this component, and the tanh-function is only in the radars azimuthal direction. That is, one can do a data fit of each range gate over each flow shear (two in each RFE), and the fitting function is \( V(x) = \tilde{V}_0 \tanh \left( \frac{x - \mu_{az}}{\tilde{L}} \right) + \mu_V \). (4.3)

The fitting parameters needed to find the gradient are given with tildes. The offsets \( \mu_{az} \) and \( \mu_V \) are necessary since azimuthal direction is relative to where we measure from, and the mean velocity can change because of the background drift. Where the argument of the tanh-function is zero, the derivate of (4.3) is \( \tilde{V}_0/\tilde{L} \), and this is the gradient in equation (4.1).

After manually marking the position of the flow shears, this was fed to a new
database and processed, yielding 470 datapoints. There will always be cases where
the fit is either obviously bad, or unreliable because of few datapoints azimuthally on
that particular range gate. We have checked the database manually for this and 62
(13.2 %) of the fits were taken out, leaving 408 relatively good fits. In range gate 7 in
Figure 4.1 we see that a negative cell is in between three positive cells and two cells are
missing, making the fit unreliable, and it was therefore taken out. It is also important
to note that as seen in Figure 4.2, cells that do not contribute to the tanh-fit are omitted.
A span of 11 cells was used as a starting point at each range gate with the flow reversal
in the middle of the 11 cells. If cells on either side clearly did not contribute to a good
fit these were omitted.

The datafit was achieved by using the least sum of absolutes (LSA), the cousin of the
Least Sum of Squares (LSS), a method widely used in science, since the data fitting is
done automatically and transparency was important.

In order to quality check the fit, one could manually plot the result but it would
be very time consuming. In the LSA approach, the absolute values of the residuals for
many different parameters are summed and the parameters that give the smallest sum
found. This is mathematically given as

\[
\text{LSA} = \min \left( \sum | y_R(x) - y_{\text{fit}}(x, \mu_{\text{az}}, \mu_V, \tilde{V}_0, \tilde{L}) | \right),
\]

where \( y_R \) is the radar measurements at point \( x \) and \( y_{\text{fit}} \) is the datafit at the same point.
This give a single measure of how good the fit is, since a best fit minimizes the residu-
als.

There are some datapoints which could seem doubtful as they are very different
from their neighbors. For the LSS method these residuals would contribute much,
which is why we chose the LSA method. The method of taking the square root of
the residuals was also tested, but the absolute method seemed to be a better approach
judged by manual inspection. For example, in range gate 10, beam 43 is very different
than its neighbors, but the absolute method seemed to work well, not weighing it very
much. With the square residual approach, the measured \( \Delta V \) would have been smaller
which would underestimate the growth rate.

We now have a way to automatically measure how good a fit each set of parameters
is, and hence need to test this over a range of parameters. After examining the data set
manually, \( \Delta V \) was expected to be between 200 and 2000 m/s and \( L \) between 0.25 and
4 beams. These beam widths correspond to minimum 2 km and maximum 138 km,
but usually in the range from 5 to 80 km. This depends on which range gate the fit is
done.

4.1.3 KHI growth time result and distribution

With all the datafits and resulting growth rates available, we can plot the distribution
of growth rates. A more intuitive way is to look at growth times, given as the inverse
of the growth rate,

\[
\tau_{\text{KHI}} = \frac{1}{\gamma_{\text{KHI}}},
\]
Physically, this is the amount of time it takes the KHI to reach the nonlinear phase, at which the instabilities stop expanding linearly in width. In this case a distribution of growth times was found, not a "typical" value of growth times. In Figure 4.3 we see the distribution as a function of growth time displayed as a histogram. Growth times exceeding 400 m/s were seen, but they were few and scattered and hence taken out as fitting outliers. The red line indicates the kernel smoothing function, added to guide the eye. A distinct probability distribution function (PDF) is not clear, but the skewed normal PDF is plotted as a green line and seems to resemble the distribution seen.

The general skewed normal distribution is given as

$$\text{SNPDF} = \frac{2}{\omega} \phi \left( \frac{x - \mu}{\omega} \right) \Phi \left[ \alpha \left( \frac{x - \mu}{\omega} \right) \right]$$

(4.4)

where $\phi$ is the standard normal distribution function and $\Phi$ is the standard cumulative normal distribution function. Plotted in the figure is this function with $\mu = 20$, $\omega = 120$ and $\alpha = 15$. Please note that the scaling in y-direction is for visual representation only, as the integral of a probability density function over the whole x-axis is per definition unity, and the scaling factor is in this case set to $4.2 \times 10^3$.

### 4.2 Using high-resolution data from the ICI-3 sounding rocket

In this section we will use data from the ICI-3 rocket (Section 3.3). ICI-3 reached its apogee of 354.5 km after 313.9 seconds of flight. This section will explore the velocity dataset and put the observations in relation to the RFE seen by the ESR.
4.2.1 The velocity dataset

The flight path of the rocket when it was located approximately in the F layer (150 to 450 seconds into the rocket flight) is shown in Figure 4.4 with circles for every 30 seconds. Also shown is the closest ESR scan for the flight. The RFE is clearly seen as westward flow in an otherwise eastward-directed background flow. The rocket flight was about 850 km in horizontal distance and lasted 597.7 seconds. We will here discuss the dataset in regards to the E-cross-B drift velocity.

Figure 4.4: ICI-3 flight path overlaid the ESR velocity fan showing the RFE.
Figure 4.5: Solar wind data from ACE and SuperDARN large-scale flow for the ICI-3 RFE.
Figure 4.6: The ICI3 RFE as seen with ESR. Colors in units of m/s.
The upper part of Figure 4.5 shows the large-scale flow at and around the ESR fan at the time of the ICI-3 flight. The fan was located at about 10-11 MLT at the morning sector edge of the the cusp inflow region. The background flow speeds was about ~300-350 m/s in the equatorward part of the fan, with slightly higher speeds of ~500-600 m/s in the poleward part. We see that in the equatorward part of the fan, the background flow was approximately in the line-of-sight direction of the radar, but in the poleward part there is a significant flow component across the fan which will not be seen by the ESR.

