B: Literature Review, Background and Science Questions

This document discusses the background and previous literature regarding radar and optical observations of the aurora. The first section covers coherent and incoherent scatter radars and open science questions involving the use of radars. The next section covers optical auroral imaging of both luminous and black auroral features, and the open science questions related to auroral imaging. The third section covers theories, models and simulations relating to small-scale auroral structures, and the relevant open science questions. The fourth section summarizes and pulls together these open questions and discusses how they will be investigated as part of this thesis project. As an appendix, the auroral emission spectra and the theory of how radars operate in the ionosphere are discussed in more detail.

B.1.1: Radars (Incoherent and Coherent scatter radars)

Radar techniques have been used since the dawn of the space age in the 1950s to study the ionosphere [Gordon, 1958]. The construction of the first ISR (Incoherent Scatter Radar) was begun in 1959 at Arecibo, Puerto Rico. Since then there have been several other ISR sites constructed around the planet, including Sondrestrom, Greenland; EISCAT in Tromso and Svalbard, Norway; Jicamarca, Peru; and Millstone Hill, Massachusetts [Kelley, 1989].

More recently a new type of ISR, AMISR (Advanced Modular Incoherent Scatter Radar), developed by SRI, International, is being built which has very high spatial and time resolution. The full AMISR system consists of 3 faces of panels, each face being approximately 32-square meters and consisting of 128 panels. The first face is currently being constructed at Poker Flat, Alaska, where it will be able to observe from the equatorward to the poleward portion of the auroral oval during substorm expansion. At Poker Flat, AMISR can also be used in conjunction with sounding rocket launches, which measure in-situ plasma parameters. After the completion of the Poker face, the other two faces will be constructed at Resolute Bay, Nunavut, Canada, near the poleward edge of the auroral oval. Once all the faces are completed, it will be decided where and when to move the panels to different locations. Eight test panels were placed at Jicamarca, Peru in December of 2004 and they were able to detect the equatorial electrojet [SRI, International]. Another 16 panels were placed at Gakona, Alaska, where the HAARP (High Frequency Active Auroral Research Program) ionospheric heating facility is located. These panels were able to detect the heater induced plasma lines and several cascade mode lines. This array of 16 panels however is not large enough to image the natural auroral ionosphere, since the integration times required are prohibitively long, on the order of many minutes. The completion of the full 128 panels at Poker Flat is thus eagerly awaited. It is expected that the 32 panels of AMISR, already in place at Poker
Flat, will be able to detect the naturally enhanced ion acoustic lines to be discussed below.

The data from an ISR can be used to get information about ionospheric electron density \( (Ne) \), electron temperature \( (Te) \), ion temperature \( (Ti) \), and line-of-sight ion flow velocity \( (Vi) \). The procedure for obtaining these quantities involves fitting theoretical spectra to the raw data. This process however has many assumptions embedded into it, the most important being that the plasma is assumed to be near-Maxwellian [Sedgemore-Schulthess, et al., 1999]. Typical ISR spectra from a thermal plasma consists of a double humped peak centered near the transmitted frequency, with the two humps offset by the ion-acoustic frequency (typically around 5 kHz). The two humps are caused by thermally excited ion-acoustic waves traveling towards and away from the radar. Significant departures from a thermal Maxwellian spectra were first observed in ISR data by Foster, et al. [1988]. These spectra contained significantly enhanced (several orders of magnitude above thermal levels) ion-acoustic lines that were extended in altitude range and lasted for a short (10s of seconds) time interval. When ISRs get very large returns from a very limited altitude range, it is assumed that the radar is scattering off of a hard target, such as a satellite, and the data are discarded, but when these large returns are extended in altitude, they are assumed to be of geophysical origin. These Naturally Enhanced Ion-Acoustic Lines (NEIAL) are of great interest because they are an indication of processes that are not fully understood and may be related to ion outflow and BBELF (Broad Band Extremely Low Frequency) waves. The generic fitting procedure that is used to determine Ne, Te, Ti, and Vi will also not work at these times and can give spurious results.

Recent efforts concerning these NEIAL attempt to identify their generation mechanism. Three main theoretical models have been proposed to explain the generation of the NEIAL. The first model was by Foster, et al. [1988] and later by Rietveld, et al. [1991], which proposed a current-driven instability carried by the thermal electrons. This theory however cannot explain simultaneously observed up and down shifted enhancements in the same volume, other than through spatial and/or temporal averaging. This is because currents in one direction produce enhancements in one shoulder, while currents in the other direction produce enhancements in the other shoulder. The second theory was that of Wahlund, et al. [1992], which suggests an ion-ion two stream instability produced by the relative drift of different ion species. The third model is that of Forme, [1993, 1999], where electron beam driven Langmuir waves can excite the ion-acoustic instability through wave-wave interactions. This theory allows for simultaneous up and down shifted enhancements to be excited in a common volume, but requires an unstable electron beam distribution that has been rarely observed in the soft electron precipitation. One example is known where an unstable electron beam distribution was observed by a sounding rocket and is described in Ergun, et al. [1991].

The first use of combined radar observations of NEIAL with high resolution narrow-angle (20 x 30 km FOV at 105 km altitude) television images was done by Sedgemore-Schulthess, et al. [1999]. They used the conjugate data to argue that it was the transient current driven instability that was producing the NEIAL. They noted that the ISR data is usually integrated in 10-second intervals, and that the auroral forms observed during the NEIAL events varied on much faster timescales (second to sub-second). This was used to say that the simultaneously observed up and down shifted
lines were the result of averaging by the radar and that they did not actually occur at the same place at the same time.

However, using interferometric methods Grydeland, et al. [2003, 2004] showed that the size of the structures producing the NEIAL were on the order of a few hundred meters in size in the horizontal direction at 500 km altitude, indicating that the actual enhancement within these structures when not averaged over the entire radar beam must be 4 to 5 orders of magnitude larger than the thermal level. Grydeland, et al. [2003, 2004] also analyzed the raw radar data and integrated it in 0.2-second intervals, which revealed that both the up and down shifted NEIAL are occurring at the same time in the same location. This also showed that the NEIAL have very high time variability, on the order of the 200 ms integration times used. They also had high-resolution narrow angle television images of the aurora during the NEIAL events. They used these observations to argue that it must be the electron beam driven Langmuir wave instability proposed by Forme, [1993, 1999] that is the mechanism for generating the NEIAL, since the current driven instabilities cannot produce collocated simultaneous up and down shifted NEIAL.

Further evidence for this wave-wave interaction theory is given in Stromme, et al. [2005], where they present radar observations of NEIAL, which also had corresponding enhancements in the up and down shifted plasma lines at the same time during the January 2004 ESR Radar and Optical Nikita campaign. They do not have optical data for the event studied due to bad weather. They use their observations as well as the time evolution of the data to further support the wave-wave interaction theory for generating the NEIAL. The low energy electron beam produces Langmuir waves by Landau growth from the region of positive slope in the electron distribution. The Langmuir wave can then decay into an oppositely directed secondary Langmuir wave and an ion-acoustic wave traveling in the direction of the original Langmuir wave. The secondary Langmuir wave can also decay, and so on cascading energy toward lower wave vectors, until the Langmuir wave amplitude is no longer above the decay threshold [Stromme, et al., 2005].

Blixt, et al. [2005] collected all the data sets that included both NEIAL and conjugate high-resolution narrow angle optical images of the aurora. There were only 4 such cases found. Using these data, they were able to conclude that very dynamic rayed aurora were necessary for the formation of the NEIAL. This type of aurora is associated with Alfvénic acceleration of electrons, which produce large numbers of low energy (sub-keV) precipitating electrons. This is also indicated in the camera data by the large altitude extent of the auroral rays [Blixt, et al., 2005]. These low energy electrons are a key component in the theory of generating NEIAL by the non-linear decay of Langmuir waves [Forme, 1993, 1999]. It is possible that NEIAL and Alfvénic aurora are also associated with the BBELF and ion outflow that are observed on satellites and rockets [Lynch, et al., 2002; Klatt, et al., 2005].

These four cases were all associated with dynamic rayed aurora in or near the radar beam during the time of the enhancements. Grydeland, et al. [2004] used the conjugate camera and radar data to conduct the first study of causal relationships between the NEIAL and the auroral rays. They find that the aurora precedes the NEIAL by about 0.8 seconds, and that there appears to be a luminosity threshold for the aurora, above which the NEIAL can occur.

The connection between increased ion outflows and enhanced ion acoustic fluctuations has been established experimentally by Ogawa, et al. [2000] and by Forme
and Fontaine [1999]. They also find that the occurrence of NEIAL are associated with enhancements of electron temperature and electron density, indicating that precipitation processes are important. Forme, et al. [1999] developed a method to estimate the plasma parameters inside the turbulent regions associated with the NEIAL where the standard analysis procedure fails. They find using their method that the electron temperature can be heated up to about 11,000 K, and that ion outflow velocities can be as high as 1300 m/s at 800 km altitude.

