Front cover
Photo: T. Lövgren

IRF-- 194.

INVESTIGATIONS OF AURORAL DYNAMICS: TECHNIQUES AND RESULTS

by

Åke Steen
Swedish Institute of Space Physics
P.O. Box 812, S-981 28 Kiruna, Sweden

IRF Scientific Report 194
October 1988

Printed in Sweden
Swedish Institute of Space Physics
Kiruna, 1988
ISSN 0984-1703

INVESTIGATIONS OF AURORAL DYNAMICS:
TECHNIQUES AND RESULTS

by

Åke Steen
Swedish Institute of Space Physics
P.O. Box 812, S-981 28 Kiruna, Sweden

Abstract

The aurora, or the northern lights, represent a direct viewing window into the near-Earth plasma universe. The fascinating auroral displays, easily detectable by the unaided human eye, are the optical result of energetic particles colliding with the atmosphere above about 85 km altitude. The complexity and variability of the auroral structures are caused by a complicated chain of plasma processes starting with the interaction between the solar wind and the magnetosphere of the Earth.

This study is an experimental investigation of the dynamics of the aurora, describing both the systems developed for the optical measurements and the results obtained.

The auroral ovals are the instantaneous distributions of the auroral luminosity surrounding the two geomagnetic poles. In the oval, east-west oriented auroral arcs often become deformed from their stable configuration. It is found that during such a deformation, a fold travelling eastward along the arc is associated with an enhanced F-region ion temperature of 2700 K, measured by EISCAT, indicative of enhanced ionospheric electric fields.

The intensity of the aurora may suddenly increase, very often combined with rapid movements along the arcs. The onset of the active period is rather localized. It is shown that for an auroral break-up, the large-scale westward travelling surge (WTS) is the last developed spiral in a sequence of spiral formations. It is proposed that the non-linear development of the Kelvin-Helmholtz instability in a velocity shear zone in the magnetosphere is the responsible process. During the passage of the WTS it is inferred from photometer recordings that the spectral hardening of the precipitating particles, associated with the WTS, shows a cessation, typically of 1 min duration.

In another event it is shown that large-amplitude long-lasting pulsations, observed both in ground-based magnetic field and photometer recordings, correspond to strong modulations of the particle intensity at the equatorial orbit (6.6 R_E). In this event a gradual transition occurs between pulses classified as Ps6/auroral torches toward pulses with characteristics of substorms. The observations are explained by the Kelvin-Helmholtz instability in a boundary layer as suggested by Rostoker and Eastman [1987].

The meridional neutral wind, at about 240 km altitude, is found to be reduced prior to or at the onset of auroral activity. These findings are suggestive of large-scale reconfigurations of the ionospheric electric fields prior to auroral onsets.

A new real time triangulation technique developed to determine the altitude of auroral arcs is presented, and an alternative method to analyze incoherent scatter data is discussed.

Keywords: Aurora, optical measurement techniques, low light-level imaging, incoherent scatter data, maximum entropy method, auroral altitudes, thermospheric neutral wind, Ps6, WTS, magnetospheric substorm, Kelvin-Helmholtz instability.