The lower part of Figure 4.5 shows the solar wind data at the position of the bow shock. The ionospheric response time was expected to be an additional 6 minutes [Moen et al., 1999]. IMF conditions corresponding to the time of launch is marked with a vertical magenta solid line (07:15 UT). At 06:40 the IMF changed from positive $B_z$ to negative, and from that time and forward, the solar wind was very steady with weak negative $B_y$ and stronger negative $B_z$. The solar wind flow speed was regular at ~380-400 km/s, and proton density was fluctuating between 5-15 n/cm$^3$. The proton density is steady at around 4 n/cm$^3$ an hour before to right after the rocket flight ended. Steady solar wind conditions makes it easier to discuss the RFE, because it seems from this data that the RFE is not caused by any sudden increases in solar wind pressures or in the IMF.

The full development of the RFE is shown in Figure 4.6 by ESR. The color axis is in units of m/s. There may be indications of the RFE in the scan starting at 07:20:59 UT, but the first clear evidence is seen in the scan starting at 07:24:11 UT. In the 07:27:23 scan the RFE was fully developed, and this was also the scan closest in time to the full rocket flight. The 07:30:35 scan was the last one where the RFE is visible. As we see in the scan after that, at 07:33:47, the RFE had disappeared. The speeds were up to 1000-1200 m/s in some of the cells, and the speeds was highest in the 07:24:11 scan.

Unfortunately, there were a lot of structures within the RFE, which makes it more difficult to compare the rocket and radar data. As is evident in the scans at 07:24:11 and 07:27:23 UT, this is not an RFE with smooth boundaries, and not many of the range gates would be used in the statistical approach as discussed earlier in this chapter. In the 07:30:35 scan the RFE is more stable with smooth boundaries, much like RFE #10 in the RFE database, which is the smoothest in the database. The ESR radar integration software has problem fitting many of the cells at lower altitudes close to the radar in some of the scans. Remember that the measurements close to the radar are done in the E and lower F region where the electron density is lower than in the F2 layer.

In Figure 4.4 three areas of the fan is marked in white and black dashed lines: one equatorward, one inside and one poleward of the RFE. The ESR measurements is taken at about the same height as the peak altitude of ICI-3. The mean of the values inside these three boxes is -540 m/s, 439 m/s and -1227 m/s equatorward, inside and poleward of the RFE, respectively. These three values fits quite nicely with the overall mean values in the rocket data. though the equatorward side could seem to be a bit understated.

The rocket velocity data is given in NED (north-east-down) coordinates. We have
Figure 4.7: Both horizontal components of the ICI-3 RFE velocity. The green line with the y-axis is the height of the rocket. Also shown are the two ESR velocities closest to the rocket measurements in both time and space, as explained in the text.

transformed the coordinate system by rotating the NED data clockwise by 135° around the vertical axis (z) so that the vertical components align parallel and perpendicular to the flow channel. This means that the down component stays the same in both coordinate systems, but the north and east are transformed. The transformation is done by right-multiplying a 3x3 transformation matrix, and is written as

\[
\begin{bmatrix}
  x_1 \\ y_1 \\ z_1
\end{bmatrix}_{\text{Coords. in RFE}} =
\begin{bmatrix}
  x_1 & x_2 & x_3 & x_4 & \cdots \\ y_1 & y_2 & y_3 & y_4 & \cdots \\ z_1 & z_2 & z_3 & z_4 & \cdots
\end{bmatrix}_{\text{Coords. in NED}} \cdot
\begin{bmatrix}
  \cos(\theta) & \sin(\theta) & 0 \\
  -\sin(\theta) & \cos(\theta) & 0 \\
  0 & 0 & 1
\end{bmatrix}_{M_{\text{trans}}}
\]

The transformation matrix \( M_{\text{trans}} \) is a function of \( \theta \), which is the angle of transformation, which is in this case \( \theta = 135^\circ \). Note that \( z_k^{\text{RFE}} = z_k^{\text{NED}} \) for all \( k \) independent of \( \theta \), since we turn around the z axis. The RFE is very closely aligned with the line-of-sight view of ESR, and shifting the coordinate system to the reference of the RFE, as explained over, decompose the rocket data into one component parallel and one
Figure 4.8: ESR components. The radar beam is shown as black line. Red is an example of the real plasma velocity vector in this plane, blue is the measured line of sight component by the ESR and pink is the component perpendicular to the line of sight, and is not measured by ESR.

perpendicular to the RFE. The parallel component will be approximately the same component as the line-of-sight velocity of ESR.

The ESR intersects the rocket path in both time and space twice: almost exactly at the poleward edge and about a minute apart at the equatorward edge of the RFE, as seen in Figure 4.4. The poleward point is shown as a white with a smaller green dot, and the equatorward ESR measurement close to the rocket measurement is shown as a white and yellow dot at the equatorward edge. The first intersection is done in the counterclockwise 07:24:11 UT ESR scan and the second in the clockwise 07:27:23 scan. Note that the position of the asterixes is shown in the figure, not the time of the ESR measurements.

