In the light of the aurora

– Optical auroral research in northernmost Europe

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Auroral Research in the Arctic Region.*

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TemaNord 2009:557

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TemaNord 2009:557

© Nordic Council of Ministers, Copenhagen 2009

ISBN 978-92-893-1900-3

Print: Kailow Express ApS

Cover photo: Aurora over Kiruna/Rick McGregor

Copies: 100

Printed on environmentally friendly paper

This publication can be ordered on www.norden.org/order. Other Nordic publications are available at www.norden.org/publications

Printed in Denmark

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Preface

The aurora, or northern lights, is the result of physical processes taking place in near-Earth space. These processes are at times quite dramatic and are caused by the interaction between the solar wind and the Earth's magnetic field. Aurora is created when charged particles from space hit the upper atmosphere. These charged particles are guided by the magnetic field of the Earth so that they usually hit the atmosphere far to the north or far to the south. Thus it is fair to say that the Arctic is a window on space. And since space is dominated by matter in the plasma state, studies of the auroral light give insight into various aspects of plasma physics.

Arctic Europe is a most convenient place to study the aurora thanks to its benevolent climate and good accessibility. Consequently, much instrumentation for auroral research has been set up in this region. Svalbard has a special standing as the only place in the northern hemisphere where dayside aurora can be studied in darkness. The reason for this is the relative position of the magnetic and geographic poles.

The region also has the world's highest concentration of northern universities and research institutions. Thus, there are several research groups living under the aurora and studying it. However, the number of persons working with optical methods at each institution is relatively small, and it was realized that much could be gained by intensified collaboration. When the Nordic Council of Ministers issued a call for their Arctic co-operation programme 2006–2008, all research groups active in optical auroral research in northernmost Europe joined in an application, Network for Groundbased Optical Auroral Research in the Arctic Region. The participating groups were The University Centre on Svalbard, University of Tromsø, Swedish Institute of Space Physics in Kiruna, University of Oulu, Sodankylä Geophysical Observatory and the Polar Geophysical Institute in Apatity.

The grant from the Nordic Council of Ministers has made it possible to conduct three workshops and several research visits between the participating groups. The workshops were held in Sodankylä in 2007, in Tromsø in 2008, and in Kiruna in 2009. It has also given the opportunity for a number of Russian scientists to participate in Annual European Meetings on Upper Atmosphere Studies by Optical Methods that were held in Kiruna in 2006 and at Andøya Rocket Range in 2007.

With this report we wish to give an introduction to optical auroral research, what we can learn from it and how it is carried out. We present optical research facilities and research groups in northernmost Europe and we report the activities of the Optical Auroral Network and the results achieved by it so far.

We feel that optical auroral research is on the threshold of important breakthroughs. During recent years instruments have been greatly improved so that optical measurements can be carried out with much better resolution than ever before. This means that for the first time we can study the finest spatial and temporal scales of the aurora. The start of our network was timely. There will be much for us to do during coming years.

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Summary

In the light of the aurora – Optical auroral research in northernmost Europe

This is a report written by partners of the Network for Groundbased Optical Auroral Research in the Arctic Region. The network was formed in response to the Arctic Cooperation Programme 2006–2008 call, issued by the Nordic Council of Ministers. It consists of all institutions in Svalbard and Northern Fennoscandia active in research on the aurora with optical methods. The aim of the report is to introduce auroral research, in particular what can be achieved by optical methods, research groups, facilities and instrumentation in the region, as well as giving an account of the activities and scientific results of the network. The network was awarded a grant in 2009 to continue its activities.

Optical aurora

The northern lights, also known as aurora borealis, is the most variable light phenomenon in the sky. It is the visible manifestation of physical processes occurring in space near Earth and is powered by the solar wind. The aurora thus contains much information on these processes and on space physics. Various events on the sun cause variations in the solar wind and thus in the aurora. Such variations also give rise to variations in the near-Earth space environment, space weather, that can affect technical systems such as satellites and power systems. To understand the message of the aurora different properties of the light are measured, such as geographical distribution, shapes and movements of auroral forms, height, colours, intensities. Ground-based measurements of the optical aurora are usually combined with other types of measurements, both from the ground and from satellites and sounding rockets.

Many different kinds of instruments are used to measure the northern lights including observatory all-sky cameras, advanced imagers, photometers and spectrographs. Recent development of optical instrumentation has opened up new possibilities to study fast variations, small scale structures and weak auroras that occur very frequently but that have previously been beyond reach. Ground-based optical instrumentation can reach the best spatial resolution of all kinds of instruments. It is also the best to distinguish between spatial and temporal variations. To interpret the data it is also necessary to use several models, for example models describing the processes in the atmosphere as the light is created.

Research groups

Northernmost Europe has the highest density anywhere in the world of research institutions at which scientists actually live under the aurora. The research groups that started the network were the University Centre in Svalbard; the Department of Physics at the University of Tromsø; the Swedish Institute of Space Physics, Kiruna; two groups at the University of Oulu, namely the Department of Physical Sciences and Sodankylä Geophysical Observatory; and the Polar Geophysical Institute in Apatity of the Kola Science Centre. Two more southern groups joined after the start of the network, the Finnish Meteorological Institute, Helsinki, Finland, and the Royal Institute of Technology in Stockholm, Sweden, and in 2009 the Department of Physics at the University of Oslo also became a member. Short descriptions of these groups and their research activities are given.

Facilities and instruments for measurements of optical aurora

Northernmost Europe is a most convenient place for studies of optical aurora, since here the auroral oval crosses regions with excellent infrastructure and a comparatively mild climate. The Fennoscandian mainland is best for studies of nightside aurora while Svalbard in the middle of the winter offers unique possibilities to investigate dayside auroras in darkness. Much infrastructure and many instruments have therefore been set up here, both by groups participating in the network and by groups from many other parts of the world such as Great Britain, Italy, China, Japan and the United States.

Network for Groundbased Optical Aurora Research in the Arctic Region

The network was given a grant of DKK 355 000, that has been used during the period 2006–2009. The goals are to strengthen the collaboration between research groups in the European Arctic region working in the field of optical aurora research and to conduct excellent scientific work. This has been done by conducting three workshops for scientists and Ph.D. students, conducting a mobility programme for visits between participating groups and providing stipends for Russian scientists for conference participation.

The first workshop was held February 19–23, 2007 in Sodankylä with 23 participants, the second in Tromsø April 7–11, 2008 with 10 participants and the third in Kiruna May 25–29, 2009 in Kiruna with 14 participants. The workshop programmes have included tutorial presentations, status reports from the different groups, exchange of experiences regarding instrumentation, common work on scientific studies, planning of measurement campaigns and study visits. An essential objective has also been to strengthen personal contacts between individuals.

The mobility programme has comprised a total of 14 visits. Most visits have been of the order of one week. Results have been presented at scientific conferences and in papers in scientific journals. Many of the studies are still ongoing and additional results are expected.

Thanks to the grant eleven Russian scientists could participate in the optical meeting in Kiruna in 2006 and two in the optical meeting in Andøya, Norway in 2007.

Research projects conducted within the network, descriptions and first results.

During the project many studies have been carried out by the groups participating in the network. Here we describe studies that have been carried out as joint projects between different groups, studies that have to a large extent been enabled thanks to the network. Publications on optical aurora during the project period are listed after chapter 6.

High resolution study of auroral structuring

The aurora is rich in small-scale structures, but most of them are poorly understood. KTH is operating the ASK instrument, the best instrument in the world for high resolution studies. In this project the University of Oulu auroral camera provided the more large-scale picture. The project found a new type of auroral structure named “ruff” and investigated their cause and relation to the previously-known larger curls and folds.

Multi-instrument observations of small-scale aurora

ASK data are combined with data from ALIS and EISCAT to study the detailed relationship between precipitating electrons from space with the actual optical emissions measured by ASK.

Enhanced electric field inside an arc

The electric field inside an auroral arc is almost always smaller than outside. This work shows that this is not always the case. It concludes that in a developing arc the electric field inside the arc may be enhanced.

Pulsating aurora studies

Pulsating aurora appear in the later phase of auroral substorms. The cause is still not understood and there are conflicting theories. The height variations during pulsation cycles were studied using triangulation from ALIS measurements. The results favour a wave-particle interaction mechanism.

Observations of capturing of magnetosheath plasma

These multi-instrument observations of the dayside aurora were shown to be consistent with reconnection tailward of the cusp and capture of magnetosheath plasma into the magnetosphere during northward IMF.

Scaling behaviour of auroral luminosity

Auroral features with widths 6–26 km showed closeness to self-similarity, pointing to a turbulent nature of the variations.

Energy transfer in molecular collisions

Below 100 km energy transfer during collisions between molecules is very important. This is a theoretical study deriving quenching rate coefficients that are needed for calculations of the energy transfer.

Modelling electron density and NO_x changes

Auroral particles affect the formation of nitric oxide in the atmosphere. This is a study to estimate the production of nitric oxide from observations of optical aurora.

Application of AIDA to data from other imagers

Data analysis of optical data is often complicated. In this project routines for tomography-like inversion developed for ALIS is being applied to colour imager data.

History of auroral research

In 1899–1900 a very well-organized Russian-Swedish expedition to Spitzbergen was mounted. This is a description of the auroral studies carried out during that expedition.

Conclusions

The network has deepened the contacts between the research groups involved and the friendship between scientists. Several new studies have been started, some results have been published and more are still in the analysis phase. The combination of workshops and mobility programme has worked well. The grant received has gone further than anticipated because of inexpensive travel and accommodation. The timeline has had to be stretched somewhat compared to the original planning, mainly because of a heavy workload of all participants. An evaluation of the network activities has been carried out by Dr. Steve Milan, University of Leicester, and the main conclusion of this evaluation is that the network has been successful and has achieved its goals.

In 2009 the network received a new grant from the Nordic Council of Ministers to continue its activities. The network has now been extended to include all groups in Norway, Sweden, Finland and on the Kola peninsula active in optical auroral research as full network partners. With the possibilities offered by modern optical instrumentation we should be able to make important contributions to the understanding of ionospheric and space physics and to the mechanisms of the aurora.

1. Optical aurora

1.1 The most variable light in the sky.

Figure 1. Aurora is the most variable light in the sky. This figure shows two auroral activations on 20 December 2006 recorded by an all-sky camera in Kiruna, one picture per minute. North is to the top. From one minute to the next an auroral arc spanning the sky changed into auroral forms filling the whole sky. The Swedish astronaut Christer Fuglesang took photographs of the same aurora from the Space Shuttle 18:50–18:56 UT. Pictures: IRF.

The aurora is the most variable of all natural light phenomena in the sky. It can at times be almost as bright as the full moon, at other times hardly visible. It takes on many different shapes such as arcs, draperies, spirals, rays, patches and diffuse surfaces. The most common colour is yellowish

green, but it also displays red, purple and other colours (Figure 2 and the cover picture). Sometimes auroral forms appear to stand still, but more often they move, frequently with amazing speeds. Auroral forms can appear and disappear or pulsate on and off.

The aurora is always present. Satellite images show that the aurora appears as continuous rings around the poles. We call these rings the northern and the southern auroral ovals. The action of the solar wind pushes the ovals towards the nightside of the Earth. During normal conditions the nightside part of the northern auroral oval often stretches across northern Fennoscandia, while in the daytime it is found above Svalbard. During magnetically active conditions the oval grows so that aurora becomes visible much further south, and during magnetically quiet times it shrinks.

Figure 2. Diversity of auroras. Page 14, Top left. Unusual auroral spiral. Photo: Mikko Syrjäsoo. Top right. An active arc. Green is the most common colour of the aurora. Photo: Carl-Fredrik Enell. Bottom. Aurora over Kiruna during the great magnetic storm 7–8 April, 2000 showing green, red, and purple emissions. Photo: Masatoshi Yamauchi. Page 15, Top. Active aurora with red lower borders. Photo: Pavel Chernouss. Bottom left. Active arc. Photo: Sergey Chernouss. An arc curving into a spiral above Apatity. Photo: Sergey Chernouss

Everything that happens in the aurora has a physical reason, most often something that has happened in space fairly close to Earth, in the Earth's magnetosphere. At least since antique times, scientists have tried to understand the mechanisms of the aurora. We now know that most of the visible aurora is caused by electrons from space that hit the upper atmos-

phere with velocities of about one tenth of the speed of light. They are slowed down by collisions with the atoms and molecules of the atmosphere and, in connection with this, some of their kinetic energy is converted into light. During a moderately strong aurora each square millimetre of the atmosphere is hit by one hundred million electrons every second. We also know that the ultimate source of energy for the aurora is the sun. Events on the sun, such as coronal mass ejections and high speed solar wind streams, have a strong influence on the magnetic field of the Earth, on electrical current systems and particle populations in near-Earth space, and thus on the aurora. The changes occurring in Earth's magnetosphere are fast, surprisingly large, and at times quite dramatic. The magnetic field changes its shape totally in just a few minutes, magnetic substorms last for a few hours and magnetic storms for a number of days. During large magnetic storms aurora may be seen all over Europe. The weather in space sometimes causes damage to, for example, satellites and power systems and thus space weather has become a research topic of large practical interest.

1.2 Reading the messages of the aurora

Figure 3. Vertical cut through the Earth's magnetosphere and its surroundings. The sun is far to the left of the picture. The magnetosphere is the region inside the magnetopause. Picture: Ingrid Sandahl.

We can regard the upper atmosphere as a large TV-screen on which the aurora shows a picture of the events in the magnetosphere. Figure 3 is a map of the average shape of the magnetosphere. The Earth is the small, half

white, half black circle, and narrow lines going from the Earth show the magnetic field. Charged particles are guided by the magnetic field in spiral shaped orbits, causing aurora at the place where the magnetic field line intersects the atmosphere, the so called foot point. Strong aurora tells us that there are many charged particles along the corresponding field line or that the electrons along that field line have been accelerated. Motions of the aurora indicate a moving source or changes in the shape of a field line. A pattern in the aurora shows that there is a pattern in the magnetosphere. The time history of the aurora tells of the time history in the magnetosphere.

The height of the aurora gives us messages about the initial energies of the electrons from space and so do the colours. A faster, more energetic, electron will penetrate more deeply into the atmosphere than a slower, less energetic one. Aurora created by electrons with an energy of 0.5 keV (kiloelectronvolts) will have a lower border at about 110 km, while 5 keV electrons will give aurora with a lower border at around 100 km.