CONTENTS

INTRODUCTION AND SUMMARY OF THE PAPERS

PAPERS

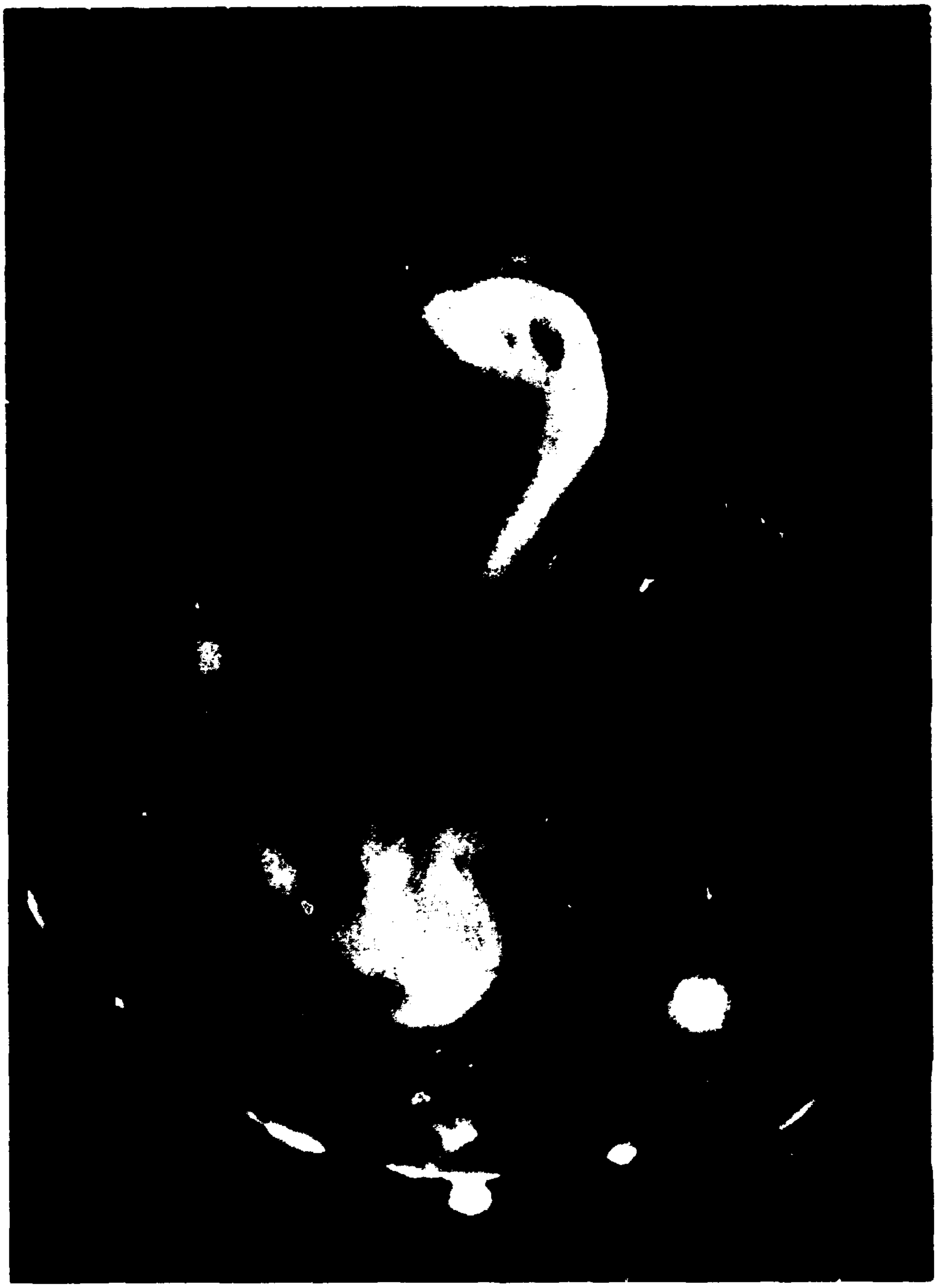

Figure 1 An active auroral display during the expansive phase of a substorm recorded by an all-sky camera in Kiruna at 2105 UT on 10 December 1986. Geomagnetic South is in the direction of the metal bar. Geomagnetic East is in the direction of the time display. The full Moon can be seen in the South-West at low elevation.

1. Introduction

The complexity and variability of auroral displays can easily be detected by the human eye. An observer watching a clear night sky, at auroral latitudes, will have a fair chance to see a drastic change in the auroral scenery during the course of the night. In the evening, quiet east-west oriented arcs can exist for hours. When magnetic midnight is approached the auroral arcs can suddenly be deformed and broken up. During the most active phase, with a duration of only a few minutes, rapid movements of the auroral luminosity occur, and short-lived (seconds), red lower borders of the arcs may appear [Gattinger et al., 1985]. The active aurora is gradually replaced by a more diffuse and patchy aurora, which sometimes shows a quasi-periodic (2-10 s) on/off oscillation in its intensity [Pemberton and Shepherd, 1975]. After about one hour or so, quiet arcs may reform and a similar sequence of events can be repeated [Horwitz, 1985]. However, for many nights the time history of the aurora can not be described as above [Pytte et al., 1978].

Since the aurora is one of the end results of the interaction between the magnetized solar wind plasma and the internal magnetic field of the Earth [Akasofu, 1981a], the system to be studied is of a three-dimensional nature with important time variations in the range 0.1 s to a few h. The validity of a conclusion drawn from any local measurement, ground-based or spaceborne, must therefore be discussed with relation to the unavoidable incomplete knowledge of the ionosphere-magnetosphere-solar wind system as a whole.

An accepted method in physics, when trying to establish a realistic model of a physical system, is to repeat an experiment with known values of the controlling parameters and to observe the outcome of the experiment. If the tested model and the physical system produce the same results, the model is judged useful, at least for the set of parameters tested. In the case of the ionosphere-magnetosphere-solar wind system it is not exactly known what the controlling parameters are. The aurora represents a part of the output from this system. Simultaneous measurements of the global distribution of the aurora with the desirable time resolution of 1 s, is even today a great challenge. Also, in the auroral case we cannot ourselves control the input parameters. Instead, we have to measure over a long period of time (preferably a solar cycle) to be sure to acquire data from a sufficiently large range of input parameters.

One of the oldest branches in auroral research is the optical technique, which today uses photons of energies in the UV, visible and near-IR range, for the detection of signatures of the auroral processes. The auroral light is the consequence of energetic particles, accelerated along the magnetic field lines, and their collision with the atmosphere above about 85 km altitude. The energetic auroral particles are mainly electrons and protons. Since the aurora produced by protons is of low intensity and diffuse, the electron aurora is normally of most interest. The diffuse nature of the proton aurora is caused by the large gyro radius of the proton ($\simeq$ 200 m for 5 keV protons) and also because the protons spend part of their trajectories as hydrogen atoms, not influenced by the magnetic field. The discrete electron aurora is produced by electrons of energies in the range typically 0.3-20 keV [Hultqvist, 1973], with a corresponding altitude interval of the maximum ionization rate between 100 and 260 km. Some of the emissions in the auroral spectrum can be used for a quantitative estimate of the energy of the primary auroral electrons (e.g., the ratio between I(OI 630.0 nm) and I(N_2^+(0,1) 427.8 nm), Rees and Luckey [1974]). The optical method represents a valuable source of information, mainly because of its ability to observe the auroral displays in two- or even three-spatial dimensions.

Two important steps towards better and more useful auroral models were taken with the introduction of the auroral oval [Feldstein, 1960], which mainly organizes the aurora in space, and the auroral substorm [Akasofu, 1964], which organizes the auroral phenomena in time. The auroral oval represents the instantenous large-scale pattern of the auroral luminosity in relation to the incoming solar wind flux. The auroral oval surrounds the corrected geomagnetic pole and is fixed relative to the sunward direction. The oval is located nearer to the pole by 10^{o} in latitude on the dayside in comparison with the nightside. The latitude of the northern and southern boundaries of the oval varies with the activity level (K_p) in the magnetosphere, which in Sweden causes aurora to be seen in the more densely populated latitudes only for $K_p > 5 - 6$ [Gussenhoven et al., 1983]. The auroral oval concept was derived initially from all-sky camera recordings and so reflects mainly the distribution of the intense aurora. As new data become available from e.g., monochromatic satellite imaging, the auroral oval concept may have to be redefined in some respects (e.g., for sun-aligned arcs, Murphree et al. [1987]). The auroral substorm is a proposed frame of reference into which the temporal variations of the aurora are organized. The auroral substorm picture [McPherron, 1970] divides the auroral activity into different phases: the quiet phase (no substorm activity), the growth phase, the expansive phase, and the recovery phase. However, several indications exist that this scheme many be too restricted and leaves many observations outside its frame of reference [Steen et al., 1988a].