All of this work above involves the use of incoherent scatter radars, however Coherent Scatter Radars (CSR) can also be used to study the auroral ionosphere. Coherent backscatter from the auroral F-region is thought to be well understood, but there is little consensus regarding the interpretation of auroral E-region coherent backscattered spectral forms [Bahcivan, et al., 2005]. Using observations from the 30 MHz radar located near Anchorage, AK and in-situ rocket measurements of the electric field, Bahcivan, et al. [2005] determine an empirical model to predict the Doppler shift of auroral E-region coherent echoes. Auroral E-region coherent echoes do not exhibit Doppler shifts that are proportional to the line of sight convection speed [Nielsen, et al., 2002]. These methods are being studied as a way to get convections speeds and hence ionospheric electric fields from the Doppler shifts of the coherent returns from the auroral E-region. The advantages of using this 30 MHz radar include its imaging capability on time scales of seconds, its capability to image the E-region ionosphere over Poker Flat perpendicularly, and that it is scattering off of ~5 meter scale irregularities in the plasma. Time sequences of the 30 MHz radar returns overlaid on auroral all-sky images indicate that the returns often come from the dark regions adjacent to discrete aurora [D. Hysell, personal communication].

B.1.2: Open Science Questions I

There are many open questions and interesting problems that were identified in the existing literature on radar observations of auroral structures. Several of these, outlined below, could be addressed with the data collected during the proposed observing campaign.

1: The link between the dynamic Alfvénic auroral ray features and the NEIAL has been established preliminarily by Blixt, et al. [2005], with 4 data points of conjugate camera and radar data of NEIAL. There has also been a connection established between the occurrence of NEIAL and increased ion outflow [Ogawa, et al., 2000]. It will be a goal of this study to collect more data with both the imagers and the radar to try to make the explicit connection between the dynamic Alfvénic auroral rays and enhanced ion outflows. There may also be a connection between the NEIAL/ion outflow and the BBELF, which has been observed in situ to be associated with ion outflow.

2: The use of AMISR will allow observation of very small-scale structure with high time resolution. The existence, or not, of large amplitude, transient, small-scale structures could then be determined. For example, Grydeland, et al. [2003, 2004], showed that the scattering structures responsible for the NEIAL were on the order of a few hundred meters. This indicated that the scattering cross section in those regions must be 4-5
orders of magnitude larger than the thermal levels in order to produce the observed enhancements averaged over the entire radar beam. It is not known if large amplitude electric fields (order of V/m) exist in the lower ionosphere on small-scales, however recent simulation work, [Streltsov and Lotko, 2003a,b, 2004], shows that such electric field structures can develop and are associated with the downward current region.

3: The 30 MHz radar returns from the auroral E-region will be examined with conjugate high time and space resolution auroral images. To date there is very little in the literature comparing these radar images to auroral images, [Bahcivan, et al., 2005]. A goal of this study would be to gain insight into what the irregularities are that the radar is scattering from, for example, density enhancements, depletions, density gradients, sheared flows, currents, etc. Another goal of this study will be to examine any causal relationship between the auroral luminosity and the radar returns.

B.2: Auroral Imaging

The first quantitative analyses of the thicknesses of auroral forms were done before the 1950s from photographs of the aurora. Stormer [1955] determined the thickness of an isolated homogeneous auroral arc to be 7.42 km, at an altitude of 200 km. Elvey [1957] estimated the thickness of an auroral arc to be less than 250 m at about 100 km altitude. Kim and Volkman [1963] did a survey of 40 auroral arcs appearing in all-sky photographs and found the thicknesses to range between 3.5 km to 18.2 km with a mean of 9.1 km, at an assumed altitude of 100 km.

B.2.1: Luminous Auroral Features

The first application of low light level television imaging of the aurora was done by Davis [1966] with an image orthicon television system. The image orthicon tube is a vacuum tube, used in television cameras from the 1940s to the 1960s, containing an electron multiplier allowing for its use in low light level conditions, making it suitable for auroral observations. The system used by Davis [1966] recorded images on photographic film at a rate of 24 or 30 frames per second, with an effective exposure time of 1/60th of a second per frame. The field of view of this imager was 12 x 16 degrees. The first large-scale survey of the thicknesses of auroral structures, using this television system, was done by Maggs and Davis [1968]. They measured the thicknesses of 581 auroral structures near the magnetic zenith. Assuming an altitude of 100 km, the sizes ranged from the instrumental cutoff of 70 m to 4440 m, with a median of 230 m. They found that rayed auroral structures tended to be thinner than homogeneous structures and that all types of aurora tended to get thinner as they got brighter. This supports the idea that the mechanisms producing the aurora become more spatially localized as their intensity increases. They also note that their results for the thicknesses are not representative of all auroral structures, since structures larger than 4.4 km exist, but were not able to be measured with the television camera used in their study.

Using the same television system, Hallinan and Davis [1970] examined the properties of the most common small-scale auroral arc distortions, namely “folds,” and
vortex-like “curls”. Their focus was mainly on the curls, but some properties of the folds were mentioned. The folds have clockwise rotation sense when viewed anti-parallel to the magnetic field, larger wavelengths (10-50 km), smaller velocities (0-5 km/s), and longer lifetimes (several to many seconds) than the curls.

The curls, identified with a Kelvin-Helmholtz instability due to fluid shear, all had a counter-clockwise rotation sense when viewed anti-parallel to the magnetic field. The spacing between curl centers (the wavelength) was measured for 83 curl systems assuming 100 km altitude. The range of wavelengths was from about 1 km to 9 km with the most frequent value around 5 km. Horizontal velocities of the curls ranged from 0 km/s to 20 km/s, with the most typical being around 5 km/s. The lifetime of the curls ranged from 0.4 s to 2.2 s with a mean of 1.3 s, indicating that they are a very transient feature. The auroral images of curls were compared to laboratory experiments of the sheet beam instability, [Webster, 1957], which produced structures with the same features as the auroral curls. It was therefore suggested that the sheet beam instability be a possible mechanism for the production of auroral curls. Hallinan and Davis [1970] draw the conclusion that the apparent horizontal velocities of the curls represent the actual motion of the plasma in the sheet, and therefore velocities of 5 km/s to 20 km/s of the curls would mean that transient horizontal electric fields of 250 mV/m to 1000 mV/m were present at some altitude.

More recently Trondsen and Cogger [1998] performed a much larger statistical study of auroral curls using a newly developed imager, the portable auroral imager (PAI) of the University of Calgary, described in detail by Trondsen [1998]. This statistical study examined 440 examples of curls recorded at Rabbit Lake, Saskatchewan, Canada. They assumed an altitude of 105 km for the curls, and their statistical results for the physical properties are summarized below:

<table>
<thead>
<tr>
<th>Property</th>
<th>Range</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1-9 km</td>
<td>3-4 km</td>
</tr>
<tr>
<td>Speed</td>
<td>0-90 km/s</td>
<td>10 km/s</td>
</tr>
<tr>
<td>Preferred</td>
<td>2-8 km/s</td>
<td></td>
</tr>
<tr>
<td>Lifetime</td>
<td>0.1-46 s</td>
<td>2.3 s</td>
</tr>
<tr>
<td>Preferred</td>
<td>0.25-0.75 s</td>
<td></td>
</tr>
<tr>
<td>Dimensions (elliptical)</td>
<td>Mean = 2.3 km^2</td>
<td>Preferred = 0.5 km^2</td>
</tr>
</tbody>
</table>

They made a distinction between bright and weak aurora, and noted any correlations between brightness and the physical properties, and their main findings are summarized in following table:

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>Similar for bright and weak aurora</td>
</tr>
<tr>
<td>Bright</td>
<td>Bright aurora have faster speeds.</td>
</tr>
<tr>
<td>Aurora</td>
<td>Bright aurora have shorter lifetimes.</td>
</tr>
<tr>
<td>No correlation</td>
<td>No correlation between curl speed and curl lifetime observed.</td>
</tr>
<tr>
<td>Bright aurora</td>
<td>Bright aurora contained both the largest and the smallest curls.</td>
</tr>
<tr>
<td>No correlation</td>
<td>No correlation between curl speed and curl area.</td>
</tr>
<tr>
<td>No correlation</td>
<td>No correlation between curl area and curl lifetime.</td>
</tr>
</tbody>
</table>

They also measured the thickness of the thin threads that connect tightly wound curls together and they were found to be extremely thin, with a mean of 270 m, and a preferred range of 100-300 m. A large subclass of zero velocity curls were examined and
found to belong to a separate group, termed auroral “kinks”. These are generated between two adjacent counter-streaming auroral arcs that come together, while “curls” are generated inside a single arc. The counter-streaming velocities are observed to be very rapid (10-100 km/s) and directed eastward along the poleward edge, and westward along the equatorward edge. The kinks seem to be fixed relative to the magnetic field lines, while the curls seem to be fixed to a given plasma element.