Figure 4 shows a schematic spectrum of an aurora. Unlike the solar spectrum below it, it is a line spectrum that only contains a limited number of colours. Each colour, or line, is the signature of a particular atom, molecule, or ion. The green auroral line with a wavelength of 558 nm (nanometers) comes from atomic oxygen, and so does the red line at 630 nm. The blue light at 428 nm is emitted from ionized nitrogen molecules. An electron moving down through the atmosphere will go through the order of one hundred collisions before it is stopped. At the top of the atmosphere it is most likely to encounter an oxygen atom, and thus the greater part of the auroral light from there is likely to come from oxygen emissions. As the electron continues down it will meet an increasing number of nitrogen molecules, and more of the emissions will come from nitrogen.

Figure 4. Schematic spectra of the aurora (above) and of the sun (below). The different auroral lines come from different atoms and molecules in the upper atmosphere. Picture: Ola Westin.

Of course, there are several factors affecting the production of auroral light. First, there is an enormous amount of primary electrons from space and they have different energies and directions of incidence. Second, many of the atmospheric particles do not jump to a higher energy level by direct collisions with the primary electrons, but by a chain of chemical reactions in the atmosphere. Third, the composition of the atmosphere

and its height variation changes in time and space. Fourth, the time between energy increase, excitation, of an atmospheric particle and emission of the energy as auroral light is variable and sometimes very long. For the blue line at 428 nm the emission is almost instantaneous, but for the red line at 630 nm the time is on average as much as 110 seconds. In this time the emitting atom may have moved a long distance and it may even have lost its excess energy in some other way than by emitting a light photon. All these factors, as well as a few not mentioned here, must be taken into account when reading the message of the aurora, and in order to do so we must have a very good understanding of the physics and chemistry of the upper atmosphere.

When working to read the message of the aurora it is also necessary to consider the geometry of the observations. The problem is well illustrated by Figure 5 that appeared in a famous book on aurora written by the French scientist DeMairan in 1754. Auroral structures often have an extent of at least a few hundred kilometres along the magnetic field of the Earth. To get information about what is happening along one particular field line we must make observations along that field line in the direction of so-called magnetic zenith. All measurements from other parts of the sky will have contributions from several different field lines, from lower altitudes close to the instrument and higher altitudes further away.

Figure 5. Viewing geometry of aurora as described by DeMairan in 1754. The line marked *x* shows magnetic zenith. From *Traité physique et historique de l'aurore boreale*, second edition, Paris 1754,

Much research about the aurora is carried out by instruments on satellites and sounding rockets performing *in situ* (local) measurements of, for example, the particles involved in the auroral mechanisms and electric and magnetic fields. But a satellite moves fast and when it records a sudden change it is difficult to determine if it happens because the satellite has entered a region with different properties, or if it is a temporal event. With imaging instruments, on the other hand, it is easy to separate temporal and spatial variations. Imagers on satellites are good at giving an overview of the aurora. Ground-based imagers can give more details. The combination of *in situ* measurements in space with measurements by imagers is a very powerful one.

1.3 Measuring the optical aurora

Different types of instruments are used to measure different properties of optical aurora. Frequently data from a number of instruments are combined in order to get more complete information about an event. In this section optical instruments are introduced.

1.3.1 All-sky cameras

An important feature of auroral studies is that we are not usually able to control our experiments. Nature makes the experiments for us without telling us in advance. We have to stay prepared and be ready to measure when something interesting happens. Every night during the dark season all-sky cameras at several observatory sites spread across the auroral zone record the light appearing in the sky. The images are typically obtained once per minute. The all-sky cameras are observatory instruments that are operated automatically to a fixed schedule, and they provide background information for space physics studies. A large network of all-sky cameras was deployed in 1957/58 during the International Geophysical Year (IGY). Analysis of all-sky images led to the discovery and description of fundamental auroral features, most importantly the auroral oval and the auroral substorm. At many of the IGY sites all-sky cameras have now been operated for more than 50 years. Data are archived and much data from recent years is freely available on Internet. At first, all-sky cameras were operated with black and white film, then with colour film. Now most of them are digital cameras. Many all-sky cameras are operated in northernmost Europe by the groups participating in the network.

The aurora has its lower border at about 100 km. At this height the area of the sky that can be observed by one single all-sky camera is 600 km wide. The average auroral oval has a diameter of about 5000 km, so from one observing site only a part of the aurora can be seen. To get a large scale picture, networks of cameras have been set up. An example is

the MIRACLE network in Fennoscandia and Svalbard that is described in section 3.2.4.

Figure 6: All-sky colour CCD camera used in the MIRACLE network.
Photo: Jyrki Mattanen

1.3.2 Measuring colours one by one

One way of sorting the huge amount of information available in the aurora is to perform measurements of one emission at the time. This is done by using filters. In auroral studies it is common to use interference filters, often with a bandwidth of 2–4 nm. Many instruments have filter wheels with a number of different filters that can be rotated into the ray path, one at the time. In this way it is possible to measure at a number of different wavelengths, one after the other. However, narrow-band filters also limit the amount of light passing through to the detector, so in order to use them the detector system must be sensitive. Most observatory all-sky cameras are operated without filters, but there are also all-sky cameras with filters, for example the cameras of the MIRACLE network.

1.3.3. Advanced auroral imagers

Everyone who has watched the aurora knows that there are frequently very fast variations and an abundance of very small structures. Some structures are only a few tens of metres. Different colours vary in different ways. An additional factor to consider is that much of the aurora is quite weak in intensity. Ordinary all-sky cameras do not have sufficient resolution to measure all these features; specialized imaging instruments

are needed. Auroral scientists have constantly been searching for more sensitive and faster optical detectors and have been quick to take advantage of new technical developments.

For recording fast variations different kinds of *auroral TV-cameras* are used, usually obtaining 25–30 frames per second. Figure 7 shows the all-sky television camera Aurora developed at the Polar Geophysical Institute in Apatity. Modern auroral TV-cameras use image-intensified charge couple device (ICCD) detectors, for example the Odin imager developed at the University of Tromsø. Auroral TV-cameras are providing much important information. However, until now, TV-systems have not been sensitive enough to allow the use of narrow-band filters; they are not as good at measuring weak and intense auroras at the same time and at measuring the exact intensity of the emissions.

Scientific grade *CCD detectors without image intensifiers* are able to measure both weak and intense emissions at the same time and can also give absolute intensities. They are usually used together with narrow band filters. Such detectors are used in the Auroral Large Imaging System (ALIS) of the Swedish Institute of Space Physics (Section 3.1.1). On the other hand they can not capture images as quickly as the TV-cameras.

Figure 7. Left: The all-sky TV camera PGI Aurora. Right: Rayed auroral arcs recorded by the all-sky TV camera at Barentsburg. Photo: Ilya Kornilov.

Today an increasing number of instruments are using electron multiplication CCD (EMCCD) detectors. These detectors have very high sensitivity, can be operated with a frame rate equal to or faster than TV cameras, and allow absolute intensity measurements. The ASK instrument (Section 3.1.1), that has been used in a number of joint studies within the network, uses three parallel cameras with EMCCD detectors and different narrow band filters. The newest MIRACLE cameras also have EMCCD detectors.

1.3.4 Photometers

A photometer is an instrument that measures the intensity of the light. A photometer tube consists of a lens, a filter and a detector. The lens collects light from the sky from a narrow field-of-view. The light goes through a filter, which admits only the wanted colour. Finally the admitted light is recorded by a detector. One photometer tube thus measures only one colour. By combining several photometer tubes with different filters, a set of auroral colours can be measured at the same time. The photometers have 5 or 6 photometer tubes or channels. Their data are collected by a computer. The photometer can look to one direction in the sky or scan across the sky in one plane.

Ordinary photometers have narrow fields-of-view, about 1 degree (twice the diameter of the moon in the sky). Wide field photometers, which often look towards zenith, have fields-of-view of several or several tens of degrees.

Photometers are frequently used in combination with imagers. In many places meridian scanning photometers are operated on a routine basis. Meridian scanning photometers sweep across the sky along the magnetic meridian measuring profiles of the auroral light.

1.3.5 Spectrographs

There are many spectral lines in the aurora, and to measure these lines spectrographs are used. Detailed studies of the spectrum of the aurora were already carried out in the later part of the 19th century.

In a spectrograph the light is separated according to wavelength. The light is collected by a lens to a narrow slit after which it is collimated by another lens system. The collimated beam is split into its colours by a prism or diffraction grating. After the grating the colours are focused to a detector, e.g. a CCD camera chip. After an exposure of some seconds with a spectrograph, a spectrum will be obtained from the target. By turning the instrument to the sky at night time, spectra of aurora will be obtained.

If the particle emitting the auroral light is moving, the wavelength will be slightly altered. By measuring this Doppler shift it will be possible to deduce the velocity of the emitting particles. This is particularly useful in studies of proton aurora, that is aurora for which the fast particles from space are protons rather than electrons.

1.3.6 Models

When interpreting the data, computer models are frequently used as the processes that we study are complex. *Electron transport models* describe what happens to a population of electrons moving down through the atmosphere. *Auroral optical emission models* give the resulting optical emission profiles. *Ion-neutral chemistry models* are used to quantify the chemical

effects of the precipitating energetic electrons and protons, such as production of nitric oxide (NO). If we have simultaneous emission intensities of different colours we can use *inversion methods* to derive some properties of the initial electron distribution. If we know the full luminosity profile along a field line we can derive quite detailed information about the initial electrons. If the aurora in a certain region of space has been measured simultaneously from different directions, *tomography-like inversion methods* can be used to obtain the three-dimensional light distribution.

When trying to identify a source region in the magnetosphere of an event in the aurora we use *models describing the magnetic field*. That is, we try to find the shape of the field line at that particular moment. Magnetic field models are also used when relating our optical data to satellite measurements. We want to find the aurora on the same field line as the satellite. Magnetic field lines change their shape very much and very fast and to make a good assumption, information from satellite measurements of the solar wind and solar magnetic field properties are used as input parameters to many of the models.

Literature and home pages about aurora

More information about aurora can be found in the following home pages and popular science publications that have been produced by network participants and institutions.

Web pages

<http://www.irf.se/Popular/>
<http://geo.phys.uit.no/articles.html>
http://aurora.fmi.fi/public_service/
<https://wiki oulu.fi/display/spacewiki>

Books

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2. Research groups

This chapter presents all research groups in northernmost Europe conducting research on optical aurora. All these groups participate in the Network for Groundbased Optical Auroral Research in the Arctic region. The network Partners come from the University Centre on Svalbard, the University of Tromsø, the Swedish Institute of Space Physics in Kiruna, the Department of Physical Sciences at the University of Oulu, Sodankylä Geophysical Observatory (also at the University of Oulu) and the Polar Geophysical Institute in Apatity. Scientists from the Finnish Meteorological Institute in Helsinki and the Royal Institute of Technology have also participated in the network activities as Associated Partners. The map in Figure 8 shows the locations of the participating institutions as well as locations of optical measurement facilities described in Chapter 3.

Figure 8. Locations of participating institutions and optical facilities. The University Centre in Svalbard is in Longyearbyen (LYR), the University of Tromsø in Tromsø (TRO), the Swedish Institute of Space Physics in Kiruna (KIR), the University of Oulu in Oulu (OUL), Sodankylä Geophysical Observatory in Sodankylä (SOD), and the Polar Geophysical Institute in Apatity (APA).

2.1 Norway

2.1.1 The University Centre in Svalbard, UNIS (<http://www.unis.no>)

Figure 9. Svalbard Science Centre in Longyearbyen. Photo: Steve Coulson, UNIS.

The University Centre in Svalbard (UNIS) is the world's northernmost higher education institution, located in Longyearbyen, Spitsbergen, at 78°N . UNIS was founded in 1993 and is a share-holding company owned by the Norwegian Ministry of Education and Research. Research and education is carried out in four main fields: Arctic Biology, Arctic Geology, Arctic Geophysics and Arctic Technology. For studies of processes related to the aurora UNIS utilizes the infrastructure in Svalbard, especially the Kjell Henriksen Observatory (KHO) (Section 3.1.2) with optical instrumentation and the EISCAT Svalbard Radars (ESR). In addition, it uses data from other observational platforms such as satellites and *in situ* sounding rockets.

A natural focus for the auroral research at UNIS is the dayside aurora. In the polar cusp, charged particles from the solar wind penetrate down to the ionosphere and generate cusp aurora. Aurora caused by protons is particularly important for the understanding of solar wind magnetospheric coupling.

UNIS is responsible for the Kjell Henriksen Observatory. The instruments owned by UNIS include different types of all-sky imagers and two Ebert-Fastie spectrometers, one at KHO and one at the Sverdrup station in Ny Ålesund (Section 3.1.3).

2.1.2. University of Tromsø, Department of Physics and Technology, UiT (<http://www.uit.no>)

The University of Tromsø is the northernmost university in the world, and was established in 1972. Auroral research is a major part of the research at the Institute of Physics and Technology (IPT). The optical auroral studies at IPT focus on coordinated observations with the EISCAT

incoherent scatter radars. Much of the work has concerned small scale and rapid phenomena, such as flaming auroral rays, associated with a special type of radar echoes named Naturally Enhanced Ion Acoustic Lines (NEIALs), flickering aurora and black aurora. In this research IPT uses a high speed (50 frames/s) narrow field-of-view imager, the Odin imager, operated either in white light or with wide band filters. Further operations with an EMCCD camera have started in collaboration with the ASK group at the Alfvén Laboratory KTH and IRF in Kiruna, and with a new platform built on a set of cameras operating at 1–5 frames/s. These new systems have been used at the EISCAT site in Ramfjord Norway giving combined observations of pulsating aurora with optics and radar, and in two 2009 campaigns in Alaska, one as ground support for a rocket campaign and one campaign with coordinated optical and radar observations of pulsating and black aurora.

The department also owns Aurolab (Figure 10), the only plasma physics laboratory of its kind in Norway, where plasma physics experiments relevant to space plasmas are carried out.

Figure 10. Aurolab, the plasma physics laboratory at the University of Tromsø. Here experiments relevant to space plasma physics are carried out. Photo: Åshild Fredriksen.

2.1.3. University of Oslo, Department of Physics, UiO (<http://uio.no>)

Auroral research at the University of Oslo has been going on for well over a century. Much attention is paid to processes in the dayside aurora and related phenomena. The group has a set of optical instruments in Ny-Ålesund, an all-sky camera at the Kjell Henriksen Observatory and one at Andøya rocket range. It also uses sounding rockets launched from Svalbard. UiO joined the network in 2009.

2.2 Sweden

2.2.1 Swedish Institute of Space Physics, Kiruna, IRF (<http://www.irf.se>)

Figure 11. The Swedish Institute of Space Physics, Kiruna. Photo: Torbjörn Lövgren, IRF.