The magnetospheric substorm, seen in the ionosphere as the auroral substorm, is a large-scale process and affects a major part of the magnetosphere [Baker et al., 1981]. However, the onset of the expansive phase of the substorm, as seen in the ionosphere, is initially a small-scale feature [Steen and Collis, 1988]. This transition between small and large scales represents one or the reasons why important contributions can be made with local auroral measurements, e.g., ground-based optical measurements.

The interactions between the ionosphere and magnetosphere, and between the magnetosphere and solar wind, represent a near-Earth manifestation of the plasma universe. The basic properties of ionized matter, plasma, are generally believed to be the same everywhere in the universe. The magnetosphere of our own planet should naturally be a first choice for a deeper study of matter in the plasma state. The aurora is a visible result of the ionosphere-magnetosphere interactions and represents a projection onto the atmosphere of magnetospheric regions, where the conditions of the magnetospheric plasma are such that field-aligned current systems are set-up and energy dissipation is started [Feldstein and Galperin, 1985]. The aurora therefore provides an ideal opportunity to study a part of the near-Earth plasma universe. Magnetospheric regions not directly connected to the auroral oval do not offer this viewing window into plasma physics. Auroral morphology is the variation in time and space of the three-dimensional ionospheric image of an important part of the near-Earth plasma universe.

Over the years several more or less complete models have been proposed for the ionosphere-magnetosphere-solar wind system. Recently, a consensus was arrived at by five authors active in magnetospheric substorm research [Rostoker et al., 1987]. The paper presents an overall phenomenology but does not describe the actual physical processes that go on in the regions of the magnetosphere which map to the nightside of the auroral oval. The energy dissipation in the ionosphere is considered to be caused by two processes operating simultaneously. The driven process dissipates energy as a direct consequence of the energy input from the solar wind into the magnetosphere. The other process is that of loading-unloading in which energy from the solar wind is first stored and then after an arbitrary period of time suddenly released by some triggering mechanism. It may be deduced from this view that the total energy (U_T) being dissipated and deposited in the ionosphere and magnetosphere (per unit time) is composed of four components [Rostoker et al., 1987],

$$U_T = U_A + U_J + U_R + U_{MT} \tag{1}$$

where U_A = the kinetic energy of auroral particles being lost in the ionosphere.

U_J = the Joule heating associated with electric currents in the ionosphere.

U_R = energy deposited in the equatorial ring current.

U_{MT} = energy stored in the magnetotail.

The total energy consumed in the magnetosphere must be supplied from the solar wind. The ε parameter introduced by Perreault and Akasofu [1978] represents an estimate of this energy coupling function [Akasofu, 1981b].

An explicit model for the magnetospheric substorm has recently been suggested by Rostoker and Eastman [1987]. The boundary layer model by Rostoker and Eastman [1987] describes the expansive phase of the magnetospheric substorm as the result of the development of a Kelvin-Helmholtz instability (KHI) in a velocity shear zone separating the central plasma sheet and the low-latitude boundary layer/plasma sheet boundary layer. The westward travelling surge (on the evening-side) and eastward drifting omega bands and torches (on the morning-side) possibly represent the development of the KHI into the non-linear regime [Steen and Collis, 1988].

The part of the Earth's atmosphere located above the mesopause (~85 km) is defined as the thermosphere. The diurnal heating pattern, caused by solar electromagnetic radiation at wavelengths shorter than 200 nm, creates pressure gradients that drive a global thermospheric circulation. However, at high latitudes a comparable amount of energy and momentum is provided by the auroral processes. To improve the understanding of the complex and dynamical interaction between the convecting ions and the neutral atmosphere, three-dimensional thermospheric general circulation models (TGCM) have been developed (e.g., Fuller-Rowell and Rees, [1980]). To numerically simulate recent observations of the behaviour of the thermospheric neutral wind in relation to auroral activity [Steen et al., 1988b] a new generation of coupled magnetospheric/ionospheric/thermospheric models is needed.

Scientific questions and topics concerned with auroral dynamics and addressed in this study are

Does the spectroscopic ratio I(427.8 nm)/I(630.0 nm) vary in a characteristic way during the passage of the westward travelling surge, as a result of associated changes in the energies of the precipitating electrons ?

- Are deformations of auroral arcs (e.g., folds) caused by ionospheric or magnetospheric processes ?

- According to the boundary layer model of the magnetospheric substorm [Rostoker and Eastman, 1987] the westward travelling surge and omega bands/torches are generated by the same process. Is it possible to observe a gradual transition between the two phenomena ?

- The growth phase [McPherron, 1970] is suggested to be a preparatory stage in the magnetosphere before onset of the substorm. A more distinct interpretation of the period before substorm onset would be as a time interval of increased magnetospheric convection, preceding the first triggering of an instability, which leads to a substorm onset.

- The time constant of the response of the thermospheric neutral wind to changes in the ion convection pattern is considered to be at least several tens of minutes. At, or even prior to, substorm onset a decrease in the meridional neutral wind is observed. The characteristic decrease seems to be associated with increased Joule heating, indicative of an enhanced and possibly reconfigured ionospheric electric field pattern.

Future satellite projects, e.g., the Norwegian initiative of an imaging observatory (AURIO) on the Polar Platform [Stadsnes et al., 1987], and new ground-based imaging experiments [Steen , 1989] may provide necessary data to bridge a part of the gap between well-founded auroral models and models which necessarily have to contain toc much guess work. Some of the most fundamental questions to be addressed by future projects are

- How does the ionospheric convection electric field pattern change with respect to variations in IMF and magnetospheric substorm activity ? Instantaneous pictures of the high latitude electric field convection pattern are needed.

- The neutral atmosphere is the base of the ionosphere and the region where most of the solar wind energy input is finally deposited. To correctly understand the variations in the convection electric field and in the luminosity and form of the auroral oval, supplementary information on the neutral wind pattern and neutral temperatures at high latitudes are needed.

- Since essential changes in the auroral oval commence on a small scale (a few tens of km) and develop within a few seconds to major reconfigurations in the distribution of the auroral luminosity, high-resolution auroral imaging is needed in both time and space. The high-resolution images may be produced by a combination of images from several ground-based stations or images from polar orbiting satellites.