Further analysis of curl systems was done by Vogt, et al. [1999], where they used a new technique, (sliced-stacked-slopes), for analyzing curl systems. This technique stacks slices of the image as a function of time, allowing structure velocities to be extracted as slopes. Using the Kelvin-Helmholtz dispersion relation, they found a discrepancy between the observed velocity shear and the predicted growth rates of the curls. They tested the assumption that the rotational vorticity of the curls comes from the velocity shear vorticity that is present in the arc system before the curls develop. They found that the observed velocity shear vorticity was insufficient to account for the subsequent increase in rotational vorticity associated with the curls, indicating that another source of vorticity is involved in driving the curl formation. These discrepancies suggest that the auroral acceleration region and/or transient processes (Alfvén waves) should be taken into account in future models involving the evolution of small-scale auroral forms.

The above discussion of auroral arc thicknesses has dealt mostly with the smallest auroral features, however there is a range of scale sizes involved in auroral structures. These scale sizes also include hundreds of kilometers for the auroral oval, and tens of kilometers for the band systems inside the oval.

Borovsky [1993] performed a large survey of all the existing theories of auroral arc formation and extracted the predicted auroral arc thickness for each theory. The author examined 12 accelerator mechanisms and 10 generator mechanisms, and found that none of them produce the small-scale structures as observed by Maggs and Davis [1968]. The theories mostly predict kilometer scale thicknesses when mapped down to the ionosphere, while the observations tend to have thicknesses around several hundred meters. Their analysis of Alfvénic acceleration is however obsolete, and this process is now believed to produce small-scale auroral features, [Chaston, et al., 2003a]. Borovsky [1993] also notes that some of these 22 mechanisms may be responsible for the larger scale auroral arcs that are observed, but that there is not enough observational data to distinguish between the different theories, and therefore suggests several optical observations that would help in distinguishing between different large-scale generation mechanisms, and these are summarized below:

1. Correlating fine-scale arcs with larger arc structures.
2. Measuring the height of fine-scale arcs.
5. Correlating all-sky-camera images with data from (geosynchronous) satellites.
6. Following Alfvén waves transiting between conjugate arcs in the northern and southern hemispheres.
7. Measuring auroral arc temporal fluctuations.
8. Correlating arc thicknesses with other arc parameters.
A survey of 109 of these large-scale arcs was done by Johnson [1996], using images from the Freja satellite. Many of these large arcs (10-100 km wide) exhibited spirals spaced quasi-periodically along the arc. These spirals, described in detail in Davis and Hallinan [1976] have been shown to be consistent with a Kelvin-Helmholtz instability acting on a current sheet [Hallinan, 1976]. These large-scale (20-600 km) spirals are always twisted in the clockwise direction when viewed anti-parallel to the magnetic field, which is consistent with the distorted current sheet model of Hallinan [1976].

A recent survey of large-scale (mesoscale) auroral arcs was done by Knudsen, et al. [2001], using images obtained with an all-sky camera at Gillam, Manitoba. They calculated widths of 3126 stable auroral arcs, with a camera filtered to accept 557.7 nm (+/- 1.1 nm) emissions with a resolution of 1.7 km at the zenith. The mean arc width was measured to be 18 km, with a standard deviation of 9 km. They observed a sharp cutoff in width below around 8 km, and this is believed to be geophysical since the instrumental cutoff is around 2 km. The widths were calculated by taking the full widths at half maximum (FWHM) of Gaussians that were fit to the intensity versus distance plots, obtained from cross-sections through the all-sky images. The intensities of the arcs ranged from 0.2 – 200 kR, averaging around 15 kR. These observations combined with the earlier observations of Maggs and Davis [1968] suggest that the mesoscale arcs and the fine-scale arcs should be considered as two separate phenomena. In the data there appears to be a lack of arcs with widths around 1 km, but a turbulent cascade from the larger scales to the smaller scales would produce a more continuous spectrum of arc widths. This gap in the data should be interpreted cautiously however, since this region of arc widths, is near the resolution limit of both studies. The authors suggest that a study optimized in the kilometer range would be necessary to verify the existence or not of a real gap in the occurrence of auroral arcs there. It was noted that the large-scale arcs typically have lifetimes on the order of minutes, while the small-scale arcs typically have lifetimes of only seconds [D. Knudsen, personal communication]. Our proposed observing campaign will have access to a camera, similar to the Calgary PAI, which can be fitted with an appropriate lens to optimize the field of view to image kilometer scale auroral structures, [M. Lessard, personal communication], which will be used together with a narrow-field and an all-sky camera to examine the existence of a gap in occurrence of auroral arc widths.

Ground camera images of the aurora can rarely be compared to in-situ plasma data, but one example of such a comparison was done by Hallinan, et al. [2001]. Using rocket measurements of the electron energy, the high altitude electric potential could be estimated. The main assumption is that a plot of the peak electron energy versus time can be regarded as a profile of the electric potential distribution above the arc. From this potential distribution, the perpendicular electric field in the acceleration region can be determined. This electric field was found to be in good agreement with the perpendicular electric field inferred from the velocities of the auroral rays as observed with the ground camera. Furthermore the measured electron energy flux agreed well with the auroral luminosity, down to scale sizes of about 10 km. The measured energy flux was also used to determine the altitude of the lower border of the auroral arcs, which was found to be around 130 km, which is higher than the expected 100-110 km.
Another comparison between camera and in-situ data was done by Stenbaek-Nielsen, et al. [1998], where they flew all-sky and narrow-field cameras on an airplane under the aurora that was conjugate to a FAST satellite pass. Their main findings were that the ion and electron data obtained at FAST altitudes (~4000 km) correlated very well down to about 2 km scales with the camera data. There were however, no structures smaller than about 2 km observed during the pass. This result indicates that the processes imposing the structure, at least down to ~ 1 km, occur at or above about 4000 km altitude. They found that the agreement between the electron precipitation data and the camera data was best when the electron data were plotted as total precipitated energy on a linear energy scale. The electron data are usually plotted on a log scale to allow more data to be incorporated on one plot, but this tends to overemphasize the low energy electrons, which makes the structures appear larger in the electron data. Using the linear plots, and the detectability limit of the cameras of about 1 erg/cm²/s, Stenbaek-Nielsen, et al. [1998], found good agreement between the FAST electron data and the optical data down to widths of a few kilometers.

B.2.2: Black Aurora and Return Current Region Aurora

Up to now only luminous auroral features have been discussed. There exists another class of aurora referred to as black aurora. The term “black aurora” was first used by Royrvik [1976] to describe a lack of auroral emissions in a small well defined region embedded within a uniform background of diffuse aurora or aurora that is intermediate between diffuse and discrete. Black aurora most commonly occur during the late recovery phase of auroral substorms [Trondsen and Cogger, 1997]. A statistical survey of the properties of black aurora, namely black patches, black arcs, and black vortices, was done by Trondsen and Cogger [1997]. They give typical dimensions of black aurora to be around 1-3 km, and velocities of hundreds of meters per second. The black aurora was also noted to be more stable and last longer than white auroral forms. The authors also found a relation between the area of the black objects and their eastward speed, indicating that the smaller objects tended to move faster than the larger ones. They also make the explicit distinction between the black aurora as defined above and the spacing between ordinary discrete auroral forms, and the latter are excluded from their study. The phenomenon of black auroral vortices was also described and an explanation given in terms of an excess of positive space charge on a flux tube.

The morphology of these “black curls” was later expanded on by Kimball and Hallinan [1998a]. The ordinary luminous curls as described above invariably have a counterclockwise rotation sense when viewed anti-parallel to the magnetic field, indicating an excess of negative space charge, associated with a converging electric field. All examples of black curls observed had clockwise rotation senses, indicating an excess of positive space charge, associated with a divergent electric field. The other observed properties of black curls, like size and speed, were observed to be similar to the ordinary white curls. The emission spectrum from an area of diffuse aurora with black curls showed signs of both electron and proton precipitation. This is consistent with the existence of adjacent upward and downward parallel electric fields above that region, therefore accelerating electrons downward in the diffuse aurora and protons downward in the black curls. They also observed for the first time the formation of a Karman vortex.
street, which is composed of alternating white and black curls. *Kimball and Hallinan* [1998b] reported for the first time the observation of “black rings”, which are black patches with embedded diffuse aurora in the middle. They also noted that the eastward drifting black patches sometimes had an associated bright patch that would move along with it, which is consistent with paired upward and downward parallel electric fields.