The mining town Kiruna, with 23 000 inhabitants in the municipality, is also home to diverse activities in space and atmospheric research. The Swedish Institute of Space Physics (Institutet för rymdfysik) has its largest work place and main office in Kiruna. Esrange Space Center controls satellites and launches sounding rockets and balloons. A large tract of land in the northern part of the municipality is the rocket launch impact area. EISCAT Scientific Association has its main office and one of its three receiving sites for the UHF system in Kiruna.

IRF was founded in 1957 as Kiruna Geophysical Observatory and was then owned by the Royal Academy of Sciences. When in 1973 it became an independent government research institute the name was changed to Kiruna Geophysical Institute and later to IRF. KGO/KGI/IRF was the first, and for many years the only, research group in Sweden to build satellite instruments. A speciality for Kiruna is the development of instruments for measuring charged and neutral particles in space. Instruments built at IRF have flown on many sounding rockets and satellites and made many contributions to the understanding of auroral processes. At present instruments from Kiruna are orbiting Mars, Venus and the moon, making it possible to compare processes powered by the solar wind at these bodies with those at the Earth.

Since the start in 1957 observatory measurements have been carried out, including measurements with all-sky cameras and magnetometers.

The Auroral Large Imaging System, ALIS, (Section 3.1.1) was developed in the early 1990s and is owned and operated by IRF.

IRF has an optical laboratory in its main building and a site for optical measurements close to the EISCAT receiving site.

2.2.2. *Royal Institute of Technology, Stockholm, KTH* (<http://www.kth.se>)

The Space and Plasma Physics group belongs to the School of Electrical Engineering at the Royal Institute of Technology (KTH). The research comprises space and laboratory experiments as well as theory. The group has specialized in *in situ* measurements. Electric field experiments and fluxgate magnetometers have been built in-house and flown on a large number of satellites and sounding rockets. Ground-based optical and radar measurements of the fine scale of aurora is a research topic which has grown rapidly with the large dataset produced by the Auroral Structure and Kinetics (ASK) instrument (Section 3.3.1). The group also uses data from other facilities, such as the EISCAT radars and optical instrumentation operated by our partners.

2.3 Finland

2.3.1. *University of Oulu, Sodankylä Geophysical Observatory, SGO* (<http://www.sgo.fi/>)

Sodankylä is a municipality of less than 9000 inhabitants, but in spite of the sparse population it is an important regional centre of northern Finnish Lapland. As part of the Finnish activities during the First Polar Year, the first measurements of the Earth's magnetic field at Sodankylä were performed in 1882. A permanent observatory was established by the Finnish Academy of Science and Letters in 1913 (4 years before Finland's independence), and continuous registrations started in 1914. In 1997 the observatory was merged with the University of Oulu and today it is an independent institute within the university with researchers in both Sodankylä and Oulu. SGO has measurement sites at several different locations from southern Finland to Svalbard and some of the instruments are part of global networks.

SGO carries out continuous observations of many geophysical phenomena in our near-Earth environment. These include optical aurora, the Earth's magnetic field, electron density of the ionosphere, cosmic radio noise, cosmic rays and seismic activity. SGO also hosts guest instruments, such as VLF (Very Low Frequency) radio receivers, an infrasound recording station and an optical Fabry-Perot interferometer owned by University College London, UK, which is used to measure winds at an

altitude of around 250 km. In addition to continuous recordings the observatory performs campaign-based measurements with the EISCAT incoherent scatter radars and its own wide-band VLF recording equipment. Sodankylä is the site of one of the three 32-metre receiving antennas of the EISCAT UHF radar. This is a very powerful facility for research on the ionosphere. EISCAT measurements are often used in combination with optical measurements.

Research at SGO is based on both measurements and related computer modelling. The long series of continuous registrations allows studies of long-term trends in the ionosphere and anthropogenic effects on near-Earth space. Much work is dedicated to studying the chemical effects of ion-neutral reactions in the lowermost ionosphere driven by auroral electron precipitation and solar proton events. In this research, active modulation of the negative ion concentrations at 60–80 km with the EISCAT Heating facility is often used. SGO also has researchers in the Finnish Inverse Problems Center of Excellence, developing radar measurement theory, software-based radar technology and mathematical inversion theory, including tomographic methods for ionospheric research.

*Figure 12. The main building of Sodankylä Geophysical Observatory.
Photo: Carl-Fredrik Enell.*

2.3.2. *University of Oulu, Department of Physical Sciences, OY*
 (<http://spaceweb.oulu.fi/>)

Figure 13. *Department of Physical Sciences building, University of Oulu. Photo: Kari Kaila.*

The University of Oulu was founded 50 years ago (1959) to promote high-level education and research in Northern Finland. The Department of Physics was established at the same time and cosmic rays and phenomena related to aurora were among the first research topics at the department. Nowadays, the Space Physics group conducts research into auroral phenomena, ionospheric, magnetospheric and heliospheric physics, the Sun and cosmic rays. The group is involved in many international projects, such as ESA's Cluster mission and the international EISCAT Association.

Research in auroral physics is based on ground-based and satellite observations. The group has constructed several different optical instruments, such as auroral TV cameras, photometers and spectrometers. Some instruments are located in Northern Finland for the entirety of the dark season (winter) and some instruments are moved to various locations in Northern Scandinavia during measurement campaigns. Auroral measurement campaigns involve experiments with the EISCAT radars in Tromsø, Kiruna and Sodankylä, as well as measurements with the EISCAT Svalbard radars. Conditions in near-Earth space are observed with the constellation of the four Cluster satellites while measurements of the solar wind impinging on the Earth's magnetosphere are obtained by satellites like ACE and Soho.

The auroral research group of the University of Oulu has extensive collaboration with its Nordic neighbours, but also with other groups all over the world. The group studies formation of auroral structures, the electric current systems associated with aurora, development of auroral and magnetospheric substorms, and the role of the solar wind in deposit-

ing energy in the high-latitude ionosphere and driving changes within the auroral oval.

2.3.3 Finnish Meteorological Institute, FMI (<http://www.fmi.fi>)

Space research is part of the research at the Finnish Meteorological Institute (FMI). Most space researchers, about 50 people, work in the FMI main office in Helsinki. FMI coordinates the ground-based instrument network MIRACLE (Section 3.2.4). The research topics that FMI focuses on include electrodynamics of the aurora and effects of energetic particle precipitation on atmospheric chemistry. But it also investigates the larger concepts such as auroral substorms and ionospheric responses to the solar wind driving as well as the coupling between the solar wind, the magnetosphere and the ionosphere. The observational large-scale studies are compared and contrasted with the magnetospheric modelling results in order to better understand the basic processes of near-Earth space.

2.4 Russia

2.4.1 Polar Geophysical Institute, Apatity, PGI (<http://pgia.ru>)

The Polar Geophysical Institute (PGI) consists of two divisions in the Murmansk region of the Russian Arctic, one located in Murmansk and one in Apatity. The institute was established in 1960 as part of the Kola Science Center of the Russian Academy of Sciences and integrated several previously-established scientific stations carrying out magnetic and optical observations on the Kola Peninsula. Today the main research topics are the structure and dynamics of the Earth's magnetosphere, physical processes of magnetospheric substorm, solar-terrestrial relations as well as effects of particle intrusions into polar areas and study of low-frequency modes in the Earth magnetosphere.

Two geophysical observatories of the institute, Lovozero on the Kola Peninsula (Section 3.2.3), and Barentsburg in the Spitsbergen Archipelago (Section 3.1.1), carry out permanent measurements of magnetic field variations and observations of northern lights. Regular observations at the cosmic ray stations in Apatity and Barentsburg are an important part of the world network for monitoring cosmic rays. A unique method of ionospheric research using the radio-tomography method was recently devised and developed by the institute.

The major goal of the institute, determining its location and history, is the detailed investigation of the upper polar ionosphere by optical and magnetic methods. Having been the leader of aurora studies in the former

Soviet Union, PGI established a division of the World Data Center of Auroral Data where the films with the unique optical materials from the Northern coast of the USSR, Antarctica and Soviet drifting stations in the Arctic were collected. PGI is involved in active cooperation with foreign scientific bodies of Finland, Norway and Sweden. Joint research on structure and dynamics of the dayside auroras in Spitsbergen is one of the most fruitful examples of such cooperation.

Figure 14. The main building of PGI in Apatity. Photo: Ingrid Sandahl

3. Facilities and instruments for measurements of optical aurora

Northernmost Europe is an excellent region for auroral studies, by many considered to be the best in the world. The climate is mild compared to other places under the auroral oval and the infrastructure is very well developed. Svalbard is the only place in the world where the dayside auroral oval can be studied in darkness. Many instruments and instrument networks for studies of the optical aurora have been set up, both by the institutions in the region and by institutions from other parts of the world. In this chapter we give an overview of the existing facilities and instruments. Locations are shown on the map in Figure 8.

3.1 Facilities in Svalbard

3.1.1 Barentsburg (<http://pgi.webhop.net>)

Figure 15. Observatory Barentsburg, Spitzbergen. Photo: PGI

Observatory Barentsburg is operated by the Polar Geophysical Institute. At present the optical equipment consists of an all-sky television camera (Figure 7) pointed toward zenith and recording the auroras in visible light. The spatial resolution is about 1 km at an altitude of 110 km near

zenith. The temporal resolution allows study of auroral processes with characteristic time less than 0.1 second. An extended set of optical instruments for auroral studies at Barentsburg as well as a new observatory building is being planned.

Figure 16 demonstrates an auroral structure that is unusual for the dayside, an auroral torch, which was registered by TV camera in Barentsburg during one of the joint observational campaigns. The all-sky image has been projected to the ionosphere and combined with ionospheric projection of the EISCAT (Tromsø) and ESR (Longyearbyen) radar beams.

Figure 16. Coordinated optical and radar measurements during the passage of an auroral torch above Spitsbergen. Left panel: The original TV image. Right panel: The ionospheric projection of the auroral image and the EISCAT (green) and ESR (yellow) beams. Picture: PGI.

3.1.2 Kjell Henriksen Observatory, Longyearbyen (<http://kho.unis.no/>)

Figure 17. The instrument section of Kjell Henriksen Observatory. Photo Fred Sigernes.

The Kjell Henriksen Observatory (KHO) is located adjacent to the EISCAT Svalbard Radar near Longyearbyen. It was inaugurated in 2008, replacing the old Auroral Station in Adventdalen. Kjell Henriksen (1938–1996) was professor of physics at the University of Tromsø and the person who started auroral observations in Adventdalen.

KHO is the largest facility of its kind in the world and consists of 30 instrument rooms with domes as well as a well-equipped service section. KHO houses instruments from a wide range of institutions from Norway, Finland, Denmark, Great Britain, Ukraine, Japan and USA. The optical instrumentation includes eight different all-sky imagers, two narrow field-of-view cameras, three spectrographs, a meridian-scanning photometer, four field-aligned photometers, three Ebert-Fastie spectrometers, a Michelson interferometer, an imaging Fabry-Perot interferometer, a scanning Doppler imager and a telescope. Additional instrumentation includes fluxgate- and search-coil magnetometers, an imaging riometer, a tomography receiver, and two auroral HF receivers. UNIS also owns and operates the SPEAR (Space Plasma Exploration by Active Radar) facility, located close to KHO.

3.2.3 Ny-Ålesund

(<http://www.kingsbay.no/>)

Eleven research institutions from ten different countries have stations at Ny-Ålesund, located at 79° N. A number of these stations have instrumentation for research on optical aurora. The Chinese Arctic and Antarctic Administration operates a 3 wavelength all-sky CCD imager at their Yellow River Station. An Ebert-Fastie spectrometer owned by UNIS is operated at the Sverdrup station of the Norwegian Polar Institute. The University of Oslo operates an all-sky camera, a four-channel meridian scanning photometer and a steerable polarization photometer, also at the Sverdrup station.

3.2 Mainland facilities and instrument networks

3.1.1 ALIS, Auroral Large Imaging System

(<http://alis.irf.se>)

ALIS is a flexible facility for studying optical phenomena in the atmosphere with scale sizes down to 100 metres and a typical temporal resolution of 5 seconds. ALIS is the first system in the world designed to obtain the three-dimensional luminosity distribution of aurora (Figure 18). This is achieved by viewing the same volume of the sky from different directions simultaneously and using tomography-like methods when analyzing

the images. ALIS is owned and operated by the Swedish Institute of Space Physics.

Figure 18: Perpendicular profiles of an auroral arc system. The distance between the profiles is 30 km. They were computed from ALIS images using a tomography-like method. Picture: Björn Gustavsson.

The map in Figure 19 shows the locations of the ALIS stations. There is also a mobile station mounted in a minibus. The right part of Figure 19 was taken during a winter service visit to one of the stations. To avoid light pollution the stations are placed at some distance from roads.

The ALIS imagers are equipped with filter wheels. For auroral studies usually the green and red oxygen lines, the blue nitrogen line and an infrared oxygen line are measured. The imagers are sensitive enough for detailed studies of subvisual aurora and can also give absolute intensities so that each pixel can act as a photometer. They can be pointed in any direction. The measurement sequences are usually programmed in advance, but can also be commanded in real time. The whole system is remote controlled via Internet and all data are freely available on the web.

IRF also operates an all-sky camera in Kiruna. Real time data, as well as all data since 2001, are found at <http://www.irf.se/allsky>.

Figure 19. Left: Locations of the Auroral Large Imaging System stations. Rings show stations with cameras during 2008–2009. Squares show more southern stations suitable for studies during solar maximum. Right: Service visit to the Silkkimuotka station.

3.2.2 Esrangle/KEOPS

(<http://www.ssc.se>)

KEOPS is here the acronym for the Kiruna Esrangle Optical Platform System. It is located on the top of the mountain Pahtavaara adjacent to Esrangle Space Center and well away from all city lights and public roads. The only road to the site goes from the gated Esrangle A-zone. The hilltop has been cleared so that it offers an unobstructed view in all directions. Instruments at KEOPS include an EMCCD camera for studies of small-scale auroral structures from Tohoko University, Japan, an FT-IR spectrometer from Korea Polar Research Institute, KORDI, Incheon, and a Fabry-Perot Interferometer from University College London.

3.2.3 Lovozero

Observatory Lovozero is located close to the village Lovozero which is sometimes called the Sámi capital of Russia. It is operated by the Polar Geophysical Institute. Present optical instrumentation consists of an all-sky television camera of the same type as the one at Barentsburg. Figure 21 demonstrates an example of a registration of short-lived auroral forms – pulsating patches – above Lovozero. In this figure the all-sky image has been projected to the ionosphere and been combined with the projection of a CLUSTER satellite pass.