Table 1: Optical research facilities in Kiruna 1979-1987

Facility	Description	Status
Standard all-sky camera (ASCA)	16 mm colour film, 6 frames/min. Information on cloudiness and auroral activity.	routine operation (IRF)
MSP (YORK)	A 4 channel meridian scanning photometer, 10 s scan time.	operated during 1979-1983 (IRF)
Auroral Dynamics Imaging System (ADIS)	A low light level TV-system. Monochromatic, 170°FoV. High time resolution auroral morphology.	operated during campaigns (IRF)
Height Measuring System (HMS)	A bistatic system for triangulation of auroral heights in real time. One-dimensional intensified Reticon arrays. Gives also information on the intensity along the magnetic meridian.	routine operation 1984/85, 85/86 (IRF)
Meridian Measuring Array (MMA)	A thermoelectric cooled 2-D CCD-camera. Digital optical disc used as a storage unit. High quality imaging of aurora.	Test operation during 1987/88 (IRF)
A3DAI	Rocket experiment, 1-D 20 channel array, 60°FoV, 3-D distribution of auroral emissions.	launched Dec.12, 1986 (IRF/UCL)
Opt.Lab	Laboratory for optical auroral research, 150 m^2, 13 domes, 6 rooms.	open since fall 1986 (IRF)
Red line FPI	Single-etalon Fabry-Perot Interferometer. Neutral wind and temperatures at 240 km altitude. 7 directions, 30 s integration time.	routine operation since 1980/81 (UCL/IRF)
Green line FPI	Single-etalon Fabry-Perot Interferometer. E-region neutral wind.	operated during campaigns (UCL/IRF)
DIS	Doppler Imaging System, bistatic. Wind pattern over 800x800 km. 120°FoV. 5 min time resolution.	monostatic: in operation, bistatic: start 1987. (UCL/IRF)
Triple FPI	Triple-etalon Fabry-Perot Interferometer. Thermospheric winds during full daylight.	start during 1987/88. Permanent 12 months 1988. (UCL/IRF)

2. The optical program in Kiruna 1979-1987

The primary goal of the optical program has been of a scientific nature, although the chosen approach resulted in significant developments on technical matters. The main scientific objective of the measurement program has been to observe characteristic dynamic variations in auroral structures and to relate these to processes in the ionosphere and magnetosphere. This study resulted in many nights of auroral observations (more than 500 nights). Trying to capture interesting auroral events from a single station is accompanied by difficulties in not being at the right local time and/or not having clear sky. The total amount of data gathered and stored from the different systems is therefore large.

At the end of the 1970's the International Magnetospheric Study period, 1976-1979 [Russell and Southwood, 1982], was an ongoing project, in which ground-based optical measurements from northern Scandinavia could make significant contributions. Also, EISCAT was in its initial construction and planning phase, with the prospect of regular operations quite soon thereafter. At that time it was realized that a major effort was necessary to strengthen the optical measurement program in Kiruna. It was then expected that the developed optical systems should be operated in combination with other instruments, e.g., EISCAT.

With a focus on the initiated optical projects, a historical review is presented in the following. What was planned and what in reality became realized did not always coincide, very often caused by shortage in manpower or funding. Several scientific auroral studies were carried out with the optical systems as the only intrumentation. Table 1 is a summary of the optical instruments developed and/or used during the period 1979-87.

An all-sky camera (ASCA) of a new design [Hyppönen et al., 1974] was installed at Kiruna in 1977. The all-sky camera technique with the photographic film as photon detector has continued to be extremely valuable ever since its general introduction during the IGY in 1957/58. The advantage of the standard all-sky camera technique is that it is well-proven and that the image is captured by a relatively inexpensive film. The main disadvantages are the usually poor time resolution and that the data are not in a digital form. In addition to being a monitor of auroral activity, the ASCA is used today for information on the degree of cloudiness, which is essential to know for interpretation of other optical measurements.

A four-channel meridian scanning photometer system (YORK) was assembled with a four-channel photometer, brought to Kiruna by Prof. Gordon Shepherd, as the key component. Background and dark signals associated with the studied emissions were obtained by varying the off-axis angle by a rotating mask [Shepherd et al., 1978]. The control and data acquisition were performed by a real time program executed on a time-sharing computer. A mirror scanned along the magnetic meridian with about 10 s scan time and each channel was sampled at 50 Hz. On January 25, 1979, the first data from YORK were obtained and it remained in operation until the spring of 1983, with only minor modifications. The experiences gained from the operation of YORK provided much of the basis for later work on auroral imaging systems. Since a scanning system does not obtain simultaneous measurements along the scanned meridian, the technique is not well suited for situations when both temporal and latitudinal variations occur in the aurora. True parallel recordings are only provided by imaging techniques. Examples of studies using data from YORK are Steen and Gustafsson [1981], Henriksen et al. [1984], and Gustafsson et al. [1985].

Low light-level imaging with TV cameras has been applied in auroral research since the middle of the 1960's [Davis, 1966]. A monochromatic TV-system (ADIS, Auroral Dynamics Imaging System) was developed for the Kiruna optical program, using an RCA ISIT TV-camera as photon detector, and a telecentric lens system [Steen, 1983]. The total field of view was manually interchangable but ADIS was normally operated with 170^0 field of view.

The ADIS was computer controlled for selection of interference filters, filter sequence and start/stop times. In addition, ADIS incorporated a Quantex digital processor for processing of the auroral images. However, it was fairly soon realized that the digitized analogue signal contained considerable noise. The low signal to noise ratio made it difficult to use ADIS for aurora with intensities much less that 1 kR measured at 427.8 nm. The basic time resolution of 20 ms provides possibilities for studies of rapid auroral variations. The time resolution is decreased somewhat due to the persistency of the phosphor, which can amount to several seconds for intense spike-like events. However, for aurora with moderate intensity, measurements by ADIS provide valuable data [Steen and Collis, 1988].