*Kimball and Hallinan* [1998b] also describe the process of veiling, which occurs when pulsating aurora overlaps the black patches or rings. Veiling occurs when the pulsation adds to the luminosity of the black aurora more than it adds to the luminosity of the surrounding diffuse aurora. One example was found in which the pulsation was purely additive to the luminosity of both the black aurora and the surrounding diffuse aurora, and therefore not an example of veiling. The examples of veiling that were observed suggest that the pitch angle diffusion limit may be responsible, [*Kimball and Hallinan*, 1998b]. It is assumed that the pulse reaches maximum luminosity when the loss cone is full, suggesting that the diffuse aurora sometimes corresponds to a full loss cone. Whether the pulsation is there or not, the luminosity of the diffuse aurora cannot increase any further if the loss cone is full. The luminosity of the black aurora however can increase, when the pulsation is there, until it is at the same luminosity as that of the background diffuse aurora. Total veiling occurs when the luminosity of the black aurora reaches that of the background diffuse aurora when the pulsation is there. Partial veiling can also occur when the luminosity of the black aurora increases more than the background, but not completely to the level of the background diffuse aurora.

The phenomena of black aurora, namely the black patches that occur embedded in the diffuse aurora, have been fairly well described from the ground camera data. The other type of black aurora, the black structures that are seen to occur along with the discrete auroral forms, have received much less attention in the ground camera data. At Dr. Mende’s suggestion we will refer to these as return current region (RCR) black aurora. Both RCR black aurora as seen from images and the RCR as seen in situ are associated with divergent electric field structures and excess negative potential. It is most likely these structures that were observed by the Freja satellite, when large (1-2 V/m) diverging electric fields were observed to exist on small (~1 km) scales at low altitudes (800-1700 km), [*Marklund, et al., 1997*]. They report that ~1 V/m diverging electric fields are occasionally observed down to 800 km altitude when the ionospheric conductivity is low, for example near midnight and during winter. The ambient ionospheric conductivity is estimated from solar EUV radiation, and an anti-correlation was found between conductivity and electric field magnitude, with the strongest electric fields occurring when the conductivity is low. There was also an anti-correlation observed between electric field magnitude and scale size, with the smaller scale structures having the larger electric fields. This implies a limit to the potential across these structures of about 1 kV. In the regions where these intense field events occur, Freja often observes intense upward fluxes of low-energy electrons. This is likely to cause localized regions of decreased density in the ionosphere (density holes) under these regions of upward electron fluxes. The authors note that, if these potential structures exist as indicated in their data, an outstanding problem is then how they are generated and maintained.

Again using Freja data *Marklund, et al.* [1998] examined the structure of large-scale auroral spirals and westward traveling surges. For this study the UV imager
onboard Freja was used to determine what type of auroral structures were present at the ionospheric footpoint of the satellite. They examined several different satellite passes but the one pass that went right through a westward traveling surge near substorm onset, showed some very large (700mV/m) electric fields at about 1700 km altitude. These large fields are most likely due to the diverging electric fields associated with the RCR black aurora. The aurora was very dynamic with much fine structure during this time, so the UV imager on Freja could not resolve the small-scale structures of the aurora. In our ground camera data, we have been able to identify several examples of these RCR black auroral structures, and their time evolution can also be followed.

B.2.3: Open Science Questions II

Much work has already been done on quantifying auroral scale sizes, motions, and lifetimes. There are however, many open questions and areas that need further study. Some of the open questions that were identified while reviewing the previous literature are listed below and could potentially be addressed with the proposed observing campaign.

1: Performing thickness measurements on camera data optimized for viewing structures in the 1-10 km size range. This could be used to determine if the gap observed in the occurrence of auroral arcs around a few kilometers in thickness is real or not, as suggested by Knudsen, et al. [2001].

2: Examine the occurrence of auroral arc widths versus scale sizes and lifetimes, as suggested by D. Knudsen [personal communication].

3: Examine how the radius of curvature of curved arcs compares to the thickness of the arc itself. This relates to one of the suggestions of Borovsky [1993], namely, correlating arc thicknesses to other arc parameters.

4: Measure and better characterize the RCR black aurora. This would fit into the work of Marklund, et al. [1997], by providing a ground-based view of the black auroral structures. The problem of how they form and are maintained could be addressed with ground-camera data, by allowing the time evolution and motion to be observed and quantified.

5: The motion of the black aurora and the RCR black aurora through the background plasma could be quantified relative to the background plasma motion, by using AMISR to measure the background plasma motion. Trondsen and Cogger [1997] quantified the motions of the black aurora relative to the ground, since the diffuse aurora didn’t contain enough structure to be followed by the ground cameras.
B.3: Theories, Models, and Simulations

There are two main types of auroral arc theories, static/quasistatic theories and more dynamic Alfvenic theories. There are numerous theoretical models of magnetosphere-ionosphere coupling that involve field-aligned (Birkeland) currents that close through the ionosphere by Pedersen and Hall currents, and have their driving energy source far from Earth, out in the magnetosphere or solar wind. These theories start generally with the basic equations, namely, the continuity and momentum equations for the ions and the electrons, Faraday’s law, Gauss’ law, and Ampere’s law. The different models then take different approaches, assumptions and approximations to solving this set of coupled equations.

B.3.1.1: Static Models

Naturally some of the first models developed are also some of the simplest, and belong to the static/quasistatic group. For example, Chiu and Schulz [1978] calculate the electrostatic potential along magnetic field lines by using quasi-neutrality in conjunction with the different plasma populations, namely the hot, anisotropic magnetospheric plasma and the ionospheric plasma. They can get several kilovolts between the ionosphere and the equator, and parallel electric fields with characteristics consistent with inverted-V electron precipitation structures. It has been widely accepted experimentally that parallel electric fields do exist, at least transiently, on magnetic field lines associated with discrete auroral arcs, [Akasofu, 1977].

The quiet auroral arc theory of Sato [1978] attempts to take into account the time-dependence of the development of quiet auroral arcs with a quasi-steady state solution. It is possible to generate a quiet arc as a result of a feedback interaction between the ionosphere and the magnetosphere. This model produces perturbations elongated in the E-W direction with widths of about 10-30 km in the ionosphere, with growth times from tens of seconds to tens of minutes depending on initial conditions. It also predicts that the potential structures associated with the arcs is about several hundred volts, therefore the electrons producing the visible arc and carrying the upward field-aligned current should have energies of several hundred eV.

B.3.1.2: Alfvenic Models

The model of Goertz and Boswell [1979] solves directly for the parallel and perpendicular electric fields, by using Fourier transforms in space, and Laplace transforms in time. The model of Goertz [1984] however uses the method of introducing scalar potentials \( \phi \) and \( \psi \) and then proceeds to derive the dispersion relation for kinetic Alfven waves. Goertz and Boswell [1979] was meant to improve upon the current system model of Mallinckrodt and Carlson [1978] that treated the magnetic field lines as essentially wires, whereas Goertz and Boswell [1979] allowed for parallel resistance to be spatially distributed and frequency dependent, therefore allowing parallel electric fields to be generated. The theory of Goertz and Boswell [1979] does not take into account any variation in the y-direction, the direction along the arc. They do however find that under
certain conditions, (namely narrow arcs and low plasma density) large parallel electric fields can develop. Furthermore they find that the energy gain of electrons accelerated by these fields is inversely proportional to the perpendicular thickness of the Alfvénic structure, and that the electron acceleration should be modulated with periods of several minutes. They calculate a time $\tau$, which represents the periodicity with which the parallel electric field will be modulated, therefore modulating the precipitating electrons. For auroral parameters $\tau$ is estimated to be on the order of 1-5 minutes. They also predict that because of velocity dispersion, the smaller structures should decay faster than the larger scale structures, and that the structures with perpendicular scales of greater than 20 km could be stable for several hours.

The above-mentioned theories are essentially 2-dimensional models, assuming no changes along the arc, (east-west direction). One of the first fully 3-D models of the small-scale discrete auroral arcs, which included electron inertial effects, was that of Seyler [1990]. This model follows the 3-D motion and evolution of small-scale structures, and it produces structures that resemble in size and motion the curls of Hallinan and Davis [1970]. The author notes however that it is difficult to make a more rigorous, quantitative comparison, since it is not clear what simulation data should be compared to the curl observations. The potential contours bear a close resemblance, but the current density would be a more appropriate comparison [Seyler, 1990]. The previous observations of curls associated them with the Kelvin-Helmholtz instability, which is a fluid instability. The model of Seyler [1990] however produces the instability in a fully electrodynamic way, called the tearing mode instability. This model also predicts the electric field spectral index, which starts out steep (around $-3$ to $-5$) at early times and then flattens out to the turbulent $-5/3$ Kolmogorov scaling after a long time. Recent work by C. Chaston is showing a $-5/3$ spectra in FAST electric field data from the RCR [C. Chaston, personal communication].