Figure 20. Observatory Lovozero, Kola Peninsula, the optical pavilion. Photo: PGI.

Figure 21. Aurora-satellite conjugation: pulsating auroras observed above Lovozero during the passage of the CLUSTER satellites. Picture: PGI.

3.2.4 MIRACLE

(http://www.fmi.fi/research_space/space_58.html)

The Magnetometers – Ionospheric Radars- All-sky Cameras Large Experiment (MIRACLE) is an instrument network for studies of aurora and auroral electrodynamics, and is maintained and operated as an international collaboration under the leadership of the Finnish Meteorological Institute. It consists of auroral imagers, magnetometers and an ionospheric radar system.

The network covers an area from subauroral to polar cap latitudes over a longitude range of about two hours of local time. Continuous optical recordings started in 1973, when film cameras were still used in monitoring the auroral activity. The new generation digital instruments replaced the old film devices in 1996, and during the last few years the upgrade of technology has brought in high-sensitive EMCCD and colour CCD instruments. The locations of the cameras are shown on the map in Figure 8. Except for the colour cameras, they are all operated with filters measuring the important auroral emissions at 427.8 nm, 557.7 nm and 630.0 nm. In addition to the three main wavelengths of the auroral emissions, the EMCCD imagers also use background filters offset about 10 nm from the auroral emissions, so that stars, the moon and any scattered artificial light can be reduced. Sodankylä Geophysical Observatory owns and runs an ICCD and an EMCCD imager as a part of the MIRACLE network.

Figure 22. Work with the MIRACLE camera in Longyearbyen, Svalbard. Photo: Noora Partamies.

3.2.5 Misato IRF Abisko (MIA) Camera

(<http://www.abisko.nu/vinter/aurorawebcam/index.html>)

The MIA camera is a low-cost auroral all-sky camera system aimed at monitoring, education and event identification. The project is a collaboration between Misato Observatory, an observatory-type museum in Japan, the Swedish Institute of Space Physics, and Abisko Tourist Station. The colour CCD camera system was developed and is owned by Misato Observatory. One camera is installed in Abisko and has been operated there by the tourist station since 2005, and another camera is installed at IRF, Kiruna. One auroral image per minute is webcast in real time. Every morning an mpeg movie with 20 second resolution is produced of the past 24 hours and archived at IRF.

3.2.6 Pittiövaara

All optical instrumentation of SGO is located at the site station on Pittiövaara (67.42°N, 26.39°E). The station has a radiolink network connection to SGO, providing convenient remote operation. The two MIRACLE cameras are installed under one common dome in a camera hut on the roof of the station building. During the dark measurement season one of the University of Oulu scanning photometers is also located there. This instrument is usually brought to the EISCAT site at Ramfjord near Tromsø during the Finnish EISCAT campaigns. The station also hosts a 630.0 nm Fabry-Perot interferometer and a colour camera from the University College London (UCL), UK.

Figure 23. The University of Oulu scanning photometer. The rotating mirror is clearly visible inside the plexiglass cover. Photo: Carl-Fredrik Enell.

3.2.7 Optical instruments in Ramfjord

(<http://uit.no/fysikk/romfysikk/3>, <http://www.stelab.nagoya-u.ac.jp/~eiscat/data/EISCAT.html>,
<http://www.dcs.lancs.ac.uk/iono/dasi/>.)

Ramfjord, 14 km SE of Tromsø, is the location of the Tromsø EISCAT site and the EISCAT heating facility. A number of optical instruments are placed at this site or in its vicinity.

The Institute of Physics and Technology, Tromsø University has built and operated the Tromsø Adaptably Combined Optical Platform (TACO) giving background observations in white light and 5577 Å with a medium field-of-view. This gives good support to EISCAT observations aimed at anything related to aurora. Further campaign based observations have been performed with the Odin imager and with the newly developed EMCCD imager system.

The Solar Terrestrial Environment Laboratory of the University of Nagoya, Japan, operates a large set of optical instruments including a digital colour camera, a four-channel photometer and a multi-wavelength all-sky imager.

DASI (Digital All-sky Imager) is a low-light level camera owned by Lancaster University, UK.

3.3 Mobile instruments

3.3.1 ASK, Auroral Structure and Kinetics

(<http://www.spp.ee.kth.se/res/tools/gb/ask/>)

The ASK (Auroral Structure and Kinetics) instrument consists of three low light narrow field-of-view imagers and two photometers, fitted with narrow passband interference filters. The instrument was designed to study the fine-scale aurora at very high temporal and spatial resolution. Galilean converters are used with the imagers, providing a field-of-view of only $3.1^\circ \times 3.1^\circ$, which corresponds to 5 km $\times$ 5 km at 100 km altitude. Images can be acquired at a framerate of more than 30 Hz. The detectors are Andor iXon back-illuminated Electron Multiplying CCDs (EMCCDs).

ASK is a collaboration between the Space Environment Physics group at University of Southampton, UK, and the Space and Plasma Physics group at the Royal Institute of Technology (KTH), Sweden. Since 2005/2006 ASK has been installed at the EISCAT Svalbard Radar (ESR) site, and operated jointly with the Spectrographic Imaging Facility (SIF) and ESR. In 2006/2007 it was temporarily moved to the EISCAT site in Ramfjordmoen, Tromsø, where it was used during tristatic radar campaigns as well as ionospheric heating campaigns.

Figure 24. Left: The ASK instrument, deployed on a shelf outside the ESR control building. Right: The ESR facility on Svalbard, with the control building where ASK is placed, between the 32-metre and 42-metre antennas. Photos: Hanna Dahlgren.

3.3.2 Optical instruments in University of Oulu

Optical instruments for auroral research have been used at the University of Oulu since 1986. The first instruments were a monochromatic TV-camera and a five-channel scanning photometer. After that several kinds of optical auroral instruments have been developed or revised: scanning photometers, zenith photometers, real speed auroral cameras, CCD cameras, spectrometers and an imaging auroral spectrograph. Several of them are in operation during winter nights at the auroral stations, and all of them are operated in auroral campaigns.

The University of Oulu photometers have 5 or 6 photometer tubes or channels. Scanning photometers have been used in Sodankylä, Karesuvanto, Kilpisjärvi and Ramfjord/Tromsø. Zenith photometers have been used mainly in Kilpisjärvi and Sodankylä.

Beside the photometers, auroral cameras are needed in order to see what kinds of aurora there are in the sky and what the weather conditions are like. The first auroral camera recorded the aurora through similar filters to those in the photometers. Later cameras have been used without filters. Two cameras take images which are recorded by VHS video recorder and they take 25 frames/sec. Three other digital cameras need a computer that controls the cameras and stores the images to their hard disks. These cameras can take several or several tens of images per minute.

From 1986 until 2007 the auroral recordings were made with the real speed cameras. There are about 1500 video tapes of auroral data in Oulu. After 2007 the routine images are taken with the digital cameras and the real speed cameras are used only in special auroral campaigns.

The imaging auroral spectrograph is used in special auroral campaigns.

4. Network for Groundbased Optical Auroral Research in the Arctic Region

4.1 Goals of the network

(<http://www.irf.se/nordopt>)

By its very nature research on the aurora is an international activity. The aurora is a global phenomenon, and only a part of it can be observed from a single site. International collaboration in the field has a more than 250 years history. When the Nordic Council of Ministers announced their call for an Arctic co-operation programme 2006–2008 it stimulated the formation of Network for Groundbased Optical Auroral Research in the Arctic Region and the grant given to the network enabled more extensive contacts.

The goals of the network are to strengthen the collaboration between research groups in the European Arctic region working in the field of optical auroral research and to conduct excellent scientific work. According to the original application this was to be done by:

- Conducting dedicated workshops for scientists and Ph. D. students.
- Conducting a mobility programme making it possible for each participating group both to send and to receive at least one person per year.
- Organizing a common Ph. D. course.
- Providing stipends for Russian scientists to attend the Optical Meeting in Kiruna in 2006.

The grant received was sufficient for all these activities except the Ph. D. course. We have conducted three workshops. In the mobility programme fourteen visits have been carried out. Thanks to the grant eleven Russian scientists could attend the Annual European Meeting on Atmospheric Studies by Optical Methods in Kiruna in 2006 and two the corresponding meeting in Andøya in 2007.

In this chapter we describe the workshops, the mobility programme and outreach activities. Scientific results are presented in Chapter 5. Additional information about the network, including the complete application and detailed workshop programmes, is found on the network web page, <http://www.irf.se/nordopt>.

4.2 Workshops

4.2.1 Sodankylä workshop 2007

(<http://www.sgo.fi/Events/NordAuropt/>)

The first workshop of the network was held at Sodankylä Geophysical Observatory during the week of February 19–23, 2007. From the point of view of the network Sodankylä is in a central location. In total there were 23 participants, out of which nine were from Sodankylä, four from Oulu, three each from Apatity and Kiruna, two from Tromsø, one from Longyearbyen and one from Stockholm.

Figure 25. Participants in the Sodankylä workshop. Standing from left: Antti Kero, Johannes Kulima, Boris Kozelov, Kari Kaila, Tima Sergienko, Torsten Aslaksen, Alexander Kozlovsky, Urban Brändström, Björn Gustavsson, Jyrki Manninen, Timo Pitkänen, Rico Behlke, Carl-Fredrik Enell, Vladimir Safargaleev, Esa Turunen. Sitting: Anita Aikio, Ingrid Sandahl, Hanna Dahlgren. Missing: Ingrid Cnossen, Tatiana Kornilova, Boris Kozelov, Tero Raita, Tauno Turunen and Thomas Ulich. Photo: Tero Raita, SGO.

The programme consisted of a mixture of invited tutorial presentations, status reports from the different groups, work on scientific topics in splinter groups, study visits, planning of joint future measurement campaigns and activities to get to know each other better. The complete conference programme is available on the conference home page at SGO. PDF-files of some presentations are found on the network home page.

There were four tutorial lectures given by workshop participants with special expertise. Vladimir Safargaleev from PGI talked about auroral signatures of magnetospheric processes. Two talks were about processes in the ionosphere. Tima Sergienko from IRF described the production of auroral emissions and Esa Turunen from SGO lectured on the chemical

effects of particle precipitation. Urban Brändström from IRF discussed calibration of optical instruments.

Before the workshop participants had been asked to identify and suggest potentially interesting topics and events for joint studies. These topics were presented and several splinter groups were formed. About half of the programme time was devoted to work in these splinter groups, and at the end of the workshop the groups presented their results. Most people participated in more than one splinter group, and on the whole the scheduling worked well.

Study visits were made to the different observing sites of SGO and FMI in the area, including Pittiövaara (Section 3.2.6). In Figure 26a some network participants are reflected in the MIRACLE dome at Pittiövaara. Figure 26b was taken during the visit to the calibration facility for the MIRACLE cameras. Calibration of optical instruments, in particular imagers, is a topic of great importance, since the field is moving towards much more quantitative and sophisticated measurements.

Figure 26. Study visits during the first workshop. (a) The MIRACLE camera at Pittiövaara. (b) The FMI calibration facility for optical instruments. This is an integrating sphere that is used to generate an area with uniform light intensity. Photos: Carl-Fredrik Enell and Ingrid Sandahl.

Some time was devoted to the planning of outreach activities and activities related to the International Polar Year. One topic here was analysis of photos taken from the space shuttle Discovery in December 2006 by the Swedish astronaut Christer Fuglesang. During the flight, network members had performed coordinated ground-based measurements. Work on a popular science article based on this was initiated. We also saw how tourists can learn about the Northern Lights during a visit to the Aurora House near Sodankylä.

During the first workshop activities to get to know each other were particularly important. Sodankylä municipality hosted an icebreaker reception and also sponsored the workshop sauna at Kommattivaara and the workshop dinner at Portin pirtti. At Kommattivaara some participants also took the opportunity to test the local ski trails.

4.2.2 Tromsø workshop 2008

The second workshop was held in Tromsø, Norway, April 7–11, 2008. There were ten participants, one from Russia, four from Finland, four from Sweden, and one from Norway. One of the Finnish participants came from FMI in Helsinki and one of the Swedish from KTH in Stockholm. The venue was Tromsø Museum, where we also got a special tour of the exhibition, including its presentation of the aurora. The display includes a modern version of the famous terrella experiment of Kristian Birkeland, designed to investigate the role of charged particles from the sun in the generation of aurora. Evening sessions were held at the Department of Physics/Northern Lights Observatory.

Figure 27. Participants in the Tromsø workshop. From left: Kari Kaila, Carl-Fredrik Enell, Hanna Dahlgren, Anita Aikio, Sanna Mäkinen, Urban Brändström, Vladimir Safargaleev, Tima Sergienko and Ingrid Sandahl. Missing: Björn Gustavsson. Photo: Björn Gustavsson.

The programme largely followed the format of the previous workshop. Two tutorials were given. Björn Gustavsson, UiT, presented a review about auroral tomography and Professor Unni-Pia Løvhaug, also from UiT, talked about Naturally Enhanced Ion Acoustic Lines, so called NEIALs. Joint data analysis of previously identified topics continued, now going into more depth.

Tromsø University has a group active in laboratory plasma physics. Professor Åshild Fredrikssen gave a tour of the laboratory including Njord – a new plasma device for space related plasma experiments. She also gave a lecture on ion cyclotron heating in laboratory and space plasmas.

Figure 28. Group discussion during the Tromsø workshop. Photo: Hanna Dahlgren.

4.2.3 Kiruna workshop 2009

The third and final workshop to be financed by the first NCM grant was held 24–29 May, 2009, at the Swedish Institute of Space Physics in Kiruna. There were 14 participants, four from Apatity, one from Sodankylä, three from Oulu, one from Helsinki, one from Stockholm, one from Tromsø and three from Kiruna. At this workshop a larger fraction of the time was devoted to work in splinter groups. This was given highest priority since we wished to bring initiated projects closer to completion. There were splinter groups on the efficient use of EMCCD cameras; electric field measurements; theory of aurora; tomography and spectroscopy and nitric oxide; analysis of campaign data from Alaska; analysis of an auroral event 23 november 2006; planning of coordinated campaigns; and work on this TemaNord report.