It became evident in 1980 that a major part of the incoherent scatter measurements by EISCAT would be made in the plane through Tromsö and Kiruna, coinciding well with the magnetic meridian plane through Kiruna. To complement the EISCAT measurements in the common program mode, a bistatic height measuring system (HMS) was planned and constructed [Steen, 1988]. The HMS was designed to obtain real time estimates of the height of auroral arcs above the EISCAT station at Tromsö and was operated on a routine basis for the two seasons 1984/85 and 1985/86. Due to limitations in the available computer power, the triangulation procedure was not executed in real time. Each station used an intensified photodiode array as detector [Steen, 1985]. The telecentric lens system imaged the field of view on the linear array, allowing simultaneous measurements to be made at all zenith angles.

To test and evaluate some recent technological developments in optical devices, a 2-D CCD imaging system has been acquired. The meridian measuring array (MMA) consists of a cooled non-intensified CCD-camera and a camera interface from Photometrics, a VME-bus system, a digital optical disc and a controlling computer. The objectives of the MMA are (1) to investigate if a high quality 2-D CCD (charge-coupled-device) array can be used for scientific auroral imaging without incorporating an image intensifier and (2) to find out if the traditional ASCA can be replaced with a new type of camera based on CCD-optical disc technologies.

A very accurate (at least in theory) determination of the altitude distribution of an auroral emission can be made with a side-looking photometer onboard a rocket. The three-dimensional distribution of an auroral emission can, in principle, be derived if the rocket is spinning and the payload contains a 1-D imager aligned with the rocket spin axis. On December 12, 1986 the AURELD-VIP-LOW rocket was launched from ESRANGE. The payload was equipped with A-Three-Dimensional-Auroral-Imager experiment (A3DAI) developed in collaboration with University College London [Rees and Steen, 1987]. A3DAI used 20 channels over 60^o field of view and the rocket spin rate was 7 Hz [Sandahl et al., 1987]. Unfortunately, the rocket was launched during a period of heavy snowfall, excluding the support of any optical ground-based measurements. Preliminary analysis of data from the A3DAI experiment shows a clearly identifiable E-region, deduced from the 427.8 nm emission. The data from the first test of this new measurement technique will be used for software development for a tomographic inversion procedure.

Any developing research program needs floor space, and with funding from The National Board of Public Buildings and The Equipment Board for the Swedish Universities, a new optical laboratory was designed and constructed [Steen, 1987]. The optical laboratory has six measurement rooms. Each room can be set at an individual temperature. Outside the measurement rooms a common long corridor is used for computers and data storage units. Plexiglas domes and openings, with and without windows, are available in each measurement room.

Direct measurements of parameters of the ionospheric plasma are obtained by EISCAT, and the auroral morphology is captured by imaging techniques. A third important component in the physics of the ionosphere-magnetosphere is the state of the neutral atmosphere. A thermospheric neutral wind measurement program has been running at Kiruna since 1981 in collaboration with Dr. David Rees, University College London. The neutral wind is measured by Fabry-Perot interferometer systems of different types [Rees et al., 1983; Rees et al., 1984a; Rees et al., 1984b; Rees et al., 1987; Steen et al., 1988b]. The interferometer station in Kiruna is part of a world wide net of interferometers [Romick et al., 1987], with the objective to determine the global circulation of the thermosphere, for which the energy and momentum input at high latitudes play an important role.

Three EISCAT experiment proposals, dedicated to the study of auroral dynamics with a combination of optical and incoherent scatter measurements, have been designed. The experiments have been executed during special Swedish EISCAT campaigns and the scientific analysis is still in progress. The scientific topics of the proposals are, respectively, I. Pulsating aurora [Steen and Gustafsson, 1980], II. Westward travelling surge [Steen et al., 1982], and III. F-region dynamics in the auroral oval and in the polar cap (unpublished manuscript).

3. Summary of papers I-VIII

The papers in this study consist of two categories, which are scientific publications (papers I, IV, V, VI, VII) and technical publications (papers II, III, VIII). The scientific papers all discuss various aspects of auroral dynamics, and the technical papers present methods and techniques which are used in the study of auroral dynamics.

PAPER I is a short note on a characteristic property of the spectroscopic ratios I(427.8 nm)/I(630.0 nm) and I(427.8 nm)/ I(557.7 nm), observed in the magnetic zenith, during the passage of the westward travelling surge (WTS). It is found that the ratios do not increase monotonically, but instead a plateau of about 1 min duration is formed. A likely interpretation of the plateau is a temporary cessation in the spectral hardening of the precipitating particles associated with the WTS. The characteristic energy corresponding to the plateau is about 1 keV above the level prior to the beginning of the surge. Without excluding that the source modulates the spectral hardening in this specific way, the possibility of an extra process is discussed. The extra process is probably activated when the current exceeds a certain value. A proposed example of such a process is the current driven instability [Kindel and Kendel, 1971], which needs a total field-aligned current of $2 \cdot 10^{-6}$ to $2 \cdot 10^{-5}$ Am^{-2}, to be turned on (the beginning of the plateau). The turn-off (the end of the plateau) of this instability is probably caused by a high ambient electron density associated with the arrival of the WTS.

EISCAT is an important instrument for the study of auroral dynamics. However, the time resolution of ionospheric parameters estimated by EISCAT is seldom comparable to the time scales of dynamic auroral processes (a few seconds and shorter). The EISCAT measurements are based on the autocorrelation function (ACF) technique. PAPER II is an attempt to investigate an alternative approach to derive the ionospheric parameters from an estimate of the power spectrum of the received radar signal. The power spectrum of the transmitted radar signal is convolved with the power spectrum of the ionospheric density fluctuations (the ionospheric spectrum). The ionospheric spectrum is related to the physical state of the ionospheric plasma in the scattering volume, and can theoretically be parameterized. The power spectrum of the measured signal is an estimate of the result of the multiplication between the receiver frequency response and the result of the convolution. The presently used fitting procedure in the time domain compares, in principle, theoretical ACF:s with measured ACF:s. The alternative approach is to compare theoretical spectra with measured spectra. Paper II is a comparison of parameters obtained by the ACF method and by the spectrum method. A nonlinear maximum entropy method is used to estimate spectra from generated time series. It is found that the spectrum method could become useful especially for determining the position of peaks in the incoherent scatter spectrum and possibly also for short integration times.