The model of Seyler and Wu [2001] expands on the model of Seyler [1990], by now concentrating on the instabilities that occur near the electron inertial length ($c/\omega_p$) scale for a parallel current sheet equilibrium. They find two general classes of instability that exist as a result of parallel electron inertia. The first is the tearing mode, while the second is the current shear driven current-convective interchange mode. The tearing modes are global modes, which act over large areas, and relax the magnetic energy to a lower state. The current-convective interchange mode is a local mode, which acts only in small localized regions near where $(k \cdot B_0) = 0$. Their results support the hypothesis that short scale BBELF waves associated with Alfvénic Structures (AS) are the result of current decay through the electromagnetic current-convective instability. The fundamental nature of this mode is that it relaxes gradients in parallel current by generating field-aligned vortices. The consequence of this process is to heat ions transversely and electrons parallel to the magnetic field. The authors note that an area needing further investigation is the importance of electron inertial scale instabilities in the structuring and evolution of small-scale auroral arcs. These small-scale instabilities could be related to the production of the NEIAL that are observed in the radar data.

Further collaboration with C. Seyler will be done to look for specific signatures of these instabilities in the camera and/or radar data.

Chaston, et al. [2003a] present a study of FAST observations, theoretical analysis, and simulations to quantitatively address the issues of the width and the brightness of
auroral arcs that are driven by inertial Alfvén waves. They determine that inertial Alfvén waves can produce aurora with optical intensities of up to 100 kR with widths in the ionosphere of around 1 km. They are also able to show that inertial Alfvén waves can produce auroral arcs with widths less than 100 m, but that it is unlikely that they are the cause for the observed width distribution [Maggs and Davis, 1968; Hallinan and Davis, 1970], because they would mostly be of sub-visual luminosity. Using a theoretical model Chaston, et al. [2003b] examined the kinetic effects of ions and electrons on small-scale Alfvén waves. Their theory predicts the most commonly occurring arc width due to Alfvén waves to be around 900 m thick and will also be statistically the brightest of the Alfvénic aurora. They predict that the thinnest possible arc that can still be visible and be produced by Alfvén waves is around 35 m. Less than 20 % of the Alfvén waves observed with FAST would be capable of producing visible aurora with widths less than 100 m, and these would also be less bright than the thicker (~ 900 m) ones, but this is not consistent with the observed auroral arc thickness distribution of Maggs and Davis [1968]. They measured an increasing distribution right down to their instrumental cutoff of 70 m thickness and also they observed the thinner ones to be brighter. The main prediction of Chaston, et al. [2003a] is that the distribution of auroral arc thicknesses from Alfvén waves, that they derive, is broad and centered around 1 km in thickness. This would fill in the gap between the small-scale arcs observed by Maggs and Davis [1968] and the large-scale arcs observed by Knudsen, et al. [2001]. This will be investigated using the camera, provided by M. Lessard, with a field of view optimized to look at kilometer scale structures.

B.3.1.3: Specific Feature Models

Some theories and models have been developed to explain specific auroral features that are observed, and the results of the models are then compared directly to auroral data. An example of such a theory is the auroral spirals theory of Hallinan [1976]. This theory explains the formation of large-scale (~50 km) auroral spirals by a deformation of a Birkeland current sheet by magnetic shear associated with the current sheet itself. This produces spirals with a clockwise rotation sense (viewed anti-parallel to the magnetic field direction) for a sheet of upward current, which is consistent with observations. This is not an instability theory, but rather a quasi-equilibrium configuration since spirals are observed to be reversible. This theory also explains the production of the medium scale (~20 km) folds, which also rotate clockwise. Folds most likely form when the action of the opposing shear associated with the (CCW) auroral curls prevents the shorter wavelength (CW) disturbances from growing. The small-scale (~5 km) curls or rays correspond to counterclockwise shear associated with the (E X B) drift surrounding a sheet of negative charge, as discussed above. It is not clear however why the presence of the small-scale curls leads to the formation of the folds.

Another model that has been directly compared to data is that of Knudsen, et al. [1992], where they modeled Alfvén waves reflecting from the high-latitude ionosphere. This was done to better understand the role of Alfvén waves in magnetosphere-ionosphere coupling and to compare the numerical results to observations from a sounding rocket and satellites. They find that the frequency-dependent phase relations between the electric and magnetic field perturbations measured by a sounding rocket
agree very well with this standing Alfven wave model. The amplitudes however differed but this was attributed to static field aligned structures that were also likely to be present along with the Alfven waves.

B.3.1.4: Coupling Models

Recently there has been increased interest in treating the ionosphere as a much more active participant in the coupling to the magnetosphere. These models allow the ionosphere to be modified, which affects the interaction back on the magnetosphere. The numerical simulation work by Streltsov and Lotko [2003a] indicate that small-scale large amplitude perpendicular electric field structures can be produced in the ionosphere by large-amplitude Alfven waves. Their model was a fluid model of Alfvenic reflection and absorption to include a dependence on frequency and amplitude, which showed that different frequency ranges were absorbed differently by the auroral acceleration region and by the ionosphere. The simulations done by Streltsov and Lotko [2003b] no longer treated the ionosphere as a passive medium but rather they allowed for activations and feedback to the magnetosphere in response to electric fields and currents imposed by large-scale Alfven waves. They show that small-scale intense electric fields and currents can be generated by an ionospheric feedback instability inside a resonant cavity formed by the ionospheric E-layer and an auroral acceleration region. Their results suggest that Alfven waves generated at high altitudes can sustain discrete auroral arcs through the parallel electric fields generated in the upward current channel of the waveform, and simultaneously drive the generation of small-scale intense perpendicular electric fields in the downward current channel of the waveform. The main factor regulating the feedback dynamics is the downward current channel of a large-scale current system, which depletes the E-region plasma density and conductivity causing perpendicular electric fields to be produced in the E-layer. Their results suggest that these large-amplitude electric fields should occur in the depleted ionospheric regions that are associated with downward field-aligned currents, and that these regions of downward current should accompany the visible auroral structures but have transverse scales smaller than the visible structures. The simulations of Streltsov and Lotko [2004] improve upon those of Streltsov and Lotko [2003b] by investigating how the parameters of the ionosphere and the low-altitude magnetosphere affect the properties of the intense electromagnetic structures, which are commonly observed by polar orbiting satellites. The time evolution of RCR structures cannot be examined by satellites, however the ground cameras can follow the time evolution of the RCR signatures in the visible aurora. This would provide useful information on how different RCR structures develop and evolve into new and different structures.

A recent statistical study was done on return current region (RCR) perpendicular electric field structures, using data from the FAST satellite by Hwang, et al. [2005a,b]. The first part of their study, Hwang, et al. [2005a] examined 70 return current region crossings above 2500 km altitude and found that more than half of them showed electric field structures indicative of curved or filamentary potential structures and not the sheetlike, straight uniform potential that does not vary along the arc direction. They defined sheetlike events as those with a constant ratio of the two perpendicular components of the electric field, and curved or filamentary events as those with a varying
An assumption made here is that for the curved or filamentary events the radius of curvature of the arc is comparable to the thickness of the arc itself. They also note that most of the strongest events (> 600 mV/m) have a sheetlike structure. This study was for downward current regions and so would correspond to the black RCR auroral arcs. The second part of their study [Hwang, et al., 2005b] compared the upgoing characteristic electron energy with the potential difference observed at the satellite, therefore estimating how much of the potential observed at the satellite was of ionospheric origin, and how much was from the U-shaped potential. They found that the ionospheric fields dominate in the sheetlike structures while the U-shaped potentials dominate in the curved or filamentary structures. This predicts that the linear black arc structures should have larger ionospheric fields associated with them and therefore faster (E x B) motions along the arc than in the curved arc structures. This is related to the open question of whether or not large electric fields exist in the E-region ionosphere, and could be addressed with the use of AMISR, to look for such fields in the RCR black aurora.