In Figure 4.7 these two measurement points are shown as a pink (poleward edge) and black (equatorward edge) asterix. The pink measurement correspond very well in time, position and in magnitude compared to the rocket. The time difference is only 5-10 seconds, and as we see in the figure, the position also correspond well. The speeds are zero in both the rocket and the ESR measurement. The equatorward crossing by the rocket is measured about 375 seconds into the rocket flight. The ESR measurement, where the position is seen by the black asterix, is done exactly a minute after the rocket measured close to the same position. Since the ESR measurement is done slightly poleward of the rocket flight, as seen in the figure, it is easy to believe that since the flow channel has drifted slightly poleward in between the ESR and rocket measurement (as seen by the negative perpendicular velocity), the ESR and rocket velocity measurements correspond very well, again at about zero.
4.2.2 KHI growth rate from the ICI-3 RFE

As we see, the second shear has a much steeper gradient, resulting in a shorter growth time. This may indicate that the flow channel were developing during the time of the measurements, which in turn means that the flow channel did not enter the ESR fan fully-developed.
4.3 Discussion

Figure 4.8a show how the radar beam is positioned in relation to the background magnetic field lines. On the left hand side, the beam is close to perpendicular to the field line, as is not the case on the right hand side. In Figure 4.8b we see the two components of the real velocity vector shown in red. The pink velocity vector, which is perpendicular to the line of sight vector, is not measured.

We have assumed in this chapter that the line of sight velocity is the major component. If the velocity is close to horizontal, the left hand side case is closer to the line of sight velocity component than the case on the right. On the bright side, Figure 4.8a show two extremes in the north-south plane which have not been identified in the RFE database. The reason for this is that the flow channels are directed approximately along constant magnetic latitude, which reduce this difference. Still, if the flow is directed horizontally, the true velocity is about $1/\cos(30^\circ) \approx 1.1547$ larger, which means the growth rates increases with the same factor, and the growth times decreases with $\cos(30^\circ) \approx 0.866$. This means that the peak in the growth time distribution at ~40 seconds decreases to ~35 seconds.

Also in the horizontal plane, the flow channels are not always directed towards the radar. Shown in Figure 4.10 is a sketch of two examples where the flow in 4.10a seems to be directed towards the radar, whereas in 4.10b it is not. If the flow is not purely directed along the flow channel direction, there is a non-negligible flow component
in the latter example, and the growth rate is overestimated (and the growth time is underestimated). In the RFE database, 7 of the 21 flow channels are not directed towards the radar and will probably have a flow rate larger than the one seen by the radar, though the effect is believed to be small, as the channels is directed $15 - 20^\circ$ off in those cases. Flow perpendicular to the flow channel direction is negligible in the hypothesis of RFE current sheets in \cite{Moen2008}.

The uncertainty in the data is important to discuss. In Figure 4.2, the standard deviations is shown with vertical red, solid lines. Generally, the uncertainties is on average around 150 m/s, but the span is obviously large. One has to keep in mind that this is a statistical method using over 400 datafits, and the uncertainties should not affect the growth time distribution that much.

To validate this statistical approach we need to compare the results found in this chapter to other studies. Until the present date there are only a few studies that have evaluated KHI growth times. \cite{Oksavik2012} used data from the ICI-2 sounding rocket which was launched into a polar cap patch and measured KHI growth time down to 30 seconds at a scale length of $L = 4 - 6$ km. It should be noted that these results were not obtained near a flow channel as in this study. \cite{Oksavik2011} found what appears to be a RFE in SuperDARN data using the Hankasalmi HF radar, and calculated
the KHI growth time. Since HF coherent scatter radars have a lower spatial resolution than the ESR as used in this study, the length scale of the shears found in the flow channel are difficult to measure. Their Figure 5 shows growth times for different scale lengths and velocities. The SuperDARN flow channel has $\Delta v = 800 \text{ m/s}$, and when assuming a scale length of one ESR cell (~10-12 km) they found a KHI growth time of about 60-75 seconds. In this study, as shown in Figure 4.9, we found KHI growth times of 38.4 and 79 seconds using ICI-3 sounding rocket data.

Figure 4.11 puts the four case study results in the context of the statistical results of Figure 4.3. As we see, the case study results fit very well with the statistical distribution. Even if the actual KHI growth times obtained from the studies by Oksavik et al. [2011, 2012] may be somewhat larger due to uncertainties related to instrument resolution, they still fit well in the statistical distribution found in Figure 4.11.
Chapter 5

On the location, HF backscatter and density enhancements of RFEs

There still remain a number of unanswered questions about RFEs: where are they located in relation to the open-closed boundary (OCB)? Are they associated with HF backscatter? Can we see density enhancements that could be related to polar cap patches? In this chapter we will try to address these questions to explore the context of this new class of flow shear.

5.1 Source region of RFEs

The question of what can explain the reversed flow events is closely related to where they are located at the day side. Are they on open or closed field lines? In what boundary layer at the day side ionosphere are they located? We will first examine NOAA satellite data to locate the OCB, and then examine DMSP satellite data to determine their magnetospheric source region.

The areas of the ionosphere can be determined by particle precipitation. Particle precipitation data from both NOAA and DMSP spacecrafts can be used to classify the ionospheric regions, and as the spacecraft orbits and instrument differ they complement each other.

5.1.1 RFEs in relation to the OCB

Determining the position of RFEs with respect to the OCB is important in order to find the mechanism(s) that causes RFEs. If RFEs appear just poleward of the OCB, the hypothesis of reconnection currents are strengthened. We will in the following present a case of where the OCB is located, and then summarize the results for all the available OCB locations.

RFE #5 first appears in the ESR data in the 10:32 UT ESR scan and lasts until 10:58 UT when the ESR run was stopped. The solar wind data from ACE shifted in time to the position of the bow shock (as explained in Section 3.6.1) is shown in Figure 5.1. Until 10:40 UT the $B_z$ component of the IMF was northward, before it started to fluctuate around zero. $B_y$ is steadily positive. The flow speeds are around 330 km/s the whole
Table 5.1: MLAT open-closed boundary observed vs. observed RFE MLAT at the start of the event. The OCB in RFE #10 is taken from Rinne [2005].

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<th>RFE</th>
<th>RFE No</th>
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time. Proton number density is around 20 n/cm$^3$ and the plasma temperature $\sim 10^5$ K. The ionospheric background convection by the SuperDARN network is shown in Figure 5.2, where we see the convection is $B_y > 0$ driven, as explained in Section 2.6. West of Svalbard the flow speed is around 1500-1800 m/s towards west.