A topic of great interest to the optical community is the future of incoherent scatter radars in northern Fennoscandia. Late in 2008 the project EISCAT_3D was included in the ESFRI roadmap. ESFRI is the European Science Forum on Research Infrastructure. EISCAT_3D, if realized, will make it possible to measure several properties of the ionosphere in three dimensions. The combination of EISCAT_3D with modern optical instruments will make it possible to tackle a vast range of unanswered questions regarding auroral processes. Simultaneously with the network workshop an EISCAT_3D User Meeting was held in Uppsala. At the beginning of our workshop Professor Asta Pellinen-Wannberg informed us of the plans for a first part of EISCAT_3D and this was followed by a

discussion about the role of EISCAT_3D in research on the aurora. On the last day of the workshop a contribution was given to the meeting in Uppsala via telephone.

Figure 29. Participants in the Kiruna workshop. Back row from left: Urban Brändström, Kari Kaila, Ilya Kornilov, Vladimir Safargaleev, Alexander Kozlovsky, Irina Golovchanskaya. Middle row: Carl-Fredrik Enell, Anne-Maaria Ahonen, Björn Gustavsson, Sergey Chernouss. Front row: Tima Sergienko, Hanna Dahlgren, Ingrid Sandahl, Noora Partamies. Photo: Torbjörn Lövgren, IRF.

4.3 Mobility program

Within the mobility programme the following 14 visits have taken place:

Andrey Kirillov from PGI visited UNIS, Longyearbyen, 21 November–3 December, 2006, for detailed theoretical studies of reactions in the ionosphere, in particular processes related to proton aurora. The work has so far resulted in two papers in *Annales Geophysicae*.

Urban Brändström from IRF and *Björn Gustavsson* from UiT visited Skibotn Field Station, Norway, 21–25 May, 2007, for joint instrument work on EMCCD imagers.

Tima Sergienko from IRF visited University of Oulu, 28 May–8 June, 2007, to deduce densities of nitric oxide and oxygen from optical and radar measurements.

Björn Gustavsson from UiT visited Sodankylä Geophysical Observatory, 17–27 August, 2007, to work with Carl-Fredrik Enell on using radiance data from ALIS calibrated by means of star spectra as input to the Sodankylä Ion-Neutral Chemistry model. The goal was to obtain the production of odd nitrogen.

Darya Shibaeva, Kola Branch of Petrozavodsk State University, spent 23 August–21 September, 2007 working with Tima Sergienko at IRF, Kiruna. The purpose of the visit was to start the analysis of pulsating auroras registered by ALIS. Preliminary results of the study were presented at the International Conference on Problems of Geocosmos St. Petersburg, Russia, 26–30 May 2008.

Hanna Dahlgren, KTH, spent 26–30 November, 2007, working with Anita Aikio and Kari Kaila at Oulu University. The purpose of the visit was to continue the collaboration on common high resolution measurements of an auroral event exhibiting curls and folds. The project was started during the first network workshop in Sodankylä. A paper has been submitted to *Geophysical Research Letters*.

Urban Brändström visited UiT, Tromsø, 3–7 April, 2008, for continued work with Björn Gustavsson on EMCCD imagers and calibration issues.

During 12–16 May, 2008, *Carl-Fredrik Enell* visited Jacek Stegman and Jonas Hedin at the Department of Meteorology, Stockholm University, to start analysing data from the Hotel Payload 2 rocket campaign that took place on Andøya in January–February 2008.

Anita Aikio and *Carl-Fredrik Enell* participated in the ASK Workshop at KTH, Stockholm, 24–26 June, 2008, where among other things the analysis of the fold/curl study continued. An article describing the results has been submitted.

Urban Brändström visited UiT, Tromsø, 13–16 October, 2008, for instrument work.

In connection with the Finnish EISCAT campaign in November–December 2008 *Carl-Fredrik Enell* visited UiT for 3 days to work on ALIS geometrical calibration and tomography for a few cases including the Hotel Payload 2 campaign.

Multi-station multi-monochromatic studies of the aurora are possible by combining the ALIS, ASK and EISCAT data sets and analysis tools from our different institutes. Such a study was initiated during the network workshops, and the study made good progress when *Björn Gustavsson* visited the Space and Plasma Physics group at KTH during 11–22 December 2008.

4.4 Outreach activities

The aurora is a fascinating phenomenon and there is a strong interest from the public to see aurora and learn more about it. Network participants have conducted a number of activities to spread information about aurora and auroral research. Activities include public popular science presentations in various places, lectures to school teachers, visits in schools and study visits by school children at our institutions, contributions to popular science programs on TV and radio and contributions to an open house event.

Our collaboration with the Swedish astronaut Christer Fuglesang regarding photography of aurora from the space shuttle Discovery in December 2006 resulted in an article in the Swedish popular science journal *Forskning och Framsteg* in 2008.

An outreach event related to the International Polar Year was organized during the Kiruna snow festival in January 2008. A number of presentations on space research were given including one about the Russian - Swedish auroral measurements in Svalbard 1899–1900. They were webcast to the Polar Gateways 2008 conference in Barrow, Alaska, as well as to the public worldwide.

5. Research projects conducted within the network, descriptions and first results

5.1. High resolution study of auroral folds, curls and structuring taking place on several spatial scales

H. Dahlgren, A. Aikio, K. Kaila, N. Ivchenko, B. Lanchester, D. Whiter, and G. Marklund

Quasi-periodic deformations of auroral arcs have long been observed and categorized into spirals, folds and curls. Spirals appear on the largest scale with a diameter of the order of 100 km and they appear typically during an auroral substorm. Folds are loops in the arc with a diameter of about 20 km. Curls are the smallest scale distortions (1–10 km) described hitherto with a counter-clockwise rotational sense when viewed from the ground in the northern hemisphere. They manifest themselves as a series of vortices, most often in motion along the arc. It is commonly assumed that the curls are produced by the Kelvin-Helmholtz instability driven by magnetospheric flow shear across the sheet of electrons producing aurora.

During the night of 23 November 2006, an auroral arc evolving into folds and curls was observed by ground-based optical instrumentation and measured by the EISCAT radar in Tromsø. The unique feature of this event was that it was observed simultaneously with two different field-of-view high-speed cameras. The ASK camera (Section 3.3.1) was able to resolve very small-scale (100s of metres) features, but was not able to see the arc in its full width. The University of Oulu auroral camera with its larger field-of-view showed that the arc was 5–8 km wide, and how folds and curls developed and travelled eastward along the arc (Figure 30). The arc moved in the north-south direction and came occasionally into the field-of-view of the ASK camera. The ASK camera revealed a new feature that has not been observed previously: small-scale boundary undulations were superimposed on curls and folds (Figure 31). Because of the appearance of these undulations, a new name, “ruff”, was given to them. Ruffs moved at the edge of folds or curls in the opposite direction to that of the larger-scale features. Ruffs typically have wavelengths of less than 3 km and amplitudes of less than 800 m and their velocity is about 10 km/s. The first theoretical calculations suggest that the Kelvin-Helmholtz instability, at least alone, cannot explain the observations. The study has been presented at the COSPAR conference in Montreal in July 2008 and

it has been submitted to Geophysical Research Letters for publication. A longer paper with more profound analysis of all data is in preparation.

Figure 30. Auroral folds as observed by the University of Oulu wide field-of-view auroral camera. The yellow square indicates the field-of-view of the ASK camera.

Figure 31. The ASK camera images from the fold shown in Figure 30. Auroral ruffs (enhanced by the white colour in some of the frames) appear at the edge of the fold and they move in the direction shown by the arrow. The fold itself moves in the opposite direction.

5.2 Combined multi-station multi-monochromatic optical and incoherent scatter observations of small-scale aurora

B. Gustavsson, H. Dahlgren, N. Ivchenko, U. Brändström, B. Lanchester, T. Sergienko, I. Sandahl, and M. Ashrafi

A detailed analysis of small-scale auroral structuring is made possible by combining a rich and unique set of optical and incoherent scatter radar

data. On December 12, 2006, the high resolution ASK instrument was operated from Tromsø. Structured aurora was recorded at a framerate of 32 Hz and with a field-of-view of just $3^\circ \times 3^\circ$. Simultaneous multi-viewpoint observations of ALIS allowed for determination of the three-dimensional distribution of volume emission rates. From the altitude variation of the 427.8 nm emission data, the electron precipitation flux was determined and compared with the fluxes obtained from EISCAT observations. The temporal variation of the electron flux was then compared to the temporal variation of structures and spectral intensities observed with ASK. Preliminary results were presented at the 36th Annual European Meeting on Atmospheric Studies by Optical Methods, Maynooth, Ireland, August, 2008.

5.3 Enhanced electric field inside an auroral arc inferred from coordinated EISCAT and ALIS observations

V. Safargaleev, T. Sergienko, A. Kozlovsky, I. Sandahl, U. Brändström, D. Shibaeva

According to theoretical predictions an auroral arc is a region of enhanced conductivity produced by electron precipitation. For this reason, the electric field within the arc should be smaller than outside. This is in agreement with most observations. In 1981 there were some events reported where the electric field inside the arc increased and appeared to be correlated with the conductivity, but these observations were questioned. After that no clear cases of the “correlating arcs” were reported and a small field inside the arc became regarded as the only possibility. Our paper is a case study of coordinated radar (EISCAT UHF) and optical (ALIS) measurements of a series of auroral arcs (Figure 32a) made during the moment of their generation. The electric field was enhanced every time when the newly appearing arc crossed the EISCAT beam (Figure 32b). These observations have sufficiently high temporal and spatial resolution to verify the presence of “correlating arcs”. We suggest that the ionospheric conductivity is not the only factor affecting the electric field inside and around the appearing arcs. In particular, the E-field could increase inside the arcs due to development of the interchange instability that may also be responsible for their formation. The study was published in *Geomagnetism and Aeronomy* in 2009.

Figure 32. (a) The geometry of the observations. Red and green polygons are fields-of-view of ALIS imagers located in Skibotn and in Kiruna, the black line is the projection of the EISCAT beam. (b) Keogram showing the arc dynamics. (c) EISCAT measurements of ionospheric parameters in the arc vicinity. Indices “0” and “1” refer to the background and disturbed values of the parameters.

5.4. Features of pulsating arcs inferred from ALIS triangulation measurements

V. Safargaleev, D. Shibaeva, T. Sergienko, I. Sandahl, U. Brändström

Pulsating auroras are characterized by repetitive intensity modulation in the auroral luminosity. In contrast to discrete auroras, the properties of pulsating auroras are less investigated, since one needs instruments of high sensitivity as well as rather high temporal and spatial resolution for their study. ALIS was designed to handle short-lived, small-scale auroral forms of low intensity. We concentrate in this ongoing project on investigation of one type of pulsating auroras – series of pulsating arcs.

It is well known that the altitude of the aurora gives information about the energy of electrons causing the luminosity. Triangulation using images from different ALIS stations shows that the altitude of the arcs was different for different arcs in a series but did not vary with the intensity variation in each individual arc within one “switch on/off” cycle. This means that the electron precipitation responsible for the formation of the pulsating arcs was caused by scattering into the loss cone via wave-particle interaction rather than by field-aligned acceleration in a parallel electric field.

These preliminary results were presented at the International Conference on Problems of Geocosmos in St. Petersburg, Russia, 26–30 May 2008.

5.5 Optical, radar, and magnetic observations of the magnetosheath plasma capturing during a positive impulse in IMF Bz-component.

V. Safargaleev, A. Kozlovsky, T. Sergienko, T.K. Yeoman, M. Uspensky, D.M. Wright, H. Nilsson, T. Turunen, and A. Kotikov

The entrance into the dayside magnetosphere of solar wind plasma plays an important role in the magnetosphere. It couples solar wind energy and momentum to near-Earth space and may lead to different magnetospheric disturbances. Theoretically, the penetration of solar wind plasma through the magnetopause is possible by a number of different mechanisms of which one, magnetic merging, is commonly regarded as dominant. So, when analyzing data from just one or a few instruments, one tends sometimes to rely on the most widespread interpretation of the observed phenomena, ignoring other possibilities. For instance, so-called Poleward Moving Auroral Forms (PMAF) observed near local noon are frequently regarded as a signature of dayside reconnection. However, one should be wary of using them to locate the cusp or the boundary between open and closed magnetic field lines, because such auroras may occur independ-

ently of the IMF conditions, appearing sometimes on closed magnetic field lines, and can be generated via field line resonances or the development of the Kelvin-Helmholtz instability. A reliable interpretation in a case study can be achieved by joint analysis of the data obtained simultaneously from different instruments. Unfortunately, such multi-instrument studies of the dayside ionosphere are still rare.

In the present paper we analyze multi-instrument observations of the high-latitude near-noon ionosphere responding to a short-lived northward excursion of the IMF B_z component. The data were collected during a joint Swedish-Finnish-Russian coordinated optical and radar campaign in Spitzbergen (Fig. 33a). The data set includes optical observations, ionospheric flows obtained from the EISCAT and CUTLASS radars (Fig. 33b), the spectral width of the HF radar backscatter, particle precipitation and plasma flow data from the DMSP F13 satellite (Fig. 33c), as well as Pc1 frequency band pulsations observed by induction magnetometers.

Prior to IMF turning northward, three auroral arcs were observed at the poleward boundary of the closed low latitude boundary layer (LLBL), inside the LLBL, and in the equatorward part of the LLBL, respectively. The northward IMF turning was accompanied by enhanced HF radar returns with a broad Doppler spectrum collocated with the arcs, which we associate with the ionospheric footprint of a just-reconnected magnetic flux tube. The auroral arcs shifted poleward whereas the backscatter region moved in the opposite direction, which is consistent, respectively, with reconnection beyond the cusp and the capturing of magnetosheath plasma during northward IMF. The local magnetic noise enhancement in the Pc1 frequency band occurred simultaneously with the anomalous radar backscatter that also supports the hypothesis on the plasma capturing.

Figure 33. (a) Location of the instruments in the region of observations. Light and dark gray areas indicate the CUTLASS and TV camera field-of-view, respectively. (b) Optical auroras and ionospheric convection model (green curves) inferred from EISCAT and CUTLASS measurements shown with red and blue arrows. The green cross is the assumed position of the focus of the high latitude reverse cell. (c) The DMSP trajectory mapped on the TV frames. The cross shows the DMSP position at the moment indicated on a frame. The green fragment corresponds to LLBL. Red arrows are the components of plasma velocity perpendicular to the DMSP trajectory.

Finally, we discuss possible interpretation errors which may be caused by limited observational data. In particular, it is shown that in the absence of reliable IMF, plasma flow and precipitation data, one could interpret the optical and CUTLASS data as a typical PMAF event generated by cusp reconnection driven by southward IMF, whereas the more complete data set is consistent with the ionospheric response to the IMF turning northward. The results were published in *Annales Geophysicae* in 2008.