The most common technique used to measure the distribution of auroral emissions along a magnetic meridian has traditionally been to scan the meridian with a mirror (meridian scanning photometer, MSP). PAPER III describes a new imaging technique, utilizing an intensified photodiode array (Reticon) as detector.

The imaged meridian is divided into 1024 picture elements (pixels). Each pixel is digitized into 4096 levels (12 bits), after an integration time (typically 1 s) controlled by a computer. To achieve longer integration times (≥ 5 s) without saturating the pixels by a thermally generated signal, the array is cooled to about -30^{o} C with a Peltier element cooler. During the initial operations the complete detector system was operated in a mode resulting in 10 R/count at 427.8 nm and 5 R/count at 630.0 nm, with corresponding saturations at 40 kR and 20 kR, respectively. The system described in Paper III contains details of system design, software development and hardware design.

PAPER IV is a study of an event during which an auroral arc in the midnight sector developed from diffuse to discrete with subsequent large-scale folding. During this transition the arc was located close to the Tromsö magnetic field line and was observed by EISCAT operating in the CP-1 mode. Ion drift velocities in the F-region, as measured by EISCAT, were consistently eastward throughout and after the whole period of development, whilst the ion temperature showed two large enhancements just prior to the appearance of the main auroral fold. The fold moved eastward and crossed the EISCAT antenna beam, appearing as a short-lived spike in electron densities at altitudes between about 100 km and 400 km. The spike in electron density came progressively later at higher altitudes. The observations are interpreted as the result of enhanced convection in the ionosphere and in the magnetosphere. The auroral arc folding, and the associated delayed arrival of the soft precipitation, is suggested to be caused by the Kelvin-Helmholtz instability in a velocity shear zone in the magnetosphere.

PAPER V is a very interesting example of auroral dynamics observed both in the ionosphere and in the magnetosphere. The long-lasting, large-amplitude pulsation event on January 10, 1983, 02-06 UT, was initially discovered in ground-based MSP data, soon after its occurrence. A first report of the event was presented at the optical meeting at Lindau, FRG in the fall of 1983 [Steen and Rees, 1983], but the interpretation was at that time not clear. After that it took four years to gather complementary ground-based and satellite data. The new data set and the new model for magnetospheric substorms advocated by G. Rostoker (e.g., Rostoker and Eastman [1987]) were combined into the interpretation of the event, contained in paper V. In the ionosphere the characteristics of the pulsations changed from being Ps6/ auroral torches towards substorms and back to Ps6 over the 4 h period. At the geostationary orbit (6.6 R_E) the corresponding characteristics were a modulation of the high energy ($\geq$ 20 keV) particle intensity and plasma dropout. The gradual transition between Ps6 pulsations and substorm structures is interpreted as being different results of the Kelvin-Helmholtz instability, caused by different states of the magnetospheric convection. Based on the observation that the event is a repetition of pulses (varying between Ps6 and substorms) a simplified scheme (not using the growth phase concept) of the substorm sequence is discussed.

Paper V is an observation of a series of eastward travelling or stationary pulses in auroral luminosity. PAPER VI describes high time-resolution measurements of the actual formation of a series of spirals in an auroral arc. Two intervals of spiral formation were observed, and the second of these generated a westward travelling surge. Since the surge formation occurred on a time scale of a few seconds, this type of observation can only be made with high time-resolution imaging devices. The auroral developments took place in the zenith above Kiruna, where they were recorded by monochromatic imagers. The subsequent poleward expansion of the activity was observed by the EISCAT radar 200 km to the north of the initial activation. Since the westward travelling surge was the last developed spiral, it is proposed that the instability (Kelvin-Helmholtz instability) responsible for the final break-up of the arc is self-destructive. A proposed model of the substorm time sequence in the form of a flow chart is presented.

The relation between the multi-cell plasma convection pattern and the circulation of the neutral air at high latitudes is not well known. PAPER VII presents observations of a characteristic decrease in magnitude of the thermospheric meridional neutral wind in relation to auroral intensifications. The decrease precedes the auroral arc activation and stops at the moment of intensification. The neutral wind is measured from Kiruna by a Fabry-Perot interferometer. To avoid erroneous conclusions, as a result of scattered light and cloudiness, data from other ground-based measurements (e.g., EISCAT) and data from the UV imager on the Viking satellite are used. The observed decrease of the meridional neutral wind is associatied with increased Joule heating prior to the auroral activation, which is interpreted as an indication that the decrease is an effect of increased neutral gas heating. Since the wind reduction occurs prior to the explosive release of substrom energy, it it likely to be associated with the directly driven process of energy dissipation [Rostoker et al., 1987].

The final paper in this study, PAPER VIII, is a technical description of a bistatic auroral height measuring system, HMS, and an illustration of initial results. Each station used a detector of the type discussed in paper III. HMS was designed to measure the heights of aurora with a time resolution of 1.5 s. The base-line between the two stations was short, 13 km, which generated similar looking meridian profiles of the measured auroral emissions. The meridian profiles were obtained with intensified photodiode arrays, operated in a monochromatic imaging mode. The estimated optimal accuracies of the determinations of the latitudinal position of an auroral arc, and the altitude of an identified auroral point, are $\pm 0.01^{\circ}$ and ±1 km, respectively. HMS is especially adapted to measure during periods of disturbances in auroral arcs. As an example, the altitude and latitude of an auroral point, for an 80 s long sequence, during an event with eastward travelling folds in an arc, is given. With a least-squares fitting procedure, the maximum in the measured auroral intensity is found, and defined as the auroral point.