B.3.1.5: Fracture Model

The large-scale motion and evolution of auroral arcs can be explained by many different approaches. They all share the common element of energized electrons in field-aligned sheets, but differ in the energization mechanism [Haerendel, et al., 1993]. Using the UHF radar at EISCAT, Haerendel, et al. [1993] measured the proper motion of auroral arcs with respect to the background plasma. For one event they measured a southward speed of 35 ± 20 m/s for an auroral arc relative to the background plasma. For a second event they measured a southward speed of 90 ± 20 m/s, and for a third they measured around 180 m/s. They interpret these results in terms of a “fracture model” where an unstable field-aligned current can “propagate into the current circuit” releasing magnetic tensions and reducing the energy content. This mechanism could in principle produce a situation that would cause a quasistationary auroral arc in the ionosphere. The overall energy balance in this circuit involves a relationship between the speed of an auroral arc with respect to the background plasma, the width of the arc, and the propagation time of an Alfvén wave between the auroral acceleration region and the generator. The fracture theory is the only theory that makes definite predictions about the proper motion of auroral arcs. The authors note that their few observations are consistent with the fracture theory but that does not prove or disprove its validity, and that further tests of the theory are needed. The fracture model is explained in more detail and the analogy to mechanical fractures is emphasized in Haerendel [1994]. In this model unstable field aligned currents are seen as the cause of field-aligned potential drops, which convert energy stored in magnetic shear stresses into particle kinetic energy, where a large fraction of this energy is carried away by runaway electrons and ions out of the acceleration region. The energy conversion rate and parallel potential drop are both linked by the critical current density needed for the instability and are both derived from the theory.
B.3.2: Open Science Questions III

1: Periodic variations of the auroral intensity on the order of minutes could be looked for in the camera data to compare to the calculations of $\tau$ from Goertz and Boswell [1979].

2: The theory of Goertz and Boswell [1979] predicts that the smaller scale Alfvenic auroral structures should decay first, giving the appearance that small-scale structures decay into larger scale ones. This can be examined by looking at the time evolution of Alfvenic auroral arc structures.

3: An attempt could be made to make a more quantitative comparison between the small-scale structures produced by the model of Seyler [1990], and the small-scale structure observed in discrete auroral arcs. If electric field can be inferred from velocities of structures, then the electric field spectral index could be calculated at different times to see if the time evolution of it is consistent with the theory.

4: The theory of Seyler and Wu [2001] predicts 2 possible instabilities at small-scales (electron inertial length) that could be responsible for the structuring, evolution, and breakup of small-scale auroral structures ($< \sim 1$ km). The camera data could be examined to look at the time evolution of such structures to gain information about how they form and breakup over time and compare this to what is predicted by the 2 different instabilities.

5: According to Hallinan [1976] larger-scale auroral folds are likely to be associated with the small-scale auroral curls. Using conjugate narrow-field and all-sky camera data such a correlation could be looked for to test this generation mechanism for folds.

6: The simulations of Streltsov and Lotko [2003b] indicate that the small-scale large-amplitude perpendicular electric fields should occur in regions adjacent to discrete auroral structures and in regions of depleted plasma density. This depleted density region could be looked for using AMISR and its spatial relation to visible auroral structures can be observed using the cameras. The coherent scatter radar could also be used to determine if the radar is scattering from these density depletions.

7: The statistical study of Hwang, et al. [2005a] would predict that more than half of the RCR potential structures crossed should be curved such that they have radii of curvature comparable to the arc thicknesses. This could be looked for in the all-sky and even the narrow-field camera data to see if the camera data is consistent with the FAST data. The camera data could also be examined to see if the more intense aurora are more sheetlike.

8: The study of Hwang, et al. [2005b] predicts that the sheetlike RCR black arc structures should have faster shear motions than the curved ones, and this could be examined with the camera data but probably more accurately with AMISR data. This also relates to whether or not large amplitude electric fields exist in the lower ionosphere, in the RCR black aurora.
9: The work of Chaston, et al. [2003a] predicts an auroral arc distribution that has not been observed in camera data, but this kind of distribution could be looked for best by optimizing the field of view of the camera, provided to us by M. Lessard, to this range of scale sizes.

10: The fracture model of Haerendel, et al. [1993] makes definite predictions about the proper motions of auroral arcs, which have been compared to three observations, however many more observations of proper motion could be made using camera data along with AMISR data.

B.4: Connections to Thesis Project

The questions listed at the end of each section are partly motivated by a need to fill in the gaps where previous studies have been lacking, partly by the need to test the predictions of theories against data, and partly by the larger question of the importance of the small-scale structure to the overall structure and evolution of the aurora.

It will be the purpose of this study to examine in detail many of the specific questions raised above, with the overall goal of examining the importance of small-scale structures, their formation, and their influence on the ionosphere. Four of the main open questions from above have been chosen to be discussed here in more detail.

B.4.1: Ionospheric Feedback

The first question is whether return current region structures significantly modify the lower ionosphere. This study would use AMISR to look for the existence of large amplitude structures in the lower ionosphere that may exist on small-scales and/or for short times. For example, significantly decreased density in the RCR could lead to decreased conductivity causing large perpendicular electric fields to exist. Such large amplitude structures have not been seen with radars before, because the spatial and temporal resolution has not been high enough to resolve them, resulting in integrated over structures, which may not stand out above the background. AMISR however, should have high enough resolution and rapid steering capability to be able to look in the right place at the right time to measure such structures. Large amplitude electric fields (~V/m) are seen by the Freja satellite to occur on small scales (≤ 1km), but it is not known if these electric fields map all the way down to the lower ionosphere. Very fast motions of auroral structures (up to 90 km/s, [Trondsen and Cogger, 1998]) are often observed in the optical data, but it is not known if, and/or where these fast motions correspond to the (E x B) velocity of the plasma. If these speeds are the (E x B) speed in the E-region that would imply that large (several V/m) electric fields exist there, perhaps only transiently. AMISR and the 30 MHz radar could also be used to measure the perpendicular flow speed in the E and F-regions to determine if the velocities inferred from the camera data correspond to large electric fields. If these large amplitude structures are found to exist in the lower ionosphere, the implication is then that the ionosphere may play a significant role in the active feedback mechanism to the magnetosphere as indicated in the simulations of Streltsov and Lotko [2003b, 2004].
This part of the study will address questions, (b), (n), and (p) from the list below. 

**Feasibility for completion this winter:** The resolution of AMISR will depend on how many panels are installed by the time of the study, to date there are only 32 out of the full 128 panels installed at Poker Flat. Currently the integration times required to image the ionosphere are much too long (order of minutes) to resolve such small-scale, transient structures. Therefore it is not yet known to what degree this part of the study will be completed this winter, since it depends on how many panels will be in place.

### B.4.2: Precipitation Driven Ion Outflows

The second question is to determine what wave modes and auroral electrodynamics are responsible for causing ion outflows. The goal here will be to establish a connection between NEIAL, BBELF, ion outflows, and Alfvenic auroral rays. The radar observations of NEIAL indicate that they often occur at the same time as ion outflows [Forme, et al., 1999]. In situ satellite measurements, [Lynch, et al., 2002] often associate ion outflows with regions of BBELF waves. The link between these is in the conjugate camera and radar data. Blixt, et al., [2005] used the 4 existing examples of conjugate high resolution camera data and radar data containing NEIAL to make a connection between the aurora and the occurrence of NEIAL. They found that very dynamic Alfvenic auroral rays occurred in the radar beam at the same time that NEIAL were observed. These Alfvenic auroral rays are associated with soft electron precipitation (< 1 keV), which is an important feature in the theories of how NEIAL develop. It will be a goal of this study to obtain more examples of conjugate high resolution camera and radar data containing NEIAL and/or ion outflow, to establish a more definitive connection between what types of auroral features are and are not associated with ion outflow. The implication of this would be that a much larger scale picture of where ion outflow is occurring could be estimated by using a distributed array of ground based camera images.

This part of the study will address questions, (a), and (f) from the list below. 

**Feasibility for completion this winter:** The current 32 panels of AMISR should be able to resolve NEIAL along the field-aligned direction because the NEIAL are significantly enhanced above the background level. The narrowfield camera system is already in place, so this portion of the study could be completed during this winters observing campaign.

### B.4.3: Mesoscale Auroral Arc Distribution

The third is the open question of determining the distribution of auroral arc scale sizes. Maggs and Davis [1968] measured the auroral arc distribution using a camera with a relatively narrow field of view (12° x 16°), and found the distribution peaked near their instrumental cutoff of ~ 70 m. A later study [Knudsen, et al., 2001] used all-sky camera images and found the distribution of arc widths to be 18 ± 9 km. There is a large discrepancy between these two distributions, and it is not known if there is a decreased occurrence in the kilometer scale range. This may have been caused by instrumental effects, observing a peak distribution centered around the field of view of the camera. There is also a recent theory by Chaston, et al., [2003] which predicts Alfvenic auroral arc
widths and brightness, and produces a wide distribution with a peak in occurrence of around 1 km for visible Alfvenic auroral arcs. This discrepancy can be tested for by optimizing the field of view of a camera to this kilometer scale range. For this observing campaign, the camera provided to us by M. Lessard will be fitted with a lens which makes the field of view bigger than a narrow-field camera but smaller than an all-sky camera. The distribution of arc widths will then be measured by three cameras with three different fields of view to look for the existence of a gap in occurrence of arc widths. It has been noted that the lifetimes of the arcs are also important, since the narrow structures measured by Maggs and Davis [1968] have lifetimes of a few seconds, while the large-scale structures measured by Knudsen, et al. [2001] have lifetimes of a few minutes [D. Knudsen, personal communication]. It is possible that the two distributions are actually for two entirely different types of auroral arc, and that for structures of a given lifetime there may only be one peak in distribution. This question of lifetime versus arc width versus occurrence will also be examined using the data from the three different cameras.