5.6 Scaling behaviour of auroral luminosity

I. Golovchanskaya, B. Kozelov, T. Sergienko, U. Brändström, H. Nilsson, I. Sandahl

Auroral images obtained by ALIS have been examined in order to study scaling properties of spatial variations in auroral luminosity. The images under examination were obtained during substorm conditions and contained active auroral forms of different types. It is shown that the data series for substorm auroral forms often reveal closeness to self-similarity, the scaling characteristics being very similar for auroral fluctuations observed in different emission lines. This study was published in *Journal of Geophysical Research* in 2008.

Figure 34 illustrates the statistical characteristics of auroral variations observed in ALIS images shown in upper panels and containing substorm auroral spots. A characteristic behaviour of the kurtosis, power-law scaling of the standard deviation, non-Gaussian PDFs and a well-pronounced collapse of re-scaled PDFs point to a turbulent nature of the considered variations.

5.7 Intermolecular energy transfers in electronic energy quenching for molecular collisions N_2 - N_2 , N_2 - O_2 , O_2 - O_2 .

A. Kirillov

The interaction of auroral electrons and protons with atmospheric N_2 and O_2 molecules causes the electronic excitation of the molecules. Some of the energy is emitted as auroral photons. But in many cases the excited molecules collide with other molecules, transferring energy and finally the excitation energy is accumulated in the lowest metastable states of N_2 and O_2 . As a result photons of a different wavelength will be emitted. Such intermolecular energy transfer is very important at altitudes below 100 km.

In order to calculate the intensities of different emissions it is necessary to know a large set of electronic energy quenching rate coefficients. Measurements of these coefficients exist for a few vibrational levels, but are needed for several more. In this study theoretical coefficients have been derived for vibrational levels from 0 to 25. The agreement with measured coefficients is excellent.

Much of this work was conducted during an exchange visit to UNIS. The results have been published in *Annales Geophysicae* in 2008.

Figure 35. Calculated quenching rate coefficients of the processes $N_2(A^3\Sigma_u^+, v) + N_2$ (solid line) and $O_2(a^1\Delta_g, v) + O_2$ (dashed line). Experimental data are shown as crosses, squares and triangles.

5.8 Modelling electron density and NO_x changes

B. Gustavsson, C.-F. Enell, E. Turunen, T. Sergienko, U. Brändström

Nitric oxide is one of the most important minor constituents of the atmosphere. It is an important ionisable component of the lower ionosphere, a radiator and important for ozone chemistry. Thus it affects the temperature profile of the middle atmosphere. Nitric oxide is produced by photochemistry driven by UV radiation from the sun and by energetic particle precipitation – aurora, solar protons and relativistic electrons.

During the polar winter, NO_x (NO and NO₂) is long-lived and subsides in the polar vortex. Thus the aurora is a possible mechanism for coupling solar activity to changes in the structure of the atmosphere.

In this project we use data from ALIS and other cameras when available to estimate the volume emission rates of the molecular nitrogen ion first negative (blue) and the oxygen green line emissions. Based on these emission rates the production and initial concentration of nitric oxide can be estimated using existing chemistry models.

Initial results were presented at the 34th Annual European Meeting on Atmospheric Studies by Optical Methods, Andøya, August, 2007.

5.9 Application of AIDA (ALIS data analysis package) to data from other imagers

B. Gustavsson and N. Partamies

This is a project in which the distribution of sizes of auroral arcs will be studied. The collaboration regarding AIDA was initiated within the network and is now carried out within a project funded by the Finnish Ministry of Education.

Tomography is a 3-dimensional reconstruction of an object that has been viewed from different angles. It is a method that was invented for medical science purposes, but tomography-like methods can also be applied to auroras. This project aims to explore how methods developed for ALIS data work for colour imager data. So far, auroral tomography has only been performed for filtered auroral images. The “sanity” check on the colour data from Canadian narrow field-of-view imagers seems promising, which is why this work was initiated in the Optical meeting in Andøya, 2007. With a working tomography software, both the altitude of the mid-scale aurora and the width of the auroral structures can be more accurately investigated.

5.10 History of auroral research

S. Chernouss and I. Sandahl

In 1899–1902 a joint Russian and Swedish expedition to Spitzbergen was organized to measure the length along the surface of the Earth of one degree along a meridian. In order to be able to start the geodetic work early in the spring it was decided to winter over. The academies of sciences in the two countries recommended taking the opportunity to perform other measurements as well, among them measurements of aurora. The responsibility for these was given to Jonas Westman at the Swedish station Treurenberg Bay and to Joseph Sykora at the Russian station Konstantinovka. Excellent observations were carried out with the best optical instrumentation available at that time, the first photographs of aurora in the high Arctic were taken (Figure 36), and new spectral lines in ultraviolet were discovered. In this history project the work of Westman and Sykora has been described and some of their data re-analyzed. The results have been presented at a number of conferences and have been published in a paper in *Annales Geophysicae*.

Figure 36. The first photos of aurora in the high Arctic were taken in 1899–1900 during the Russian-Swedish expedition to Spitzbergen.

6. Conclusions

6.1 Experiences gained

It takes some time to start a network. When participants are busy at their home institutions the network activities must feel valuable enough to be given high priority. Therefore the timeline has been stretched somewhat as compared to the original plan. The time span of three years has turned out to be very appropriate. We can now conclude that we have succeeded in achieving the goals of the Auroral Optical Network. Contacts between research groups and friendship between scientists have deepened. A number of new joint studies have been started. Some have already led to publications, but more are in the data analysis phase.

The combination of workshops and mobility programme has worked well, but exchange visits have been shorter than originally anticipated, typically one week. The main reason for this is that most scientists have many duties including measurement campaigns and teaching and it is difficult to fit in longer periods away.

The grant has gone further than anticipated, mainly because participants have used inexpensive travel and accommodation.

The UNIS group has used a smaller fraction of the project money than expected. One reason for this is that there has been much emphasis on measurements in Svalbard during the International Polar Year and the work to start up the Kjell Henriksen Observatory has been very demanding. The group has also had access to Norwegian funding for exchange with Russia.

Quite early it was concluded that we should also include groups in Stockholm, Helsinki and Oslo in the network activities, since these groups are responsible for important optical instrumentation and have considerable expertise. The groups at KTH (Stockholm) and FMI (Helsinki) have participated during the present grant period. The group at the University of Oslo is a partner of the new grant.

6.2 Evaluation of the network

An evaluation of the network has been conducted by Dr. Steve Milan of the Radio and Space Plasma Physics Group, Department of Physics and Astronomy, University of Leicester. As background material Dr. Milan has used the application, status reports and interviews with different network participants. Some interviews have been conducted during the 2009 conference of the European Geophysical Union and some via telephone. The

overall conclusion is that the network has been successful in achieving its goals. The full evaluation report is available on the network web page.

6.3 The road ahead

Good experiences from the first network period led participants to submit an application for an extension early in 2009, now also fully including institutions from Helsinki, Stockholm and Oslo. This means that now all groups in Norway, Sweden, Finland and the Kola Peninsula active in optical aurora research are full network partners. A grant of DKK 230000 for 2009 was awarded. The full application is available on the network web page. The list below shows the goals as they are listed in the application:

1. Conduct one dedicated workshop per year for scientists and Ph. D. students in the field of Optical Auroral Research.
2. Conduct a mobility programme making it possible for each participating group to send one person to visit to one of the other groups or to receive one visitor each year.
3. Organize an Optical School for young scientists combined with a common Ph. D. course on Optical Aurora Research at one of the sites in the time frame 2010–2011.
4. Provide a total of 15 stipends during the project period for participation in the Annual European Meetings on Atmospheric Studies by Optical Methods.
5. Produce 1–2 first author papers in refereed journals per group per year as a direct result of the collaboration.
6. Carry out activities each year within each group to inform the public about aurora and auroral research.
7. Create a roadmap for future optical instrumentation for auroral studies in northern Europe.
8. Produce a booklet about the project and about the research on optical aurora carried out by the participating groups.

The grant received was smaller than the sum applied for, and during the third workshop priorities were discussed. It was agreed that the most important goals are numbers 1, 2, and 5.

6.4 Acknowledgements

We are very grateful to the Nordic Council of Ministers for the grant that made network activities possible.

The administration was carried out by the Swedish Institute of Space Physics in Kiruna. Network leader has been Professor Ingrid Sandahl. The economy has been handled in a very professional way by Yvonne Freiner.

We would also like to thank all local workshop organizers. Workshop One was organised by a committee at Sodankylä Geophysical Observatory led by Esa Turunen and Carl-Fredrik Enell and the practical arrangements were handled by Nina Riipi, Anna-Liisa Piippo and Tarja Mäkihalvari. We also thank the municipality of Sodankylä for hosting the icebreaker reception and for renting the Kommatti sauna and the Portinpirtti where the conference dinner was held. Workshop Two was organized by Björn Gustavsson with the help of Liv Larssen, both from the University of Tromsø. Responsible for the third workshop were Ingrid Sandahl and Eivor Jonsson, Swedish Institute of Space Physics.

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Yhteenveto

Revontulien valossa – Optinen revontulitutkimus Pohjois-Euroopassa

Tämän raportin ovat kirjoittaneet Arktisen alueen optisen revontulitutkimuksen yhteistyöverkoston (Network for Ground-based Optical Auroral Research in the Arctic Region) jäsenet. Yhteistyöverkosto muodostettiin Pohjoismaiden ministerineuvoston (Nordic Council of Ministers) Arktisen yhteistyön ohjelmaan (Arctic Cooperation Programme) vuosina 2006–2008 ja siihen kuuluvat kaikki Huippuvuorilla, Pohjois-Fennoskandiassa ja Kuolan niemimaalla revontulitutkimusta tekevät yliopistot ja tutkimuslaitokset. Raportin tarkoituksena on esitellä optisilla menetelmillä tehtävää revontulitutkimusta, yhteistyön piiriin kuuluvat tutkimusryhmät ja heidän käyttämänsä mittalaitteet, sekä selvittää tutkimusyhteistyön tieteellisiä tuloksia.

Revontulet

Revontulet, latinankieliseltä nimeltään aurora borealis, ovat yötaivaamme vaihtelevin ja kaunein valoilmiö. Revontulien energianlähteenä on aurinko ja auringosta karkaavat hiukkaset, jotka päätyvät Maan lähiavaruuteen ja sieltä monien fysikaalisten prosessien kautta yläilmakehään. Siksi revontulet voivat kertoa meille paljon Maan lähiavaruuden ilmiöistä. Auringosta puhaltaa jatkuvasti aurinkotuuli, jonka ominaisuudet vaihtelevat. Lisäksi Auringossa tapahtuu ajoittain lyhytkestoisia hiukkas- ja säteilypurkauksia, jotka vaikuttavat Maan lähiavaruuteen ja siellä vallitsevaan avaruussäähän. Purkauksista voimakkaimmat voivat aiheuttaa teknisiä ongelmia satelliiteissa ja sähköjakeluverkoissa. Ymmärtääksemme revontulien viestin, mittaamme revontulivalon eri ominaisuuksia, kuten maantieteellistä jakaumaa sekä revontulimuotojen liikettä, korkeutta, väriä ja voimakkuutta. Näkyvän revontulivalon maanpintamittauksia tulkitaan yleensä yhdessä muiden maanpintamittausten sekä satelliitti- ja rakettihavaintojen kanssa.

Revontulien havainnointiin käytetään monia erilaisia optisia mittalaitteita. Näitä ovat mm. kalansilmälinssillä tai muunlaisella optiikalla varustetut revontulikamerat, fotometrit ja spektrometrit. Viime vuosien tekninen kehitys optiikan osalta on avannut uusia mahdollisuuksia tutkia revontulien nopeita aikavaihteluita, pieniä rakenteita ja himmeitä revontulimuotoja, joiden havainnointi on tähän saakka ollut melkein mahdotonta. Maanpintamittalaitteiden mittaustarkkuus on parempi kuin minkään muun revontulian mittaavan instrumentin tarkkuus. Maanpinnalta mitatusta aineistosta voidaan myös erottaa revontulien aika- ja paikkavaihtelut toisistaan.

Havaintojen tulkitsemiseksi tarvitaan lisäksi malleja ja simulaatioita niistä fysikaalisista ja kemiallisista prosesseista, joita revontulissa esiintyy.

Tutkimusryhmät

Pohjois-Eurooppa on ainutlaatuista aluetta maailmassa, sillä revontulien esiintymisalueella sijaitsee useita tutkimuslaitoksia ja yliopistoja. Aluksi Pohjoismaiseen yhteistyöverkostoon kuuluivat Huippuvuorten yliopistokeskus (University Centre in Svalbard, UNIS), Tromssan yliopiston fysiikan laitos, Ruotsin avaruusfysiikan tutkimuslaitos (Institutet för Rymdfysik, IRF) Kiirunassa, Oulun yliopiston fysikaalisten tieteiden laitos ja Sodankylän geofysiikan observatorio, sekä Kuolan tiedekeskuksen geofysiikan tutkimuslaitos Apatityssa (Polar Geophysical Institute in Apatity of the Kola Science Centre). Myöhemmin yhteistyöverkostoon liittyivät myös Ilmatieteen laitos Helsingistä, Tukholman teknillinen korkeakoulu (Kungliga Tekniska Högskolan, KTH) sekä Oslon yliopiston fysiikan laitos. Tässä raportissa kuvataan lyhyesti em. tutkimusryhmät ja niiden toiminta.

Revontulimittalaitteet

Pohjois-Eurooppa on revontulitutkimuksen suotuisinta aluetta, sillä täällä sijaitsee runsaasti mittausasemia ja ilmasto on myös suhteellisen leuto. Fennoskandia on paras paikka keskiyön revontulien havainnointiin, kun taas Huippuvuorten kaamosaika tarjoaa ainutlaatuisen mahdollisuuden revontulien mittaamiseen keskellä päivää. Siksi huomattava määrä revontulimittausasemia on perustettu juuri näille alueille ja niitä ylläpitävät Pohjoismaisen yhteistyöverkoston jäsenryhmien lisäksi avaruustutkimuslaitokset mm. Englannista, Italiasta, Kiinasta, Japanista ja Yhdysvalloista.

Arktisen optisen revontulitutkimuksen yhteistyöverkosto

Yhteistyöverkostolle myönnettiin 355 000 Tanskan kruunun suuruinen apuraha vuosille 2006–2009. Verkoston tavoitteina on vahvistaa yhteistyötä niiden tutkimusryhmien välillä, jotka tekevät optisia revontulimittauksia Euroopan arktisilla alueilla, sekä tehdä huipputason tieteellistä revontulitutkimusta. Näissä puitteissa on järjestetty kolme työpajatyypistä tutkijoiden ja jatko-opiskelijoiden kokousta, tuettu tutkijoiden liikkuvuutta ryhmien välillä sekä myönnetty stipendejä venäläisille tutkijoille Optiseen kokoukseen (Annual European Meeting on Atmospheric Studies by Optical Methods) osallistumista varten.