Papers III and VIII discuss applications of relatively new imaging technology (see also the presentation of MMA in chapter 2 and Table 1). However, anticipated advancements in imaging, storage and computer/communication technology make it necessary to discuss and speculate on much more sophisticated ground-based auroral imaging systems. An example of that is the proposal of a Grand Imaging System (GIS, Steen [1989]) consisting of a net of medium (65^0) field of view imagers, separated by about 50 km. The suggested total number of stations in GIS is 45 to 50. All stations in GIS are controlled by a center (CC: controlling center), causing simultaneous sub-images to be taken with a time resolution of 1 s or less and with a resolution of 512x512 picture elements. Since each station observes close to the zenith, it is only necessary to apply small photometric corrections. The sub-images are combined at CC into a grand image, covering an area of about 900 km (longitude) x 400 km (latitude), with a suggested resolution of 5000x2000 picture elements. From the two-dimensional maps of true auroral intensities, three-dimensional images of the distribution of auroral intensities could be derived using a triangulation procedure and overlapping fields of view. Another scientific objective of GIS is the derivation of two-dimensional maps of the energy characteristics of the precipitating particles using the method of spectroscopic ratios [Rees and Luckey, 1974].

4. Acknowledgements

The work presented in this thesis has been made possible by numerous people. The stimulating discussion with Prof. Georg Gustafsson, IRF-Uppsala, during the early part of this work, are the seeds to many of the projects which I have tried to carry through. The efforts by Mr. Christer Jurén, IRF-Kiruna, (not acknowledged elsewhere) to teach me concurrent computer programming, were important for one of the earlier ground-based measurement systems, and are very much appreciated. I have been privileged with a fruitful collaboration with Prof. Gordon Shepherd, York University, Canada. The co-operation with Dr. David Rees and his group at University College London, England, has formed an important part of my research activities. I also thank Dr. Peter Collis, EISCAT, for valuable discussions and clarifying comments on several aspects of the papers presented in the thesis. The continuing support by Prof. Bengt Hultqvist, on the optical research program in Kiruna, has been of great help to me. I am also indebted to the co-authors on several of the papers in this report.

I also wish to thank the staff of IRF in Kiruna for skillful work (on mechanics, electronics, typescripts, photographs and offsets) and for sharing almost 12 years of my working life with me.

The hardware costs for the projects in this report have been covered with funds from IRF, NFR and AFGL (contract AFOSR-84-0084).

5. References

Akasofu, S.-I., The development of the auroral substorm, Planet. Space Sci., 12, 273, 1964.

Akasofu, S.-I., The aurora: an electrical discharge phenomenon surrounding the Earth, Rep. Prog. Phys., 44, 1123, 1981a.

Akasofu, S.-I., Energy coupling between the solar wind and the magnetosphere, Space Sci. Rev., 28, 121, 1981b.

Baker, D.N., E.W. Hones, Jr., P.R. Higbie, R.D. Belian, and P. Stauning, Global properties of the magnetosphere during a substorm growth phase: a case study, J. Geophys. Res., 86, 8941, 1981.

Davis, T.N., The application of image orthicon techniques to auroral observation, Space Sci. Rev. 6, 222, 1966.

Feldstein, Y. I., Geographical distribution of aurorae and azimuths of auroral arcs, in Investigations of the Aurorae, no. 4, edited by B. A. Bagarjatsky, Academy of Sciences of the USSR, Moscow, pp.61, 1960.

Feldstein, Y.I., and Yu.I. Galperin, The auroral luminosity structure in the high-latitude upper atmosphere: its dynamics and relationship to the large-scale structure of the Earth's magnetosphere, Rev. Geophys., 23, 217, 1985.

Fuller-Rowell, T.J., and D. Rees, A three-dimensional time dependent global model of the thermosphere, J. Atmos. Sci.,37, 2545, 1980.

Gattinger, R.L., F.R. Harris, and A. Vallance Jones, The height, spectrum and mechanism of type-B red aurora and its bearing on the excitation of O('S) in aurora, Planet. Space Sci., 33, 207, 1985.

Gustafsson, G., D.S. Evans, H. Ranta, R. Pellinen, G. Schmidtke, Å. Steen, and H. Lauche, Energy input and spectral variations of precipitated particles during three nights of the Energy Budget Campaign, J. Atmos. Terr. Phys., 47, 73, 1985.

Gussenhoven, M.S., D.A. Hardy, and N. Heinemann, Systematics of the equatorward diffuse auroral boundary, J. Geophys. Res., 88, 5692, 1983.

Henriksen, K., W. Stoffregen, B. Lybekk, and Å. Steen, Photometer and spectrometer search of the oxygen green and red lines during artificial ionospheric heating in the auroral zone, Annales Geophysicae, 2, 1, 73, 1984.

Horwitz, J.L., The substorm as an internal magnetospheric instability: substorms and their characteristic time scales during intervals of steady interplanetary magnetic field, J. Geophys. Res., 90, 4164, 1985.

Hultqvist, B., Auroral particles, in Cosmical Geophysics, edited by A. Egeland, O. Holter, and A. Omholt, Universitetsforlaget, Oslo, 1973.

Hyppönen, M., R. Pellinen, C. Sucksdorff, and R. Torniainen, Digital all-sky camera, Finn. Met.Inst. Tech. Rep. 9, Helsinki, 1974.

Kindel, J.M., and C.F. Kennel, Topside current instabilities, J. Geophys. Res., 76, 3055, 1971.

McPherron, R.L., Growth phase of magnetospheric substorms, J. Geophys. Res., 75, 5592, 1970.

Murphree, J.S., L.L. Cogger, C.D. Anger, D.D. Wallis, and G.G. Shepherd, Oval intensifications associated with polar arcs, Geophys. Res. Lett., 14, 403, 1987.

Pemberton, E.V., and G.G. Shepherd, Spatial characteristics of auroral brightness fluctuation spectra, Can. J. Phys., 53, 504, 1975.

Perrault, P.D., and S.-I. Akasofu, A study of geomagnetic storms, Geophys. J. Roy. Astron. Soc., 54, 547, 1978.

Pytte, T., R.L. McPherron, E.W. Hones, Jr., and H.I. West, Jr., Multiple-satellite studies of magnetospheric substorms: distinction between polar magnetic substorms and convection-driven negative bays, J. Geophys. Res., 83, 663, 1978.