This part of the study will address questions, (e), (l), (r), and (f) from the list below.

**Feasibility for completion this winter:** This part of the study should also be able to be completed this winter, since the additional camera provided by M. Lessard will allow investigation optimized in the occurrence gap of arc widths, and the all-sky and narrowfield cameras are already in place.

**B.4.4: Discrete or RCR Black Auroral Morphology**

The fourth question involves investigating and quantifying the morphology and structure of the black aurora that occurs with discrete aurora, referred to as RCR black aurora. Most of the previous studies of black aurora have focused on the black aurora that occurs embedded within the diffuse aurora [Trondsen and Cogger, 1997; Kimball and Hallinan, 1998a,b]. Little attention however has been paid to this RCR black aurora, and it is suspected that this RCR black aurora may be affecting the ionosphere by creating density holes, which will affect the conductivity and therefore the electric fields. This relates back to the first question of the existence of significant ionospheric modification. The relationship between RCR black aurora and the adjacent discrete aurora will also be investigated and compared to in situ measurements of the return current region made by the FAST satellite. The statistical study of Hwang, et al. [2005a,b] makes the distinction between two types of RCR potential structures, sheetlike, and curved or filamentary. They however do not have any temporal information about these structures, for example, does one type evolve into the other, or are they entirely independent of one another? These questions can be addressed with the ground camera data by examining the evolution of the RCR black auroral structures.

This part of the study will address questions, (f), (g), (h), (n), and (p) from the list below.

**Feasibility for completion this winter:** This portion of the study involves mostly only camera observations, and therefore should also be completed this winter. The 30 MHz coherent scatter radar may also be used to investigate the RCR black aurora, but it is not
yet known how this radar will be operated, since someone has to be present at the site to operate it.

**B.4.5: Summary**

In summary many questions have been raised and will be here reiterated. This is a list of many possible questions that could be addressed with the data set we hope to acquire. We may only address some of these, however it is almost inevitable that we will also address different and new questions, ones that we have not thought of yet, that will become clear only when we have examined the data in detail.

Plans are currently being made to go to Poker Flat, Alaska this upcoming winter to perform the camera and radar observations of the aurora. There will be two trips, first during the 21 February – 6 March moon down period, and again during the 22 March – 5 April moon down period.

- a) A connection between Alfvenic auroral rays and enhanced ion outflows through NEIAL/BBELF?
- b) Existence of large-amplitude, transient, small-scale structures in the lower ionosphere?
- c) What are the irregularities that 30 MHz radar scatters from?
- d) Causal relationship between auroral luminosity and 30 MHz radar returns?
- e) Optimize camera viewing in 1-10 km range, existence of data gap, and to test Alfvenic aura theory?
- f) Correlating arc thicknesses to other arc parameters?
- g) How black aura (w/discrete aura) forms and evolves in time?
- h) Quantify motion of black aurora with respect to the background plasma using AMISR?
- i) Any periodic variations of auroral intensity on the order of minutes to test theory of Goertz and Boswell [1979]?
- j) Time evolution of auroral arcs: large to small, or small to large, or neither?
- k) Electric field spectral index as a function of time, compare to theory?
- l) Time evolution of formation and breakup of small-scale structures?
- m) Are auroral folds associated with auroral curls?
- n) Density holes in downward current region exist with black aura?
- o) Radii of curvature of arcs compared to thicknesses of arcs?
- p) Linear black structures have faster motions than curved ones?
- q) Proper motions of arcs and predictions of fracture model?
- r) Lifetimes of arcs compared to occurrence and width?

*Note: The papers summarized and discussed above are by no means a complete list of the papers relevant to this project, and a few more relevant papers that were not discussed above will be here listed:*

Auroral imaging and observations:
(Chaston, et. al., 2005), “Energy deposition by Alfven waves into the dayside auroral oval: Cluster and FAST observations”
(Doe, et. al., 1993), “Observations of Nightside Auroral Cavities”
(Mende, et. al., 2003), “FAST and IMAGE-FUV observations of a substorm onset”
(Semeter, et. al., 2001a), “Persistent quasiperiodic precipitation of suprathermal ambient electrons in decaying auroral arcs”
(Semeter, et. al., 2001b), “Simultaneous multispectral imaging of the discrete aurora”
(Semeter, 2003), “Critical comparison of OII(732-733 nm), OI(630 nm), and N2(1PG) emissions in auroral rays”
(Semeter, et. al., 2005), “The ionospheric response to wave-accelerated electrons at the poleward auroral boundary”

Theories, models, and simulations:

(Lotko, 2004), “Inductive magnetosphere-ionosphere coupling”
(Lysak, 1991), “Feedback Instability of the ionospheric Resonant Cavity”
(Lysak and Song, 2002), “Energetics of the ionospheric feedback interaction”
(Seyler and Xu, 2003), “The relationship between field-aligned currents and low-frequency electromagnetic fluctuations”
(Wu and Seyler, 2003), “Instability of inertial Alfven waves in transverse sheared flow”

Appendix:

Since a significant portion of this thesis will be based on optical observations of the aurora, it was deemed necessary to elaborate more on the auroral emission spectrum (Appendix A.1). This study will be mostly concerned with the perpendicular motions of auroral structures, and the detailed emissions as a function of altitude are not necessary, therefore no multi-spectral imaging will be used. A constant altitude of 100 km will be assumed for the lower borders of auroral structures.

Since radar observations will be an important complement to the camera data, the theory of incoherent and coherent scatter radars will also be discussed in more detail (Appendix A.2).

A.1: Auroral Spectral Emissions

The most dominant auroral emission is the green line at 557.7 nm, which is produced by the metastable transition from the 1S state to the 1D state of atomic oxygen. This transition has a lifetime of 0.74 s. Lifetime refers to the average amount of time that an electron will stay in the excited state, because of the probabilistic nature of the de-excitation accompanied by photon emission. Since this atom spends a finite amount of time in the excited state, there is a probability that it can lose its excitation by a collision with another particle or molecule with no corresponding photon emission. This process is referred to as collisional quenching, and it is an important process in determining the altitude distribution of auroral emissions. For example, the 557.7 nm line is collisionally quenched below about 100 km altitude due to the increasing density of neutrals at lower
This emission is mostly induced by secondary electrons having energies in the few to 10 eV range.

Another very prominent emission line is the 630.0 nm red line of atomic oxygen. This is also a metastable transition, from the 1D state to the 3P state with a lifetime of 110 s. This excited state, which is more sensitive to collisions, is mostly collisionally quenched below about 200 km altitude. This excited state is produced by electrons with energies in the few eV range. (Note: an ultraviolet photon (297.2 nm) can be produced by a transition directly from the 1S state to the 3P state of atomic oxygen). These different oxygen lines are shown in Figure A.1.

![Diagram showing the auroral emission lines of atomic oxygen. From Paschmann, et al. [2003], after Roach and Smith [1967].](image)

Typical precipitating auroral electrons have energies in the 1 keV to 10 keV range and therefore deposit most of their energy in the 150 km to 100 km altitude range, thus producing the green (557.7 nm) light there. However if there is a significantly soft precipitating electron spectrum (< 1 keV) much of the energy gets deposited above 200 km altitude and this produces the red (630.0 nm) light at higher altitudes. If the precipitating electron spectrum has significant fluxes above 10 keV energies, then some of the energy can get deposited in the 80 to 100 km altitude range, where a magenta color is often observed [Hallinan, et al., 1998]. The typical altitudes of energy deposition by ion-electron pair production for precipitating electrons is shown in Figure A.2.
Figure A.2: The typical altitudes where primary precipitating auroral electrons deposit their energy by ion-electron production. From Paschmann, et al. [2003], after Rees [1963].

This magenta color is produced by emissions with much shorter lifetimes that do not get collisionally quenched before they de-excite and emit photons. The green line is not present in this altitude range because of its relatively long (0.74 s) excited lifetime and collisions are acting much faster there which de-excite the atoms and prevent the 557.7 nm photons from being emitted. There are three main groups of emission lines that cause this magenta color, which is produced at higher altitudes as well, but is often not observed there because the intensity of the green line overwhelms these other lines. The first group of lines are in the blue part of the spectrum with wavelengths of 391.4 nm, 427.8 nm, and 470.9 nm and are from the first negative bands of N2+. These are simultaneously ionized and excited by precipitating electrons with energies in few hundred eV range. The lifetimes of these excited states are around 70 nanoseconds [Vallence Jones, 1974] and therefore are referred to as prompt emissions, meaning that the lifetimes are much smaller than any relevant timescale of auroral phenomena, which are seconds down to milliseconds.

