3D imaging reveals electrod

Rishbeth prizewinners Hanna Dahlgren and colleagues investigate the nature of an auroral arc appearing within the deep polar cap region, which won the 2014 Rishbeth Poster Award at Hot Springs MIST.

1 (Left): North face of the Resolute Bay Incoherent Scatter Radar (RISR-N), which probes the plasma parameters in the polar cap ionosphere, and (right) crossed dipole antennas on RISR-N. (C Heinselman)

Dynamic displays of aurora can be seen in the skies at high latitudes, as a consequence of energetic charged particles that are guided down to the ionosphere along geomagnetic field lines. To first order, Earth's magnetic field is approximately that of a dipole, with its south magnetic pole in the geographic north. This geometry leads to the most spectacular and studied auroral displays in an oval around each pole, associated with magnetic field lines that are "closed"; that is, both ends connect to a geomagnetic pole. At higher latitudes, closer to the poles, the field lines are distorted, stretching far from Earth; they connect with the stream of plasma from the Sun, the solar wind, which carries with it the interplanetary magnetic field (IMF). The ionospheric regions geographically poleward of the auroral ovals where the magnetic field lines are "open" are known as the polar caps.

Until just a few decades ago the polar caps were believed to be very quiet, without disturbances or auroral displays. Thanks to technological advances that increased the sensitivity of ground-based imagers, it became clear that the dark and empty polar cap skies were not that quiet after all, but often subject to faint but dynamic and structured auroral arcs. These polar cap arcs are regularly called Sun-aligned arcs, because they tend to align along the noon–midnight meridian. Observations from satellites have shown that these arcs can extend all the way across the polar cap, from one side of the auroral oval to the other, in which case they are referred to as transpolar arcs or theta aurora, as the overall shape of the aurora resembles the Greek letter θ. However, not all polar cap arcs are transpolar, some are smaller and more dynamic.

Several theories have been proposed over the years to explain how and where the polar cap aurora forms; there is still no consensus on what causes auroral arcs in a region that is expected to be void of the particle precipitation that gives rise to auroral emissions. Some observations indicate that the arcs are caused by energetic electrons that originate in the tail of the magnetosphere, and that they occur on closed geomagnetic field lines that penetrate into the polar cap from the auroral oval (e.g. Zhu *et al.* 1997, Milan *et al.* 2005), whereas other arcs have been found to have energies consistent with open field lines (e.g. Obara *et al.* 1993). Detailed observations both from the ground and *in situ* are necessary to shed light on the formation of the polar cap aurora.

3D radar data

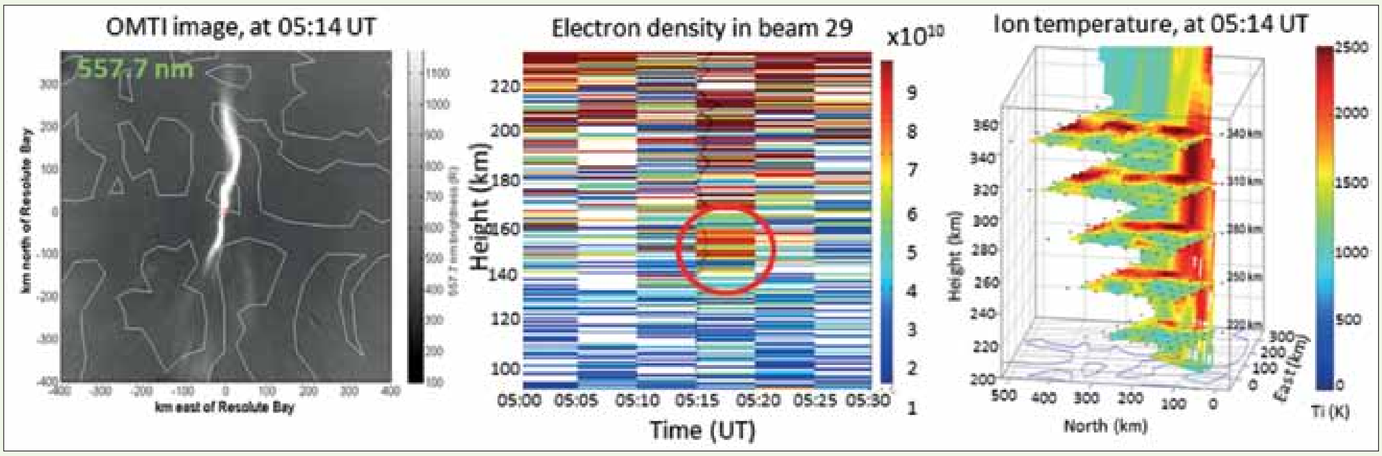
The Resolute Bay Incoherent Scatter Radar – North (RISR-N) in Resolute Bay, Canada, is a recently installed north-looking phased array incoherent scatter radar facility, operating at 443 MHz. The ingenious design includes several thousands of identical small UHF transceivers (figure 1, bottom) whose resulting radar beam can be steered electronically in different directions on a pulse-to-pulse basis without any mechanical moving parts – the steering of the beam is done by adjusting the phase of the signal from the individual antennas. For the observations of the event described here, the radar was pointing in a predefined 6×7 beam grid, which, when integrating the observations over a minute or more, gives a true three-dimensional image of the ionospheric plasma parameters. The radar provides estimates of the electron density, electron and ion temperatures and ion drifts within the measured volume.