Rees, M.H., and D. Luckey, Auroral electron energy derived from ratio of spectroscopic emissions 1. Model computations, J. Geophys. Res., 79, 5181, 1974.

Rees, D., and Å. Steen, A new technique for rocket and space-borne investigations of time-dependent auroral morphology, Proceedings of the 8th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Sunne, Sweden, ESA SP-270, pp. 249, 1987.

Rees, D., P.J. Charleton, N. Lloyd, Å. Steen, and G. Witt, Interferometric and Doppler imaging studies of the auroral thermosphere from Kiruna Geophysical Institute, Proceedings ESA Symposium on European Rocket & Balloon Programmes, Interlachen, ESA SP-183, pp.53, 1983.

Rees, D., A. H. Greenaway, R. Gordon, I. McWirther, P.J. Charleton, and Å. Steen, The Doppler imaging system: Initial observations of the auroral thermosphere, Planet. Space Sci., 32, 273, 1984a.

Rees, D., R.W. Smith, P.J. Charleton, F.G. McCormac, N. Lloyd, and Å. Steen, The generation of vertical thermospheric winds and gravity waves at auroral latitudes. I. Observations of vertical winds. Planet. Space Sci., 32, 667, 1984b.

Rees, D., N.D. Lloyd, T.J. Fuller-Rowell, and Å. Steen, Variations of thermospheric winds in Northern Scandinavia between 1980 and 1986: A study of geomagnetic activitiy effects during the last solar cycle, Surv. Geophys., 9, 197, 1987.

Romick, G.J., T.L. Killeen, D.G. Torr, B.A. Tinsley, and R.A. Behnke, CEDAR: an aeronomy initiative, EOS, Trans. AGU, 68, no.2, 19, 1987.

Rostoker, G., and T. Eastman, A boundary layer model for magnetospheric substorms, J. Geophys. Res., 92, 12187, 1987.

Rostoker, G., S.-I. Akasofu, W. Baumjohann, Y. Kamide, and R.L. McPherron, The roles of direct input of energy from the solar wind and unloading of stored magnetotail energy in driving magnetospheric substorms, Space Sci. Rev., 46, 93, 1987.

Russell, C.T., and D.J. Southwood, editors. The IMS Source Book, AGU, Washington D.C., 1982.

Sandahl, I., Å. Steen, A. Pellinen-Wannberg, B. Holback, F. Söraas, and J.S. Murphree, First results from the Viking associated AURELD-VIP rocket and EISCAT campaign, Proceedings of the 8th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Sunne, Sweden, ESA SP-270, pp. 55, 1987.

Shepherd, G.G., A.J. Deans, and Y.P. Neo, SCIMP-A scanning, interferometric multiplex photometer, Can. J. Phys., 56, 681, 1978.

Stadsnes, J., K. Aarsnes, C.D. Anger, J. Bjordal, A. Brekke, D. Bryant, K. Brönstad, J. Carter, C. Chaloner, L.L. Cogger, C.S. Deehr, A. Egeland, D.J. Gorney, K. Henriksen, U. Hoppe, W.L. Imhof, I.B. Iversen, R. Lundin, D.L. McKenzie, B.N. Maehlum, K. Måseide, D. Ramsden, M.H. Rees, C.J. Rice, T.J. Rosenberg, I. Sandahl, I. Singstad, K. Stamnes, Å. Steen, F. Söraas, M.J.

Taylor, S. Ullaland, E.Ungstrup, E.V. Thrane, R.R. Vondrak, and H.D. Voss, AURIO - A proposal for flying an auroral imaging observatory on the polar platform in the space station/Columbus programme, Proceedings of the 8th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Sunne, Sweden, ESA SP-270, pp. 401, 1987.

Steen, Å., Spatial monitoring of auroral emissions, Proceedings from the 10th Annual Meeting on Upper Atmosphere Studies by Optical Methods, edited by J. Clairemidi, Grasse, France, 1982, also available as KGI Report No 182, 1983.

Steen, Å., Intensified photodiode array applied to one dimensional auroral imaging, Rev. Sci. Instrum., 56, 116, 1985.

Steen, Å., A new facility for optical auroral measurements, IAGA News, 26, 76, 1987.

Steen, Å., An auroral height measuring system designed for real time operation, Rev. Sci. Instrum., In press, 1988.

Steen, Å., New auroral imaging techniques, Paper presented at the XVI Annual Meeting on Upper Atmospheric Studies by Optical Methods, Oulu, Finland, to appear in Planet. Space Sci., 1989.

Steen, Å., and P.N. Collis, High time-resolution imaging of auroral arc deformation at substorm onset, Planet. Space Sci., 36, 715, 1988.

Steen, Å., and G. Gustafsson, Proposal for EISCAT-measurements. Combined optical and incoherent scatter radar measurements to study auroral dynamics. I. Pulsating aurora, KGI Report No 177, 1980.

Steen, Å., and G. Gustafsson, The spectral hardening associated with the westward travelling surge, Planet. Space Sci., 29, 1011, 1981.

Steen, Å., and D. Rees, Optical characteristics of a Ps6 event, Proceedings of the 11th Annual Meeting of Upper Atmosphere Studies by Optical Methods, Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, FRG, edited by G. Lange-Hesse and H. Lauche, 1983.

Steen, Å., D. Rees, and G. Gustafsson, Proposal for EISCAT measurements. Combined optical and incoherent scatter radar measurements to study auroral dynamics. II. The westward travelling surge, KGI Report No 178, 1982.

Steen, Å., P.N. Collis, D. Evans, G. Kremser, S. Capelle, D. Rees, and B.T. Tsurutani, Observations of a gradual transition between Ps 6 activity with auroral torches and surgelike pulsations during strong geomagnetic disturbances, J. Geophys. Res., 93, 8713, 1988a.

Steen, Å., D. Rees, P.N. Collis, and J.S. Murphree, What role does the F-region neutral wind play in auroral intensifications?, Planet. Space Sci., 36, 851, 1988b.