NOAA spacecrafts 15 and 16 were operating at the time of interest and 7 passes are located near RFEs. Three NOAA-15 passes were rejected for further use due to unfavorable orbits. The remaining 4 passes, all NOAA-16, can be used to locate the OCB as they pass close to the RFEs and are almost perpendicular to the OCB.

The magnetospheric particles on closed field lines are known to have electron energies above 30 keV and solar wind particles on open field lines below 1 keV. [Bythrow et al., 1981] This enables us to determine the transition between open and closed field lines from the precipitating particle measurements from satellites in the ionosphere. At the transition from open to closed, the number flux peak will shift from cold to hot. Since the electrons have larger velocities than ions, and hence smaller propagation time from the reconnection site, a distinct electron edge is known to appear just poleward of the OCB [Lockwood, 1998], and is a common technique to locate the OCB [Sandholt et al., 2002; Moen et al., 2004; Johnsen and Lorentzen, 2012].

The NOAA-16 pass from 10:50:40 to 10:56:40 UT through RFE #5 is shown as a solid blue line in Figure 5.3, overlaid on the ESR velocity plot. NOAA data are shown in Figure 5.4. The electron edge is shown with a light green arrow in Figure 5.4a, where a sudden increase in the flux of low energy electrons is seen in the 154-224 eV and 688-1000 eV energy bands. This is interpreted as the OCB. We approximate the OCB as circular around the magnetic pole, which around noon is often a good approximation [Sotirelis et al., 1998]. Therefore the OCB is shown as a light green circle in Figure 5.3. Note that this is the position of the OCB at the height of the spacecraft (840 km), and the field lines converge together poleward with decreasing height. The red circle is the OCB traced down along the northward directed magnetic field lines.
Figure 5.1: ACE-data (OMNI) for 15-Dec-2001, where the start of RFE #5 is marked in magenta with the six minutes time lag as described in the text to 500 km (the approx height of the upper ESR RFE measurements), and at sea level in the solid blue circle.

Table 5.1 summarizes the four OCB MLAT measurements found in the NOAA-16 data, all located around magnetic noon. Also shown in the table is the approximate magnetic latitude of the RFE at the start of the event (temporal) and in the middle of the flow channel (spatial). The mean magnetic latitude of the RFEs is 75.1 with a standard deviation of 1.65 degrees.

**CUTLASS spectral widths**

Moen et al. [2001] found a close relationship between cusp-like auroral signatures and a border of wide spectral widths from the CUTLASS HF radars (CSR), and they used spectral widths of 220 m/s as the cusp boundary, identified as the spectral width boundary (SWB). Chisham and Freeman [2004] showed that such a SWB exist at all
Figure 5.2: Large-scale convection map at similar times as Figure 5.4 (RFE #5). NOAA-16 trajectory is shown in blue, approximately the same line and arrow as in the previous figure. The black contours is the electric potential and will, since $\mathbf{E} = \nabla \phi = -\mathbf{v} \times \mathbf{B}$, be convection streamlines. The blue arrow show the approximate position of the RFE.

MLT, but varies in both latitude, gradient and amplitude as a function of MLT. Chisham et al. [2005] did further analysis in the afternoon sector using DMSP OCB measurements, and found that SWB correlate well with the OCB poleward of 74° MLAT, but a poorer correlation is found equatorward of 74°. Their work shows that if used with care, SWB could approximate the OCB quite well.

SuperDARN spectral width data using beam 8 of the Hankasalmi radar has been examined, but there are a lot of data gaps in the area of the SWB resembling the case of Chisham and Freeman [2004, Figure 1d]. We have therefore, as well as due to the uncertainty of the OCB location shown in Chisham et al. [2005], decided not to use SWB as a proxy of the OCB in this thesis. A more advanced and reliable smoothing technique as found in Chisham and Freeman [2003] could probably increase the reliability of the SWB in some of the cases, but this falls well outside the scope of this thesis.

### 5.1.2 RFE location in the dayside ionosphere

The DMSP trajectory of the pass near RFE #9 is shown in Figure 5.5. The large-scale convection from SuperDARN is shown in Figure 5.9. The RFE is located in the afternoon sector. A strong westward flow is seen west and north of Svalbard. The RFE is seen in the eastern part of the fan indicated by a red arrow in Figure 5.5. Yellow color indicate flow away from ESR, whereas the blue background indicates flow towards the ESR. The large green circle marks the open-closed boundary traced to a height of 500 km following the magnetic field line, as measured by the NOAA-16 spacecraft as explained in the previous section. The ions in the DMSP data in Figure 5.6 have a clear
Figure 5.3: An example of a NOAA-16 pass over the north pole. Longyearbyen is shown with a magenta asterisk and geomagnetic coordinates in MLAT/MLT in gray lines. Magnetic noon is indicated with a solid line and dotted lines represent 2 hours in MLT and ten degrees of magnetic latitude. The ESR plot closest to the trajectory pass over Svalbard of RFE #5 is also shown (~10:54-10:57 UT). The blue arrow points to the RFE along the spacecraft orbit.

distinct number flux peak at 1 keV from 08:54:15 to 08:57:45 UT and the ions have a clear low-energy cutoff, which can also be seen in the particle spectra (not shown). Note that the ion energy y-axis is mirrored of that of the electrons. Such a low-energy cutoff is explained by open flux only, as the low-energy (slowly precipitating) ions not yet have reached the ionosphere. Variable spectral densities seen as variable number flux and spectral temperatures, seen as the point at maximum number flux, in the electrons were previously reported in the LLBL [Newell et al., 1991b]. The boundaries shown in the bottom of the figure are from the automated database of [Newell et al., 1991c].

DMSP SSIES flow data is shown in Figure 5.7. The red arrow points to a single measurement which might indicate the presence of the flow channel outside the field-of-view of the ESR, but as the datapoints prior to this measurement are missing, it is difficult to confirm this. The horizontal velocities are variable, indicating open field lines.