On 20 February 2012, a thin polar cap arc formed near the evening edge of the auroral oval, and then drifted southeastward across the sky over Resolute Bay. The arc was captured with one of the Optical Mesosphere and Thermosphere Imagers (OMTI), run by the Solar-Terrestrial Environment Laboratory at Nagoya University, Japan. The images showed a fast-moving (250 m s^{-1}), thin (~10 km wide) bright auroral arc passing through magnetic zenith at 05:15 UT (figure 2, left). As the arc passed one of the RISR-N beams, an ionization signature appeared in the electron density measurements near 150 km altitude (figure 2, middle). The height of the ionization is the typical stopping height for precipitating low-energy electrons with an energy of about 700 eV. The right panel of figure 2 is a volumetric image of the ion temperature in the F-region ionosphere above Resolute Bay, reconstructed from the 3D measurements from RISR-N. The data are visualized by showing horizontal slices at selected altitudes as well as a vertical slice behind it. The small black dots indicate the actual location of the 6×7 radar beam grid at each height. A strong enhancement of up to 2000 K is seen as a north–south-extended band. The enhancement coincides with the region eastward of the auroral arc, and moves with the arc through the radar field of view. In this region of enhanced ion temperature, the radar also measures a significant plasma depletion.

Polar cap auroral arc current system

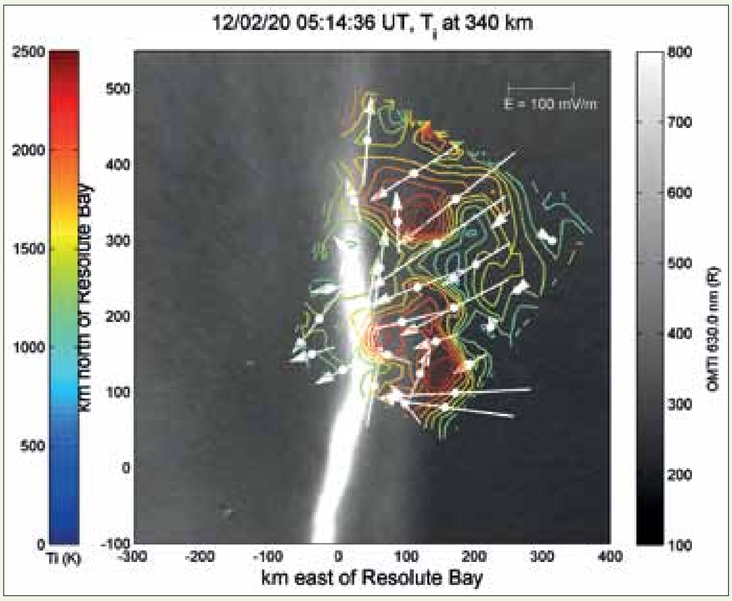
Combining the optical and radar measurements leads to a better understanding of the electrodynamics in and around the arc. In figure 3, ion temperature contours as measured with the radar are plotted on top of the optical image. It becomes clear that the ion temperature enhancement is situated not where the arc is, but adjacent to it, on the leading edge as the arc drifts overhead. RISR-N also provides measurements of the drifts of the ions in the ionosphere. In the F-region ionosphere the plasma is collisionless. The motion of the plasma is governed by the local **E**×**B**-drift, in a direction that is perpendicular to both the local electric field **E** and the geomagnetic field **B**. From the radar's measurements of the ion drifts it is thus possible to deduce the local electric fields around the auroral arc. The white arrows in figure 3 show the estimated horizontal electric fields in the vicinity of the arc. Strong (up to 200 mV/m)