Ensimmäiseen työpajaan Sodankylässä 19.–23.2.2007 osallistui 23 tutkijaa, toiseen Tromssassa 7.–11.4.2008 10 tutkijaa, ja kolmanteen Kiirunassa 25.–29.5.2009 14 tutkijaa. Kaikkien kokousten ohjelmaan kuului tieteellisiä esitelmiä, laitoskohtaisia tilannekatsauksia, mittalaitetekoke-

muksien vaihtoa, työskentelyä yhteisten tutkimusprojektien parissa sekä mittauskampanjoiden suunnittelua. Tärkeänä tavoitteena on alusta lähtien pidetty henkilökohtaisten kontaktien vahvistamista tutkijoiden välillä.

Liikkuvuusohjelman (mobility programme) puitteissa toteutettiin kaikkiaan 12 tutkijavierailua. Suurin osa vierailuista oli noin viikon mittaisia. Tutkimusvierailujen tuloksia on esitetty useissa tieteellisissä kokouksissa ja niistä on myös julkaistu tieteellisiä artikkeleita. Monet projekteista ovat vielä kesken ja lisää tuloksia on siten odotettavissa.

Yhteistyörahoituksen johdosta 14 venäläistä tutkijaa pääsi osallistumaan Kiirunassa järjestettyyn Optiseen kokoukseen vuonna 2006 ja kaksi venäläistä tutkijaa Andøyen Optiseen kokoukseen vuonna 2007.

Yhteistyöverkoston tutkimusprojektit ja niiden ensimmäiset tulokset

Useita tutkimusprojekteja on aloitettu yhteistyöverkoston jäsenten välillä. Tässä raportissa kuvailemme aihealueet ja projektit, joissa yhteistyöverkoston tuki on ollut välttämätön. Rahoituskauden aikana tehdyt tieteelliset julkaisut on listattu kappaleessa 6.

Revontulirakenteiden tutkimus suurella mittaustarkkuudella

Revontulissa on paljon pieniä rakenteita, joista tiedetään toistaiseksi hyvin vähän. KTH:n Auroral Structure and Kinetics (ASK) mittalaite on mittaustarkkuudeltaan paras olemassa oleva kuvaussysteemi pienien rakenteiden havainnoimiseksi. Tässä tutkimuksessa Oulun yliopiston laajakulmaisen revontulikameran ja ASK-kameran kuvia yhdistämällä tutkittiin uutta pör-röksi nimettyä revontulimuotoa (ruff), sen muodostumista sekä suhdetta aiemmin löydettyihin revontulipyörteisiin (curl) ja revontulipoimuihin (fold).

Pienen mittakaavan revontulia usean instrumentin havaitsemana

Tutkimusprojektissa ASK-aineistoa yhdistetään ruotsalaisen Auroral Large Imaging System (ALIS) kameroiden kuviin ja kansainvälisen EIS-CAT-ionosfääritutkan mittauksiin. Tavoitteena on tutkia yksityiskohtaisesti revontulia aiheuttavan elektronisateen ja näkyvän revontulivalon välistä yhteyttä.

Revontulikaaren yhteydessä voimistuva sähkökenttä

Tyypillisesti revontulikaaren sisällä havaittava sähkökenttä on pienempi kuin kaaren ulkopuolella havaittu kenttä. Tässä tutkimuksessa esitetään poikkeuksellisen voimakkaan sähkökentän kehittyminen uudessa, syntyvässä revontulikaaressa.

Revontulipulsaatiot

Revontulipulsaatiota, eli sykkiviä revontulia, esiintyy tyypillisesti revontulipurkauksen loppupuolella. Näiden ilmiöiden syntymekanismi on edelleen epäselvä ja monet niitä selittävät teoriat ovat keskenään ristiriitaisia. Tässä

tutkimuksessa tarkastellaan sykkivän revontulen korkeuden muutoksia. ALIS-kamerakuvista korkeus määritetään kolmiomittauksen avulla. Ensimmäiset tulokset viittaavat siihen, että aalto-hiukkasvuorovaikutus synnyttää pulsaatioita.

Havaintoja magnetisheathin plasmasta

Usean mittalaitteen havainnot päiväpuolen napaonkalon alueella osoittavat, että aurinkotuulen shokittunut (magnetosheath) plasma tunkeutuu magnetosfääriin myös silloin, kun planeettain välisen magneettikentän (Interplanetary Magnetic field, IMF) suunta on pohjoinen. Perinteisesti tämä havainto liittyy IMF:n eteläiseen suuntaan ja sen aiheuttamaan magneettiseen rekonnektioon.

Revontulivalon skaalapituuksia

6–26 km suuruisten revontulirakenteiden kokojakauma on osoittautunut eksponentiaaliseksi. Tämä viittaa rakenteiden turbulenttiseen syntyprosessiin ja itsensäkaltaiseen (self-similar) systeemiin.

Energiansiirto ilmakehän molekyyliden törmäyksissä

Alle 100 km:n korkeuksilla tapahtuvissa revontulien syntymekanismeissa ilmakehän molekyyliden väliset törmäykset ovat tärkeä energiansiirtomuoto. Tämä tutkimus keskittyy kyseisen energiansiirron teoreettiseen mallintamiseen.

Elektronitiheyden ja NO_x-typpiyhdisteiden muutosten mallintaminen

Revontulia aiheuttavat hiukkaset vaikuttavat ilmakehässä myös NO_x-typpiyhdisteiden syntyyn. Tässä tutkimuksessa pyritään arvioimaan typpiyhdisteiden määrää revontulivalon intensiteetin perusteella.

Radioaaltojen synnyttämät revontulet

Voimakkaat radioaallot voivat synnyttää keinotekoisia revontulia. Tätä ilmiötä voidaan tutkia ionosfäärin tarjoamassa luonnollisessa laboratoriossa, jonne radioaaltoja lähetetään Tromssasta EISCAT- kuumenninlaitteiston avulla. Radioaaltojen synnyttämää revontulivaloa voidaan havaita optisin mittalaittein. Tällaisia kokeita tehtiin mm. marraskuussa 2001 ja maaliskuussa 2002.

AIDA-analyysimenetelmien käyttö muiden kameroiden kuville

Optisten mittausten analysointiin käytetään usein hyvin monimutkaisia ohjelmistoja. Tässä projektissa ALIS-kameroille tarkoitettua AIDA-tomografiaohjelmistoa sovelletaan revontulivärikameroille, joiden kuvamateriaali tallennetaan suoraan monivärikuvina.

Revontulitutkimuksen historiaa

Venäläis-ruotsalainen tutkimusretkikunta suuntasi matkansa Huippuvuorille vuosina 1899–1900. Projektin tarkoituksena on laatia kuvaus revontulista, joita tutkimusmatkan aikana havaittiin.

Johtopäätökset

Pohjoismainen tutkimusyhteistyöverkosto on syventänyt tutkimusryhmien välistä yhteistyötä ja luonut ystävyssuhteita yksittäisten tutkijoiden välille. Useita tutkimusprojekteja on saatu alkuun, paljon uusia tuloksia on julkaistu ja monta projektia on vielä työn alla. Mahdollisuus sekä yhteisiin kokouksiin että yksittäisten tutkijoiden vierailuihin (liikkuvuusohjelma) on toiminut hyvin. Saatu rahoitus on edullisten matkakulujen ansiosta riittänyt arvioitua paremmin. Rahoituskautta pidennettiin alkuperäisestä suunnitelmasta, johtuen pääasiassa yhteistyöverkoston jäsenten suurista työtaakoista omissa laitoksissaan. Verkoston toiminnan arvioineen tohtori Steve Milenin (Leicesterin yliopisto, UK) mukaan verkosto on menestyksekkäästi saavuttanut tavoitteensa.

Pohjoismaden ministerineuvosto myönsi yhteistyöverkostolle jatkorahoituksen vuonna 2009. Verkosto on laajentunut käsittämään kaikki Norjan, Ruotsin, Suomen ja Kuolan niemimaan optista revontulitutkimusta tekevät tutkimusryhmät. Uusien optisten mittalaitteiden ja tiiviin yhteistyön avulla verkostolla on mahdollisuus merkittävästi parantaa ionosfäärin, avaruusfysiikan, ja sitä kautta revontulien syntymekanismien ymmärrystä.

Заключение

В свете полярных сияний – Исследование полярных сияний оптическими методами на севере Европы

Этот доклад написан партнерами, входящими в Группу исследований полярных сияний в Арктическом регионе наземными оптическими методами. Группа была организована в соответствии с положениями Программы сотрудничества в Арктике в 2006–2008 Совета министров Северных стран. В неё входят представители институтов, расположенных в Скандинавии, на Кольском полуострове и на архипелаге Шпицберген и занимающихся изучением полярных сияний оптическими методами. Цель доклада – ознакомить общественность с достижениями в исследовании полярных сияний оптическими методами, представить рабочие группы, оптические установки и приборы в регионе, а также перечислить направления научной деятельности и научные результаты Группы. В 2009 г. Группа получила грант на продолжение научных исследований.

Оптические наблюдения полярных сияний

Полярные сияния – самое изменчивое из известных природных световых явлений на небе. Они являются ионосферным проявлением процессов, происходящих в околоземном космическом пространстве, и служат удобным «инструментом» космических геофизиков для исследования космической погоды наземными методами. Различные явления на Солнце через вариации в солнечном ветре оказывают влияние на состояние околоземного космического пространства (космической погоды), что не может не сказаться на работе космических аппаратов. Изменения космической погоды могут оказывать также негативное влияние на линии электропередач и состояние трубопроводов.

Чтобы понять, какую информацию могут дать полярные сияния, изучаются их различные характеристики: глобальное распределение, типы и динамика авроральных форм, высота, спектр и интенсивность. Наземные наблюдения полярных сияний обычно дополняются другими наблюдениями, как наземными, так и со спутников и ракет.

Измерения проводятся различными приборами, установленными на обсерваториях, в том числе, оптическими камерами, фотометрами и спектрографами. Последние достижения в оптической аппаратуре открыли новые возможности для изучения быстрых вариаций в ди-

намике сияний, мелкомасштабных структур, а также слабых свечений, которые ранее оставались за рамками исследований. Наземные оптические приборы обеспечивают максимальное пространственное разрешение. Они наилучшим образом позволяют различить пространственные и временные вариации. Для интерпретации данных также необходимо использовать некоторые модели, например, модели, описывающие процессы высвечивания в атмосфере.

Исследовательские группы

Северная Европа имеет наибольшую в мире плотность научно-исследовательских институтов, ученые которых живут прямо под полярными сияниями. Исследовательские коллективы, которые первоначально вошли в состав Группы, представляли Университетский Центр на Шпицбергене, физический факультет университета Тромсё, шведский Институт космической физики (г. Кируна), Университет Оулу, геофизическую обсерваторию Соданкюля и Полярный геофизический институт Кольского научного центра РАН. Позднее к ним присоединились «низкоширотные регионы»: Финский метеорологический институт из Хельсинки и Королевский технический институт из Стокгольма, а в 2009 г. – физический факультет Университета Осло. Краткое описание исследовательских групп всех этих учреждения, а также направлений их научной деятельности, приведено в настоящем докладе.

Установки и аппаратура для изучения полярных сияний оптическими методами

Северная Европа – наиболее удобное место для изучения полярных сияний, т.к. здесь авроральный овал, то есть то место, где статистически чаще всего наблюдаются сияния, располагается над регионами с отлично развитой инфраструктурой и достаточно мягким климатом. Скандинавский и Кольский полуострова – наилучшее с точки зрения место для исследований ночных полярных сияний, а арх. Шпицберген в середине зимнего периода даёт уникальную возможность изучать дневные полярные сияния. Поэтому в этом регионе была создана разветвленная инфраструктура и установлены многочисленные средства наблюдения как группами, участвующими в настоящем проекте, так и другими группами из Великобритании, Италии, Китая, Японии и США.

Группа исследований полярных сияний в Арктическом регионе наземными оптическими методами

Группа получила грант в 355 000 датских крон, который был использован для работы в 2006–2009 гг. для укрепления сотрудничества между исследовательскими группами в европейском Арктическом регионе, работающими в области исследований полярных сияний. С этой целью были проведены 3 рабочих встречи, участниками которых были не только ученые и инженеры, но и аспиранты, осуществлена программа многосторонних визитов и выделена поддержка для участия российских ученых в ежегодных европейских конференциях по исследованию верхней атмосферы оптическими методами.

Первая рабочая встреча участников проекта была проведена 19–23 февраля 2007 г. в Соданкюля (23 участника), вторая 7–11 апреля 2008 г. в Тромсё (10 участников), третья 25–29 мая 2009 г. в Кируне (14 участников). Программы заседаний включали лекции, информационные доклады, обмен опытом по использованию аппаратуры, совместную научную работу, планирование наблюдательных кампаний и научных визитов. Важным фактором также явилось укрепление персональных контактов между участниками.

Программа обмена учёными включала 14 визитов, в основном, продолжительностью 1 неделя. Результаты были доложены на различных научных конференциях и опубликованы в различных статьях в научных журналах. Многие исследования, начатые в ходе обменных визитов, продолжаются.

На средства гранта 11 российских ученых смогли участвовать в двух ежегодных конференциях по исследованиям атмосферы оптическими методами, проведенными в Кируне в 2006г. и в Андойе (Норвегия) в 2007 г.

Исследовательский проект, выполняемый Группой: содержание и первые результаты.

В ходе реализации проекта был выполнен ряд совместных научных исследований. В этом докладе ниже будут кратко описаны их результаты. Публикации участников проекта перечислены после главы 6.

Исследования структуры полярных сияний с хорошим пространственным разрешением

В полярных сияниях наблюдается множество мелкомасштабных структур, физика которых пока не выяснена. Для исследований использовалась оптическая установка Королевского технического института, Стокгольм (далее ASK), которая на сегодняшний день является лучшим в мире инструментом для изучения мелкомасштабных структур, в комбинации с авроральной камерой Университета Оулу,

обладающей бóльшим полем зрения. Это позволило обнаружить и описать новый тип авроральных структур, по форме напоминающих гребень. Их связь с ранее известными крупномасштабными вихрями и складками изучается.