The layer closest to the RFE #9 in the DMSP pass in Figure 5.6 resembles a clear example of an open LLBL, as identified by [Newell and Meng, 1998] (see their Figure 2). The LLBL can often be seen to be closed on the dawn and dusk flanks (if $B_y \approx 0$), but almost always open around noon [Newell and Meng, 1998].

With the results shown with DMSP data here and with the OCB locations in the previous section, it seems to be clear that RFEs appear on open field lines, probably
5.2 Case study: 20th December, 2001

This section will examine RFE #18 and #19 on December 20th, 2001. The large-scale convection was driven by a large positive $B_y$-component, which is evident from the SuperDARN convection shown in Figure 5.8. Notice that SuperDARN did not see the flow channel. The OMNI solar wind data is shown in Figure 5.10. The IMF was southward until 10:51 UT at the bow shock, which correspond to about 10:58 UT in the ionosphere. Flow speeds were around 380 km/s, the proton density $\sim$3 cm$^{-3}$ and the temperature $\sim$6000 K.

RFE #18 and #19 followed each other closely: RFE #18 started in the 10:29 scan and

Figure 5.4: NOAA-16 data of RFE #5

first in the newly open LLBL boundary layer. This supports the hypothesis of Moen et al. [2008] where the RFE may be part of a reconnection current.
Figure 5.5: DMSP F13 trajectory on 16-Dec-2001, near RFE #9. Start and end times are shown in a green and red box respectively. Geographic north is upwards and magnetic coordinates in MLAT/MLT format is shown in gray. The red circles indicate start of a new whole minute, between the start time at 8:53 UT and the end time as 8:59 UT. See the text for more.

left the ESR fan after the 10:48 scan, while RFE #19 started in the 10:51 scan and lasted until ESR was stopped just before 11:00. The ESR ion flow is shown in the left column of Figures 5.11-5.14 (page 81-84). The corresponding electron density plots are shown in the right column, and will be discussed later. The two flow channels are clearly marked with a black ellipse.

RFE #18 is first measured at about 10:30:50 UT in the middle of the 10:29 scan seen as a small channel with flow towards the radar. At 10:34:20 UT the flow channel has expanded to about the full width of 180 km. The flow speeds are around 1000 m/s towards the ESR with single measurements up to 2000 m/s. In the three following scans the width and speed stay roughly unchanged. The channel spans the entire field-of-view (about 600 km) and moves poleward. Between 10:36:30 and 10:42:20 UT, it moves about 200 km (center to center). RFE #19 is first seen by ESR at 10:53:10 UT in the 10:51 scan, and in the next scan seem to have evolved slightly.

Note that the overall position of both flow channels seems to move along with the potential contours (which means frozen into the background convection) seen in the SuperDARN data.
Figure 5.6: DMSP particle data around RFE #9 with boundaries from the Newell et al. [1991c] database. The satellite crossed near the RFE as seen in the ESR plot in Figure 5.5 between 08:54:30 and 08:56:00 UT.

Figure 5.7: DMSP flow data from the SSIES instrument. See the text for details.
Figure 5.8: SuperDARN convection plot around RFE #18/#19, 20th December, 2001. Same setup in as Figure 5.2 and 5.9.
**Figure 5.9:** SuperDARN plot at the time of RFE #9

**Figure 5.10:** Solar wind data on 20th December
Figure 5.11: ESR ion velocity and electron density of RFE #18/#19, scan 1-3
Figure 5.12: ESR ion velocity and electron density of RFE #18/#19, scan 4-6
Figure 5.13: ESR ion velocity and electron density of RFE #18/#19, scan 7-9
5.2.1 Electron density enhancements

All the RFEs were carefully checked for a relation to electron density enhancements in the ESR Ne data, and a relationship has been found. Clear enhancements are not seen for all flow channels. Often, the background density in the region of the RFE is high and we suggest that an increase in electron density is present in those cases but lost in the high-density background. One of the reasons why RFE #18 and #19 were used as a case study is the clear density enhancement associated with them.

Oksavik et al. [2006] investigated a case of a polar cap patch, and a clear plasma trough is seen between the EUV ionized electrons in the south and the patch in the north. They concluded that since a clear trough was seen, the polar cap patch could not come from the EUV-ionized electrons at the sunlit ionosphere further south. Polar cap patch formation is often explained by sunlit electron enhancements via the tongue-of-ionization (TOI), but a TOI cannot explain the creation of PCP since a clear trough is seen. They explained the creation of the polar cap patch from particle precipitation.

In the right column in Figures 5.11-5.14 the electron density of the corresponding ion velocity scan in the left column is shown. In the 10:25 scan just before the RFE is seen, there is a high-density area in the (near) sunlit south, and a lower-density area just north of it (in the middle of the fan). In range gate 9 this peaks at an average $10^{11.82}$ m$^{-3}$ at a height of ~350 km, and the lower-density peaks at the same place at $10^{11.13}$ m$^{-3}$. In the low-altitude areas near the radar, the average density is about $10^{10.2}$ m$^{-3}$ (175 km and lower).
Figure 5.15: A closer look at RFE density enhancements.

85
The ESR run started 10:06:47 UT with a PCP like density patch moved poleward. It could seem like it originated from the EUV ionized area just before the run started. A small part of the patch can be seen in the northern part of the 10:25 scan.

In the 10:29 scan, a small (7 cells) density enhancement can be seen in the lower altitudes on the equatorward border of the RFE. In the following 10:32 scan a clear long (~400 km) and thin (~35 km) enhancement is seen. This is clearest in the lower altitudes where the background density is low (around and below $10^{10} \text{ m}^{-3}$). In the 10:35 scan, the enhancement has grown to a width of about 100 km. In the next scan, the density has increased further up to $10^{12} \text{ m}^{-3}$. It does not change much in the 10:41 scan. In the scan after that, the flow channel reach the edge of the ESR scan, and the density seem to have a more circular shape. In the 10:51 scan the flow channel and density enhancement has drifted outside the ESR field-of-view. In that scan, RFE #19 is seen for the first time, and a new density enhancement is also evident from the plot. The 10:54 scan shows the same.