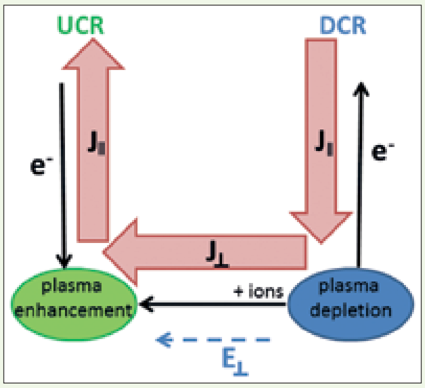
ynamics of polar cap aurora



2 (Left): OMTI all-sky image of the polar cap arc. (Middle): Height profile from one of the radar beams shows ionization at 150 km, coinciding with the crossing of the optical arc through that beam. (Right): Volumetric image of the ion temperature in the ionosphere as the arc passes the radar field-of-view. A band of temperature enhancements is seen east of the arc.

3: When plotting the ion temperature contours as measured by RISR-N on top of the optical image of the polar cap arc, it becomes clear that there is a region of enhanced ion temperatures adjacent to the optical arc, which moves with the arc. Electric field measurements (white arrows) indicate strong ionospheric fields in that region.





4: Sketch of an auroral current system. The precipitating electrons cause a plasma enhancement in the ionosphere. Strong electric fields will lead to frictional heating of the ions and a plasma depletion due to an enhanced recombination rate, both of which are seen in the radar data adjacent to the polar cap arc.

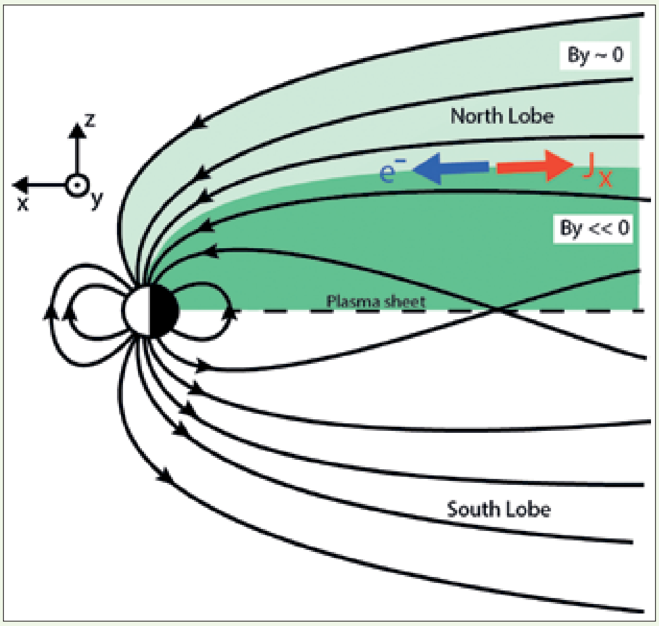
electric fields are seen in the region of the temperature enhancement, pointing towards the auroral arc.

The data indicate that we are seeing the signatures of an auroral arc current system that is typical in the auroral oval; the precipitating electrons that give rise to the auroral arc are associated with an upward field-aligned current, and the system is closed by horizontal currents in the ionosphere and a downward current adjacent to the arc. A schematic of this auroral current system is shown in figure 4. In the ionosphere, the horizontal electric field will cause frictional heating, which results in the observed enhanced ion temperatures, which in turn increases the ion–electron recombination rate, leading to an electron density depletion in the region.

Possible magnetospheric source

The ground-based OMTI and RISR-N instruments show evidence of a current system that is connected between the ionosphere and the magnetosphere. What physical process is responsible for generating such a current? One important clue is to find out whether the arc takes place on open or closed magnetic field lines; that is, are the field lines in the arc connected to the plasma sheet in the equatorial plane of the magnetotail, a source of hot and dense plasma, or do they map to the much less dense lobe regions, connected to the IMF in the solar wind? *In situ* particle data from spacecraft would be able to provide a direct answer to this, but unfortunately there were no satellites in or near the magnetospheric flux tube mapping to the arc at this time. However, the low energy of the precipitating electrons seems to indicate the latter: that the arc occurs on open field lines from the lobe.