The next two groups of lines are overlapping and both in the red to near infrared portion of the spectrum. The first of these are referred to as the red Meinel bands, and they also come from N2+. They have wavelengths of 706.4 nm, 785.2 nm, and 808.2
nm, and are excited by around 35 eV of energy. These are associated with primary precipitating electrons since the average energy lost by a primary precipitating electron per ion-electron pair produced is around 35 eV. These excited states have lifetimes around 14 microseconds, [Vallence Jones, 1974], which are also considered to be prompt emissions. The next group of red lines are from the first positive bands of neutral N2, and some of the more prominent ones are 750.5 nm, 775.3 nm, 662.4 nm, 670.5 nm, and 678.9 nm. These have lifetimes around 6 microseconds, [Vallence Jones, 1974], which is again much shorter than auroral timescales. The main properties of these lines are summarized in Table A.1.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Color</th>
<th>Lifetimes</th>
<th>Emission occurs</th>
<th>Excited Species</th>
<th>Excited by Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>557.7</td>
<td>Green</td>
<td>0.74 s</td>
<td>above ~100 km</td>
<td>O</td>
<td>secondary: few to 10 eV range</td>
</tr>
<tr>
<td>630.0</td>
<td>Red</td>
<td>110 s</td>
<td>above ~200 km</td>
<td>O</td>
<td>few eV</td>
</tr>
<tr>
<td>391.4, 427.8, 470.9</td>
<td>Blue</td>
<td>~70 ns</td>
<td>above ~80 km</td>
<td>N2/N2+</td>
<td>few hundred eV</td>
</tr>
<tr>
<td>706.4, 785.2, 808.2</td>
<td>Red, near IR</td>
<td>~14 us</td>
<td>above ~80 km</td>
<td>N2+</td>
<td>primary: ~35 eV</td>
</tr>
<tr>
<td>750.5, 775.3, 662.4</td>
<td>Red</td>
<td>~6 us</td>
<td>above ~80 km</td>
<td>N2</td>
<td>primary: ~35 eV</td>
</tr>
</tbody>
</table>

Table A.1: Summary of the properties of the major auroral emission lines.

It is the combination of these blue first negative bands of N2+, these red Meinel bands of N2+, and these red first positive bands of neutral N2 that produce the magenta color that is observed at the bottom edge of very active aurora [Hallinan, et al., 1998]. Figure A.3 shows the typical upper atmospheric composition, indicating that even up to around 500 km altitude there is a large amount of N2 and O present to produce these emission lines.

When it is desired to observe the aurora with high time resolution (sub second-millisecond), it is these two red bands that are most often used. What is done is to use a high-pass cutoff filter, for example, Sedgemore-Schultess, et al. [1999] used a 675 nm cutoff filter and Grydeland, et al. [2003, 2004] used a 650 nm cutoff filter to suppress the slow emissions at 630.0 nm and 557.7 nm and focus on these two red bands, which produce almost instantaneous (microsecond-nanosecond) emissions. This allows the auroral features to be observed at the speeds that they occur, without any spatial smearing out that will occur in the slower emissions. The University of Alaska, Fairbanks (UAF) narrow-field imager to be used in this study can be equipped with a red filter on it (I don’t know the specific details of it yet) to observe some or all of these faster emissions.

Precipitating protons can also produce auroral emissions, the most important being the Hα at (656.3 nm) and Hβ at (486.1 nm) emissions from hydrogen atoms. A precipitating proton can capture and electron producing an excited hydrogen atom, which then de-excites to produce an Hα or Hβ photon depending on its initial level of excitation.

Ultraviolet (UV) auroral emissions do occur, but they are not observed on the ground since the UV light gets absorbed by the atmosphere. These UV emissions are however important for space-based observations and two of the main UV emissions are 130.4 nm from atomic oxygen, and 135.6 nm from N2, which is called the Lyman-Birge-Hopfield (LBH) line.
A.2: Radar Measurements

Ionosondes are used frequently to infer the ionospheric plasma density as a function of altitude. Ionosondes work by transmitting radar signals, usually in the 1-20 MHz range, and receiving a returned “echo” at a later time. The transmitted signal reflects from the ionosphere at the altitude where its frequency equals the local plasma frequency. The plasma frequency is proportional to the square root of the plasma density, \( f_p \approx 9000\sqrt{n} \text{ Hz} \), where \( n \) is measured in \#/cubic centimeter, and in the ionosphere it usually ranges in the few MHz range, typically around 5-6 MHz for the F-region density peak. Ionosondes can measure the ionospheric plasma density as a function of altitude by varying the transmitted frequency, which measures densities at different altitudes, and the altitudes are estimated by using the signal travel time. Ionosondes can only measure plasma density at altitudes below the peak density, which is usually the F-region peak at around 400 km altitude. This is because transmitted frequencies above the peak plasma frequency will pass right through the ionosphere. Occasionally however the E-region density around 100 km can become enhanced by electron precipitation and be larger than the F-region therefore preventing measurements of the density at higher altitudes.

A.2.1: Incoherent Scatter Radars (ISR)

Incoherent scatter radars (ISR) work in a way similar to ionosondes, in that they transmit a radar signal and receive a reflected echo from the ionosphere. ISR however usually only emit at one frequency which is much higher than the peak plasma frequency, usually a few hundred MHz, and even up to \( \sim 1200 \text{ MHz} \) [Kelley, 1989]. Since the frequencies used by ISR are much higher than the plasma frequency, almost all of the transmitted signal just passes right through the ionosphere and out into space. ISR can probe the ionosphere above the F-region peak since they do not suffer the reflection problems of ionosondes. The transmitted signals are emitted in pulses so that the
distance to the echoing region (altitude) can be calculated as \((\text{delay time})/2c\). There is however a very small amount of the transmitted signal that gets reflected by the ionosphere and is received back to the radar. It is the spectrum of this received signal that contains the information about the ionospheric region being investigated. A schematic of an example returned spectrum is shown in Figure A.4, which shows the typical double humped shape, \(f_T\) is the transmitted frequency, \(f_o\) is the mean Doppler shift, which gives the line-of-sight velocity, and \(\Delta f\) is a measure of the spectral width, which can be used to get ion temperature.

![Schematic of a typical ISR return spectrum](image)

**Figure A.4:** Schematic of a typical ISR return spectrum plotted as power versus frequency. From *Kelley* [1989].

The power in the returned echo is proportional to the number density of electrons in the region of the ionosphere being investigated by the radar. This is because the transmitted wave causes all electrons encountered to oscillate, resulting in a re-radiated signal at almost the same frequency as that which was transmitted. There is a spread in the frequencies re-radiated due to the constant thermal motion of the electrons. The two peaks in the returned spectrum come from \((f_o \pm \text{the ion-acoustic speed})\), because the thermal fluctuations can be thought of as a superposition of damped sound waves, and therefore the spread in the frequency of the medium is of the order of \(k_mC_s\), where \(k_m\) is the wave number of the thermal fluctuations in the medium and \(C_s\) is the sound speed or ion-acoustic speed. The relative intensity of these peaks in the spectrum yields the electron temperature. It is sometimes observed in the data that one or both of the shoulders becomes significantly enhanced and these are the NEIAL discussed in more detail above.

### A.2.2: Coherent Scatter Radars (CSR)

Coherent scatter radars (CSR) operate in the frequency range in between ionosondes and ISR, in the 20-50 MHz range. ISR scatter off of thermal fluctuations in the plasma, but these thermal fluctuations can be are acted on by instabilities producing fluctuations in the plasma with amplitudes much larger than thermal levels, and it is these larger fluctuations that CSR can scatter off of. The theory of scattering from fluctuations is well understood, and for irregularities in the medium with wave number \(k_m\) the radar scatters according to the relationship given in *Kelley* [1989]:

\[
\text{Intensity} \propto \frac{1}{k_m^2} \quad \text{for} \quad k_m C_s \ll 1
\]
\[ k_T = k_s + k_m \]

Here, \( k_T \) is the wave number of the transmitted wave and \( k_s \) is the wave number of the scattered wave, but for backscatter, \( k_s = -k_T \). Therefore:

\[ k_m = 2k_T \]

Thus the fluctuations in the medium causing the backscatter are on the order of 1/2 of the transmitted wavelength, this is sometimes called the Bragg condition.

Most of the plasma instabilities that are detectable with CSR, produce waves with their \( k \) vectors nearly perpendicular to the magnetic field. Equatorial CSR can therefore observe fluctuations overhead since the magnetic field is nearly horizontal there. CSR in the auroral region however must be placed far away from the region of interest since the magnetic field there is nearly vertical, and a low observing angle is required to have the radar line-of-sight perpendicular to the magnetic field [Kelley, 1989].

**B.5: References**