The location of the density enhancement is important with respect to the RFEs. In Figure 5.15, the equatorward border of the RFE in the 10:35 and 10:38 scan are overlaid the density plot. As we see the equatorward edge of the RFE aligns pretty much perfectly to the electron density enhancements. We see that the enhancements also follow the RFEs as they move.

A patch of high-density electrons appears in the ESR data at 10:38, moves northward and exit the fan in the 10:51 scan. We will return to that in the discussion.

5.2.2 RFEs in relation to HF backscatter by the CUTLASS radars

The CUTLASS Pykkvibaer (pyk) and Hankasalmi (han) radars point over Svalbard and covers the entire ESR fans used in this study. The ESR dataset was combined with the CUTLASS data to explore the correlation between HF backscatter and the irregularities that need to exist because of the KHI. Unfortunately, because of problems with propagation geometry, one cannot always see backscatter in the radar field of view. No backscatter does not necessarily means lack of backscatter irregularities. The backscatter power is compared to the ESR line-of-sight velocity in pairs in Figures 5.18 to 5.35 (pages 88-90) with two earlier scans shown in Figures 5.16 and 5.17 to show that there is no backscatter echoes before the RFE. The view in the ESR and SuperDARN plot are exactly the same to ease the comparison. Grey shading represent ground scatter.

The RFE is first seen in the 10:29 ESR scan (Figure 5.18) as a very small channel. At 10:32 the RFE has grown large, and an area of radar echoes is seen inside of the RFE. The power is scattered from 15 dB and upwards on a few cells. In the 10:37 CUTLASS scan (10:35 ESR scan) the same echo has increased in power to about 25-30 dB over 6-7 cells. In the next scan at 10:40 (10:38 at ESR), the same echo area is seen, but with a decrease in power to about 15-20 dB. Note that the borders of the RFE were hard to find, and are for that reason not plotted. In the 10:46 CUTLASS scan (10:45 ESR) only a few scattered cells at about 10 dB are seen. In the 10:49 scan, the echoes are seen to increase somewhat in power again (a few cells at about 15 dB), and this echo
patch is also seen after the RFE has left the ESR field of view (as seen in the 10:51 ESR scan). When RFE #19 appears at ESR at 10:51 and 10:54, no backscatter echoes are seen in the corresponding CUTLASS data, but note that this might be due to propagation geometry issues. Since the time difference between the the start of RFE #18 at the same location as the start of RFE #19 is short, such an explanation might seem unlikely.

Literal or no backscatter echoes are seen in the Iceland CUTLASS radar data.

Though not shown here, the RFE sequence of #14, #15 and #16, which follow each other closely, also show backscatter echoes approximately at the same location both at the Pykkvibaer Iceland radar and the Hankasalmi Finland radar. In fact, all of the RFEs that seem to have CUTLASS coverage around the flow channel indeed develops backscatter. In some of the cases backscatter already exist and it is difficult to see if additional backscatter power gets developed around the RFE, but this is at least the case for some of the RFEs. In the clear cases it seems that backscatter develops within the two minute resolution of the CUTLASS radars. Details on this is left for later studies.

The evolution of this small patch after the RFE #18 has left the ESR field of view is shown in Figures 5.38-5.41 (pages 94-95). In the 10:49-10:51 scans, the PCP is circled in black. In the 10:52 and 10:53 scans, two small patches are shown: one at the RFE and another we really cannot see where comes from. At 10:54 these two small patches seem to merge and the later scans shown this merged (slightly bigger) patch and how it convect polewards. The reason to mention this is that the two-step mechanism of Carlson et al. [2007] builds upon the idea that KHI at flow shears and the GDI feeds upon these larger irregularities, which is backscatter targets.

Figure 5.16: SuperDARN backscatter before RFE #18

Figure 5.17: SuperDARN backscatter before RFE #18
Figure 5.24: ESR with borders, scan 4

Figure 5.25: SuperDARN backscatter with RFE borders, scan 4

Figure 5.26: ESR with borders, scan 6

Figure 5.27: SuperDARN backscatter with RFE borders, scan 6

Figure 5.28: ESR with borders, scan 5

Figure 5.29: SuperDARN backscatter with RFE borders, scan 5
5.3 Discussion

A multi-instrument observation near some of the RFEs in the Rinne et al. [2007] database was presented in this chapter. In Section 5.1 we saw that the RFE seems to appear a few degrees latitude north of the first indication of OCB as measured by NOAA spacecraft, and using DMSP spacecrafts we could see clear indications of the RFE started in the low-latitude boundary layer. Later they seem to move northward through the cusp.

Moen et al. [2008] found that some of the RFE tends to move northward along a auroral filament while others tend to stay in the background aurora. They used RFE #18 and #19 as examples, and though one could question if #19 doesn’t move northward with the auroral background, indeed some of the RFE do not (e.g. #8).

From the MHD approximation we know that the ion and electrons both move with the velocity $v = E \times B / B^2$. As a first approximation one could say that the magnetic field is perpendicular to the ground at high-latitudes. Then the E-field is perpendicular to the velocity in the horizontal layer. The electric E-field of a RFE based on the velocities is seen in Figure 5.36. Converging E-fields are seen at the equatorward flow shear and a divergent field at the poleward shear. Convergent (divergent) E-field represents an
Figure 5.37: The RFE current/electric field system. The blue current loop is in the equatorward of the RFE (R1 current to the CPS on closed field lines), red current loop is poleward of the RFE (a open cusp reconnection current). Notice that there is no connection between the current loops due to a low conductivity. The green E-field inbetween the two current loops is the short-circuit discussed in Moen et al. [2008], which is giving the RFE seen in the ESR data. The pink arrows is flow direction. The opposing E-field gives rise to flow in opposite directions.