A global network of coherent scatter radars, the Super Dual Auroral Radar Network (SuperDARN) provides, among other things, estimates of the ionospheric plasma flow pattern over the polar cap. These data show an anti-sunward plasma flow over the polar cap for an extended period of time before and during the observations of the arc. These flows are a signature of dayside reconnection, which means that the



5: Model of Earth's magnetosphere. As an interplanetary current sheet gets wrapped around the magnetosphere, the sheet slowly progresses through the magnetospheric lobe inward towards the plasma sheet. The observed gradient in IMF B_y is such that the current is directed in the negative *x*-direction, causing electrons to move down to the polar cap ionosphere.

interplanetary magnetic field is oriented such that magnetic reconnection between the geomagnetic field and the IMF was occurring on the dayside of the Earth. The newly connected field lines, on one side connected to Earth and on the other to the interplanetary medium, are then convected over the polar cap as the solar wind sweeps past Earth.

The Advanced Composition Explorer (ACE) spacecraft is located in the Lagrangian point between the Sun and Earth and provides continuous measurements of the IMF in the solar wind "upstream" from the Earth. A short while before the polar cap arc appeared over Resolute Bay, the *y*-component of the IMF, IMF B_y, underwent a sudden and rapid change from strongly negative (–10 nT) to zero. Wherever there is a strong gradient in a magnetic field, a current will exist, as described by Ampère's law. The solar wind must then be carrying with it a current sheet, which becomes connected to the geomagnetic field through the dayside reconnection and wrapped around Earth's magnetosphere. Figure 5 shows a sketch of Earth and the central parts of the magnetosphere, where the black lines indicate the configuration and direction of the magnetic field. The Sun is to the far left, and the magnetic field lines on the right-hand side of the sketch do not just end but are connected to the IMF (not shown in the sketch). When the polar cap arc passes over Resolute Bay, the sharp B_y gradient will have reached a distance of about 30 Earth radii (R_E) down the tail of the magnetosphere. The magnetic field lines that wrap around Earth will slowly merge inward towards the plasma sheet in the tail, so that at 30 R_E down the tail, the current sheet would have become oriented in the *x*–*y* plane and reached into the north lobe region of the magnetotail, as illustrated in figure 5. Closer to the plasma sheet the field lines are older, and hence have a stronger twist arising from a large IMF B_y component. The current will move electrons towards the polar cap ionosphere, where they may give rise to the observed auroral emissions. These electrons will, according to this model, be low-energy electrons on open field lines that map out to the magnetospheric lobe, which is consistent with the observations from the ground. Calculations of the magnitude of the current from the plasma sheet that is redirected into the ionosphere are also comparable with the measured field-aligned current estimated from the optical and radar data.

"It is likely there will not be one common process to account for the variety of polar cap auroral structures"

A picture emerges

The ground-based measurements indicate that the transient polar cap arc observed over Resolute Bay on 20 February 2012 may have been caused by electron precipitation from the magnetospheric lobe region, where the geomagnetic field lines connect to the interplanetary magnetic field. It is possible that an interplanetary current sheet that travels with the solar wind and reaches Earth can couple to the ionosphere through reconnection between the magnetic field lines in the solar wind and those in the magnetosphere. The precipitating electrons carried by the current will be low-energy electrons transported on open field lines down to the ionosphere, where they deposit their energy by exciting atmospheric species to give auroral emissions. The data support this theory, but there are several remaining uncertainties and assumptions made regarding this interpretation. The observations from the ground show not just one auroral arc at the time, but a train of arcs, with the one discussed here being the brightest. It seems possible that rather than drawing a static picture of a magnetospheric source, the arcs may be generated in a coupled system between the solar wind, Earth's magnetosphere and ionosphere, where the ionosphere plays an active role. Alfvén waves travelling between the regions can be reflected and secondary waves generated, leading to a bifurcation of the current sheet. At the time of the sudden change in IMF B_y from strongly negative to zero, there is also a change in polarity of the *z*-component, which changes direction from positive to negative. This abrupt change will cause a large-scale reconfiguration of the magnetosphere, and it is not clear what impact this change has on the formation of the polar cap arc.

Many questions remain before we can get a full understanding of the dynamic processes behind the aurora that occurs in a region generally without auroral arcs. It is most likely there will not be one common process to account for the variety of polar cap auroral structures that can be seen. With the development of more sophisticated instruments and by combining data sets, we are at a point where we can improve our understanding of the electrodynamic processes that couple the ionosphere and magnetosphere in the high-latitude regions. ●

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