Комбинированные наблюдения мелкомасштабных структур в полярных сияниях

Одновременные наблюдения установкой ASK и радаром EISCAT позволили изучить детальную связь между выпадающими из магнитосферы электронами и реально наблюдаемыми оптическими эмиссиями.

Усиление электрического поля внутри дуги

Электрическое поле внутри авроральной дуги почти всегда слабее, чем снаружи. Исследование показало, что в момент генерации дуги электрическое поле в ней может быть увеличенным.

Исследования пульсирующих полярных сияний

Пульсирующие полярные сияния появляются на поздней стадии суббури. Их механизм до сих пор не выяснен, и существующие теории противоречат друг другу. В одной из работ изучались изменения высоты во время цикла авроральных пульсаций методом триангуляции. Результаты свидетельствуют в пользу механизма, связанного с взаимодействием волна-частица.

Наблюдение захвата плазмы переходного слоя

Комбинация оптических наблюдений с радарными и спутниковыми измерениями позволила отождествить наблюдаемую в дневные часы авроральную активность с захватом плазмы переходного слоя в результате пересоединения полюсное каспов.

Масштабирование авроральной светимости

Спектральный анализ авроральных структур с масштабами 6–26 км показал, что их генерация связана с развитием турбулентности.

Перенос энергии при молекулярных столкновениях

Учет переноса энергии при молекулярных столкновениях важен на высотах ниже 100 км. Была произведена теоретическая оценка коэффициентов скорости гашения, необходимых при расчетах переноса энергии.

Моделирование изменений электронной концентрации и концентрации NO_x

Авроральные частицы влияют на образование окиси азота в атмосфере. В одной из работ оценивается скорость образования окиси азота по оптическим наблюдениям сияний.

Применение пакета AIDA к данным, полученным другими оптическими установками

Анализ оптических данных представляет сложную процедуру. В ходе реализации проекта программы, используемые ранее для решения обратных задач типа оптической томографии в проекте ALIS, были адаптированы для работы с данными других оптических установок.

История исследований полярных сияний

В 1899–1900 гг. состоялась прекрасно организованная российско-шведская экспедиция на Шпицберген. В одной из работ приведено описание исследований полярных сияний, выполненных во время этой экспедиции.

Выводы

В ходе реализации проекта укрепились научные контакты между исследовательскими коллективами- участниками проекта. Непосредственное общение учёных положило начало новым работам. Результаты некоторых совместных исследований уже опубликованы, часть микропроектов находятся в активной стадии доработки. Хорошо зарекомендовало себя сочетание рабочих совещаний с обменными визитами отдельных ученых. Средств гранта хватило на более продолжительный срок, чем ожидалось, благодаря невысокой стоимости проезда и проживания. Это дало возможность увеличить срок реализации проекта по сравнению с предполагаемым. Оценка работы Группы была проведена независимым экспертом Dr. Steve Milan из Университета г. Лейстер (Англия). На основе этой оценки можно сделать вывод, что работа группы была успешной, и цели, в основном, достигнуты.

В 2009 г. Группа получила новый грант Совета министров Северных стран на продолжение работы. Группа была расширена – в её состав в качестве полноправных партнеров входят теперь практически все исследовательские группы Норвегии, Швеции, Финляндии и Кольского полуострова, активно изучающие полярные сияния оптическими методами. С возможностями, которые дают современные оптические установки, мы сможем внести существенный вклад в понимание не только механизмов полярных сияний, но и физических процессов в плазме околоземного космического пространства, проявлением которых является это красочное явление природы.

Sammanfattning

Upplyst av norrsken – Forskning om optiskt norrsken i nordligaste Europa

Detta är en rapport skriven av Nätverket för markbaserad optisk norrskenforskning i det arktiska området. Nätverket bildades som ett svar på Nordiska ministerrådets utlysning för ett Arktiskt samarbetsprogram 2006–2008. Det omfattar alla institutioner på Svalbard och i norra Fennoskandia som bedriver forskning om norrsken med optiska metoder. Syftet med rapporten är att ge en introduktion om norrskenforskning, i synnerhet vad som kan uppnås med optiska metoder, om forskningsgrupper, infrastruktur och instrument i regionen, samt att redogöra för nätverkets aktiviteter och vetenskapliga resultat. Nätverket har 2009 erhållit anslag för att fortsätta sin verksamhet.

Optiskt norrsken

Norrskenet är det mest variabla av alla ljusfenomen på himlen. Det är ett synligt resultat av fysikaliska processer som äger rum i rymden nära jorden och det får sin energi från solvinden. Norrskenet innehåller därför mycket information om dessa processer och om rymdfysik. Olika händelser på solen leder till variationer i solvinden och därigenom i norrskenet. Sådana variationer ger upphov till variationer i rymdmiljön nära jorden, rymdväder, som kan påverka tekniska system såsom satelliter och eldistribution. För att tolka informationen i norrsken mäts olika egenskaper hos ljuset såsom geografisk utbredning, former och rörelser hos norrskensstrukturer, höjd, färger, intensiteter. Markbaserade mätningar av norrskenljus kombineras vanligen med andra slags mätningar, både från marken och från satelliter och sondraketer.

Många olika slags instrument används för att mäta norrsken: firmamentkameror, avancerade avbildande instrument, fotometrar och spektrografer. De senaste årens utveckling av optiska instrument har öppnat upp nya möjligheter att studera snabba variationer, småskaliga strukturer och ljussvaga norrsken som är mycket vanliga men som tidigare befunnit sig utom räckhåll för instrumenten. Markbaserade optiska instrument kan ge bättre upplösning än någon annan typ av instrument. De är också överlägsna när det gäller att skilja på rums- och tidsvariationer. För att tolka data är det också nödvändigt att använda åtskilliga modeller, till exempel modeller som beskriver processerna i atmosfären när ljuset skapas.

Forskningsgrupper

Nordligaste Europa har världens högsta täthet av forskningsinstitutioner vid vilka forskare faktiskt bor under norrskenet. De grupper som startade nätverket var: Universitetscentret på Svalbard, Institutionen för fysik vid Tromsø Universitet, Institutet för rymdfysik i Kiruna, två grupper vid Universitetet i Uleåborg nämligen Institutionen för fysik och Sodankylä geofysiska observatorium och Polar Geophysical Institute i Apatity, en del av Kola Science Centre. Två sydligare grupper anslöt sig strax efter starten, Meteorologiska institutet i Helsingfors och Kungliga tekniska högskolan i Stockholm. År 2009 blev även Avdelningen för Fysik vid Oslo universitet medlem. Korta beskrivningar av dessa grupper och deras aktivitet ges.

Anläggningar och instrument för mätning av optiskt norrsken

Nordligaste Europa är mycket väl lämpat för studier av optiskt norrsken eftersom norrskensovalen här sträcker sig över områden med utmärkt infrastruktur och förhållandevis mildt klimat. Det fennoskandiska fastlandet och Kolahalvön lämpar sig bäst för studier av nattsidans norrsken medan Svalbard vid midvintertid erbjuder unika möjligheter att undersöka dagsidans norrsken i mörker. Mycket infrastruktur och många instrument har därför installerats i regionen, både av grupper som deltar i nätverket och av grupper från många andra delar av världen såsom Storbritannien, Italien, Kina, Japan och USA.

Nätverk för markbaserad optisk norrskenforskning i det arktiska området

Nätverket erhöll ett anslag på DKK 355 000 som har använts under perioden 2006–2009. Målen är att stärka samarbetet mellan forskargrupper i den europeiska arktiska regionen som arbetar med optisk norrskenforskning och att bedriva högklassigt vetenskapligt arbete. Detta har gjorts genom att genomföra tre workshops för forskare och doktorander, genomföra ett mobilitetsprogram med besök mellan de deltagande grupperna och erbjuda stipendier för ryska forskare att delta i konferenser.

Den första workshopen hölls den 19–23 februari 2007 i Sodankylä med 23 deltagare, den andra i Tromsø den 7–11 april 2008 med 10 deltagare och den tredje i Kiruna den 25–29 maj 2009 med 14 deltagare. Programmen har omfattat föreläsningar, statusrapporter från de olika grupperna, utbyte av erfarenheter angående instrument, gemensamt arbete på vetenskapliga studier, planering av mätkampanjer och studiebesök. En viktig målsättning har också varit att stärka personliga kontakter mellan individer.

Mobilitetsprogrammet har totalt omfattat 14 besök. De flesta besöken har varat omkring en vecka. Resultat har presenterats vid olika vetenskap-

liga konferenser och ett antal artiklar i vetenskapliga tidskrifter. Många studier pågår fortfarande och ytterligare resultat väntas.

Tack vare anslaget kunde elva ryska forskare delta i det optiska mötet i Kiruna 2006 and två i det optiska mötet i Andøya, Norge 2007.

Forskningsprojekt inom nätverket, beskrivningar och första resultat.

Under projektiden har många studier bedrivits av de grupper som deltar i nätverket. Här beskriver vi studier som varit gemensamma projekt, studier som till stor del möjliggjorts tack vare nätverket. Publikationer av nätverksdeltagarna rörande optiskt norrsken listas efter kapitel 6.

Högupplöst studie av strukturer i norrsken

Norrskenet har en rikedom på småskaliga strukturer, men de flesta av dessa är dåligt förstådda. KTH arbetar med ASK-instrumentet som är världens bästa instrument för högupplösta studier. I detta projekt gav en kamera från Uleåborgs universitet den storskaliga bilden. Man hittade en ny typ av norrskensstruktur som fick namnet «ruff» och dess orsak och relation till de tidigare kända större «curls» och «folds» undersöktes.

Undersökning av småskaligt norrsken med flera instrument.

Data från ASK användes tillsammans med data från ALIS och EISCAT för att studera det detaljerade sambandet mellan elektroner från rymden och de optiska emissionerna mätta med ASK.

Förhöjt elektriskt fält i en norrskenbåge

Det elektriska fältet inne i en norrskenbåge är nästan alltid mindre än utanför. Detta arbete visar att så inte alltid är fallet. Slutsatsen är att i en båge under utveckling kan det elektriska fältet inne i bågen bli förhöjt.

Studier av pulserande norrsken

Pulserande norrsken uppträder i den senare delen av norrskesutbrott. Orsaken är ännu inte förstådd och det finns teorier som står i motsats till varandra. Höjdvariationer under en pulsationscykel studerades genom att triangulera med ALIS-mätningar. Resultatet stöder mekanismer som bygger på växelverkan mellan vågor och partiklar.

Observationer av infångning av plasma från magnetoskiktet

Dessa observationer av dagsidans norrsken med flera instrument kunde visas stämma med magnetisk återkoppling på polsidan om cuspen och infångning av plasma från magnetoskiktet till magnetosfären under nordriktat interplanetärt magnetfält.

Skalningsegenskaper hos norrskensstrukturer

Norrskensstrukturer i storleken 6–26 km visade skalningsegenskaper som tyder på en turbulent natur hos variationerna.

Energiöverföring vid kollisioner mellan molekyler

Under 100 km höjd är energiöverföring mellan molekyler mycket viktig. Detta är en teoretisk härledning av koefficienter för utsläkningshastighet som behövs för att beräkna energiöverföringen.

Modellering av elektrontäthet och variationer av kväveoxidhalt

Norrskenspartiklar påverkar bildningen av kväveoxider i atmosfären. I denna studie undersöks produktionen av kväveoxid med utgångspunkt från observationer av optiskt norrsken.

Användning av AIDA på data från andra avbildande instrument

Analys av optiska data är ofta komplicerad. I detta projekt användes mjukvara för tomografi-liknande inversion som utvecklats för ALIS på data från en färgkamera.

Norrskensforskningshistoria

Vintern 1899–1900 företogs en mycket välorganiserad rysk-svensk expedition till Spetsbergen. Detta är en beskrivning av de norrskensstudier som bedrevs av den expeditionen.

Slutsatser

Nätverket har fördjupat kontakterna mellan de deltagande forskningsgrupperna och vänskap mellan forskare. Åtskilliga nya studier har inletts, några resultat har publicerats och fler ligger i analysfas. Kombinationen av workshops och mobilitetsprogram har fungerat väl. Anslaget har räckt till mer än förväntat tack vare att billiga resor och billigt boende har utnyttjats. Tidsschemat har tänjts ut i viss mån jämfört med den första planen, huvudsakligen på grund av deltagarnas arbetsbelastning. En utvärdering av nätverkets aktiviteter har genomförts av Dr. Steve Milan från universitetet i Leicester och den huvudsakliga slutsatsen är att nätverket varit framgångsrikt och på det hela taget uppnått sina mål.

År 2009 erhöll nätverket ett nytt anslag från Nordiska ministerrådet för att fortsätta sina aktiviteter. Nätverket har nu utvidgats så att det omfattar alla grupper i Norge, Sverige, Finland och på Kolahalvön som är aktiva i optisk norrskensforskning. Med de möjligheter som moderna optiska instrument erbjuder bör vi kunna ge viktiga bidrag till förståelsen av jonofärs- och rymdfysik och därmed till mekanismerna i norrskenet.

Appendix

List of acronyms

ALIS	Auroral Large Imaging System
ASK	Auroral Structure and Kinetics
CCD	Charge-Coupled Device
CUTLASS	Co-operative UK Twin Auroral Sounding System
DMSP	Defense Meteorological Satellites Program
EISCAT	European Incoherent SCAtter radar
EMCCD	Electron Multiplication Charge-Coupled Device
ESR	EISCAT Svalbard Radar
FMI	Finnish Meteorological Institute
HF	High Frequency
IMF	Interplanetary Magnetic Field
KGO	Kiruna Geophysical Observatory
KGI	Kiruna Geophysical Institute
KHO	Kjell Henriksen Observatory
KTH	Royal Institute of Technology (Kungliga Tekniska Högskolan)
ICCD	Image-intensified Charge-Coupled Device
IGY	International Geophysical Year
IRF	Swedish Institute of Space Physics (Institutet för RymdFysik)
IPT	Institute of Physics and Technology (at UiT)
MIRACLE	Magnetometers – Ionospheric Radars – All-sky Cameras Large Experiment
NEIAL	Naturally Enhanced Ion Acoustic Line
OY	University of Oulu (Oulun Yliopisto)
PDF	Probability Density Function
PGI	Polar Geophysical Institute
PMAF	Poleward Moving Auroral Forms
SGO	Sodankylä Geophysical Observatory
UiO	University of Oslo (Universitetet i Oslo)
UiT	University of Tromsø (Universitetet i Tromsø)
UHF	Ultra High Frequency
UNIS	The University Centre In Svalbard
UV	UltraViolet
VLf	Very Low Frequency