As an explanation of the RFE, Moen et al. [2008] suggested that two different current systems are set up at the RFE, and the electric field seen inside the flow reversal is just a short circuiting between these two different current systems, which is unrelated to each other. A graphical version of their current system is seen in Figure 5.37. The southern current, closed at CPS on closed field lines, is seen in blue, and a reconnection current on open field lines is drawn in red. Their explanation for this short-circuiting is that the dark, non-sunlit ionosphere could support such a short-circuiting if there

upward (downward) current. Remember that this is on open field lines. An upward current is often carried by precipitating electrons.

We have also seen evidence of HF backscatter associated with RFEs. Although only RFE #18 was used here, backscatter echoes are also seen in RFEs #14, #15 and #16. Oksavik et al. [2006] found isolated polar cap patches seen in both CUTLASS radar and ESR data that could not come from the sunlit ionosphere further south via the tongue-of-ionization, and attributed the creation to particle precipitation. It is uncertain whether all of the decameter scale irregularities giving HF backscatter comes from the KH irregularities or some may come from particle precipitation from the RFE current system. Moen et al. [2012] outline a two-step process where KHI produces irregularities of the size larger than decameter scale which the gradient-drift instability in turn feeds off of, and further breaks these hectometer irregularities down to decameter scale. In section 5.2.2 we saw that backscatter echoes appeared only a few minutes after the RFE was first seen.

As an explanation of the RFE, Moen et al. [2008] suggested that two different current systems are set up at the RFE, and the electric field seen inside the flow reversal is just a short circuiting between these two different current systems, which is unrelated to each other. A graphical version of their current system is seen in Figure 5.37. The southern current, closed at CPS on closed field lines, is seen in blue, and a reconnection current on open field lines is drawn in red. Their explanation for this short-circuiting is that the dark, non-sunlit ionosphere could support such a short-circuiting if there
is no particle precipitation in between these two Birkeland current arcs, which would cause increased conductivity making short-circuiting impossible. This requires that RFE only appear in the non-sunlit ionosphere where the conductivity is low.
Chapter 6

Summary and future work

In this thesis we have investigated RFEs both with a statistical approach and case studies to gain more information about the Kelvin-Helmholtz instability arising from the shears delimiting the RFEs from the background flow. In the statistical approach, we used an ESR ground-based radar dataset from 2001 originally designed to investigate polar cap patches in the high-latitude ionosphere. In the case study in Section 4.2 we used both the ESR radar and the data from the sounding rocket ICI-3, launched 3rd of December, 2011.

The flow shears on each side of the RFE are ideal for the development of KHI irregularities. KHI is a magnetohydrodynamic instability which is instable for mediums where a strong flow shears exist, as in such flow channels. This thesis has provided quantification of the growth rates, that may be of value to further studies of the role of the KHI in a space weather context.

In Section 4.1 we found a distribution of the KHI growth time from a statistical approach of 21 RFEs. This distribution was similar to a skewed normal distribution with a peak at about 40 seconds, and a tail which ends at about 350-400 seconds. The high resolution rocket data analyzed in Section 4.2 fits this distribution very well, as the two growth times found in that case was 38.4 and 79 seconds. Oksavik et al. [2011, 2012] also support the results found here.

Further, in Chapter 5 we did several case studies to find unexplored properties of the RFEs. We found that the RFEs seem to appear a few degrees poleward of the OCB, which corroborates the idea that the RFEs are related to flux transfer events [Oksavik et al., 2004; Rinne et al., 2007; Moen et al., 2008]. There is also a sharp density enhancement associated the equatorward boundary for a number of RFEs, consistent with precipitating electrons (upward FAC) from the converging electric field at the flow boundary and the PMAFs seen in Moen et al. [2008]. We also saw an area of enhanced HF backscatter developed as observed by the CUTLASS Hankasalmi radar associated with an RFE observed by ESR.

Future work

Probably the most important property to investigate in the future is the summer-winter assymetry suggested by Moen et al. [2008]. If the current sheet hypothesis is
correct, RFEs cannot exist on the dayside in the summer, because of the high conductivity by solar EUV ionization of the plasma. ESR should be run in the SP-NO-FASM mode around magnetic noon over some days to provide evidence to the lack, or not, of these flow channels.

More rocket measurements will help out understanding of irregularity studies from instabilities even more. ICI-4 will be quite similar to ICI-3 and will be launched from Andøya, not Svalbard. ICI-5 will be different, as it will have daughter payloads that will provide measurements of the surrounding plasma of the rocket, which will be a big step in the research of irregularities. Rockets provide very valuable high-resolution measurements, as has been important for this thesis, and multi-point high-resolution rocket measurements will be another leap in the study of KHI and GDI irregularity studies. Also planned is small-scale student satellites with the m-NLP Langmuir electron density instrument, approximately the same as on the ICI rockets. Such small, inexpensive satellite make multi-point measurements over some months possible to investigate the polar cap ionosphere on several different phenomena as KHI, GDI and PCPs. Both case studies and statistical studies may be possible on such satellite projects. Two important projects in the near future is the UiO CubeSTAR satellite and the ESA/NASA QB-50 project.

Numerical simulations either by kinetic models, electrostatic approximation or ideal MHD approximation would help to to verify the work of Keskinen et al. [1988]. One can do simulations on exactly these type of events. One important possibility here will be to verify the simulations with multi-point rocket data to confirm that the result by real measurements.

98
Appendix A

Keskinen equations from CGS to SI units

Keskinen et al. [1988] include several equations with CGS Gaussian units. We want to translate these to SI units, which is done here. We use here these relations:

\[ q_{\text{CGS}} = \frac{q_{\text{SI}}}{\sqrt{4\pi\varepsilon_0}} \]  
\[ E_{\text{CGS}} = \sqrt{4\pi\varepsilon_0}E_{\text{SI}} \]  
\[ B_{\text{CGS}} = \sqrt{\frac{4\pi}{\mu_0}}B_{\text{SI}} \]  
\[ c = \frac{1}{\sqrt{\mu_0\varepsilon_0}} \]

Here \( g \) is charge, \( E \) is electric field, \( B \) is magnetic field and \( c \) is speed of light.

Their continuity equation (2) is the same in both units:

\[ \frac{\partial n}{\partial t} + \nabla \cdot n\mathbf{v} = 0. \]  
(A.5)

Their ion momentum equation (3) on the other hand, is different. In CGS this is

\[ \frac{1}{\Omega_i} \left( \frac{\partial}{\partial t} + \mathbf{v}_i \cdot \mathbf{\nabla} \right) \mathbf{v}_i = \left( \frac{c}{B} \mathbf{E} + \mathbf{v}_i \times \mathbf{e}_z \right) + \frac{v_i}{\Omega_i} (\mathbf{v}_n - \mathbf{v}_i) \]  
(A.6)

\[ \frac{cm_i}{q_iB} \left( \frac{\partial}{\partial t} + \mathbf{v}_i \cdot \mathbf{\nabla} \right) \mathbf{v}_i = \left( \frac{c}{B} \mathbf{E} + \mathbf{v}_i \times \mathbf{e}_z \right) + \frac{q_iB}{cm_i} \mathbf{v}_i \mathbf{v}_i (\mathbf{v}_n - \mathbf{v}_i) \]  
(A.7)

\[ \left( \frac{\partial}{\partial t} + \mathbf{v}_i \cdot \mathbf{\nabla} \right) \mathbf{v}_i = \frac{1}{cm_i} \mathbf{F_L} + v_i (\mathbf{v}_n - \mathbf{v}_i) \]  
(A.8)

\[ \left( \frac{\partial}{\partial t} + \mathbf{v}_i \cdot \mathbf{\nabla} \right) \mathbf{v}_i = \frac{1}{m_i} \mathbf{F_L} + v_i (\mathbf{v}_n - \mathbf{v}_i) \]  
(A.9)

where \( \Omega_i = q_iB/cm_i \) is the ion cyclotron frequency and

\[ \mathbf{F_L} = q_i \left( \mathbf{E} + \frac{1}{c} \mathbf{v}_i \times \mathbf{B} \right) \]  
(A.10)
is the Lorentz force in CGS units, and where we have assumed a magnetic field in strictly z-direction ($\mathbf{B} = B_0 \mathbf{e}_z$). In SI units, the Lorentz force is
\[ \mathbf{F}_L = q_i (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}). \] (A.11)
This makes equation (A.6) in SI units
\[ \left( \frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla \right) \mathbf{v}_i = \frac{q_i}{m_i} (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) + v_i (\mathbf{v}_n - \mathbf{v}_i) \] (A.12)
Further on, their equation (3) is in CGS units
\[ \mathbf{v}_i = \mathbf{V} + \frac{c v_i}{B \Omega_i} \left( \mathbf{E} + \frac{1}{c} \mathbf{v}_n \times \mathbf{B} \right) + \frac{c}{B \Omega_i} \left( \frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla \right) \mathbf{E}. \] (A.13)
The ion cyclotron frequency is in CGS units $\Omega_i = q_i B/cm_i$, which is in SI units
\[ \Omega_i = \frac{1}{\sqrt{4\pi\varepsilon_0}} \frac{\sqrt{4\pi\mu_0} B}{m_i} = \frac{q_i B}{m_i}. \]
We take for simplicity the Pedersen and polarization drift terms separately. The Pedersen term is in SI units
\[ \frac{m_i}{q_i B} \frac{1}{\sqrt{4\pi\varepsilon_0}} \frac{\sqrt{4\pi\mu_0} B}{4\pi} v_i \left( \sqrt{4\pi\varepsilon_0} \mathbf{E} + \sqrt{\mu_0\varepsilon_0} \mathbf{v}_n \times \sqrt{4\pi\mu_0} \mathbf{B} \right) \] (A.14)
\[ = \frac{m_i}{q_i B^2} \frac{1}{\sqrt{4\pi\varepsilon_0}} \frac{1}{\sqrt{4\pi\mu_0}} v_i \left( \sqrt{4\pi\varepsilon_0} \mathbf{E} + \sqrt{4\pi\varepsilon_0} \mathbf{v}_n \times \mathbf{B} \right) \] (A.15)
\[ = \frac{m_i}{q_i B^2} \sqrt{4\pi\varepsilon_0} v_i \left( \mathbf{E} + \mathbf{v}_n \times \mathbf{B} \right) \] (A.16)
\[ = \frac{m_i}{q_i B^2} v_i \left( \mathbf{E} + \mathbf{v}_n \times \mathbf{B} \right). \] (A.17)
The polarization drift term is in SI units
\[ \frac{m_i}{q_i B} \frac{1}{\sqrt{4\pi\varepsilon_0}} \frac{1}{\sqrt{4\pi\mu_0}} \left( \frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla \right) \sqrt{4\pi\varepsilon_0} \mathbf{E} \] (A.18)
\[ = \frac{m_i}{q_i B^2} \frac{4\pi\varepsilon_0}{\varepsilon_0 \mu_0} \left( \frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla \right) \mathbf{E} \] (A.19)
\[ = \frac{m_i}{q_i B^2} \left( \frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla \right) \mathbf{E}. \] (A.20)
Equation (A.13) is then in SI units
\[ \mathbf{v}_i = \mathbf{V} + \frac{m_i}{q_i B^2} v_i \left( \mathbf{E} + \mathbf{v}_n \times \mathbf{B} \right) + \frac{m_i}{q_i B^2} \left( \frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla \right) \mathbf{E}. \] (A.21)
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