EISCAT radar and optical studies of black aurora: a signature of magnetospheric turbulence?

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Abstract: Black auroras are recognised as spatially well-defined regions within a uniform diffuse auroral background where the optical emission is significantly reduced, or possibly totally absent. Black auroras typically appear post-magnetic midnight and during the substorm recovery phase, but not exclusively so. Their horizontal size is typically 1x5 km, elongated in the east-west direction, and they move predominantly in an eastward direction with a speed of 1-4 km/s. There is no accepted theory for the phenomenon of black aurora, although they seem associated with substorms. We report on the first incoherent scatter radar observations of black aurora by EISCAT, coupled to white-light TV recordings of the phenomenon. From a 2002 observation, we show that non-sheared black auroras are most probably not associated with field-aligned currents. From 2002 and 2003 observations, we show that the apparent motion of the black aurora is most probably controlled by the drift of particles in the magnetosphere and not ExB drift in the ionosphere. The drift speed is therefore dependent on the energy of the precipitating particles forming the diffuse background. From 2005 bi-static observations, we attempt to confirm this by relating the height and propagation speed of the black aurora to precipitating particle energy within the surrounding background diffuse aurora. Hence, the mechanism for black aurora is most probably active within the magnetosphere and substorm associated plasma turbulence within the magnetosphere may account for the optical morphology of the black aurora, in particular the lack of pitch angle diffusion into the loss cone.

Key words: Black aurora.

1. Introduction

Black auroras, first reported by [1], are regions devoid of optical emissions, occurring within the normal aurora, where an observer may reasonably expect aurora to be normally present, i.e. not just a black sky. They are a fairly common phenomenon, which has been under-reported in the literature. Their morphology has been studied from the ground by [2, 3, 4] and their main features have been summarised by [5]: Black auroras are mostly east-west aligned arc segments or patches, with a typical size of 0.5-1.5 x 2.5-5 (up to 20) km. They normally occur post-substorm, typically in a diffuse aurora background, and drift eastward post-magnetic midnight with a typical velocity of 0.5-1.5 (up to 4) km/s. They may exhibit shear or vortices. Although the mechanism is unknown, satellite observations suggest they occur in regions of downward field-aligned current. In many respects, the black aurora is analogous to the negative of normal aurora [2]. Hence, just like normal aurora, the different morphologies of the black aurora (e.g. sheared forms showing vorticity versus un-sheared forms having smooth boundaries) may be due to different mechanisms.

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2. Satellite Observations

Although no optical observations were available to confirm the presence of black auroras, [6, 7, 8] found small regions (down to $\approx 1-2$ km) of excess positive space charge in FREJA satellite data at auroral latitudes in the altitude range between 800 and 1700 km. These observations they associated with intense diverging electric fields (up to $\approx 1-2$ V/m), downward field-aligned currents, depletion of the thermal background plasma, dropouts of precipitating electrons, and strong wave activity. They speculated that the satellite observations were associated with east-west aligned black aurora vortex streets. [7, 8] found that the black aurora is the optical and electrodynamical counterpart to small-scale auroral forms.

In joint aircraft-based optical and FAST satellite observations, [9] found that the black vortex streets consisted of spatial regions where the pitch angle diffusion was strongly suppressed for > 2 keV electrons, causing precipitation dropouts of the higher energy particles. They estimated the altitude of the aurora immediately adjacent to the black aurora to be 115 km.

3. Radar Observations

The first combined radar-optical observations were performed by [10] from Skibotn, Norway. They found that the drift velocity of un-sheared black arc segments had no relationship to the ionospheric E-region ExB plasma drift as inferred by the Scandinavian Twin Auroral Radar Experiment (STARE), although both drifts had the same general direction, i.e. eastward.

The un-sheared black aurora, embedded in a diffuse background, was studied by [11, 12] using the European Incoherent Scatter facility (EISCAT), located near Tromsø, Norway, in

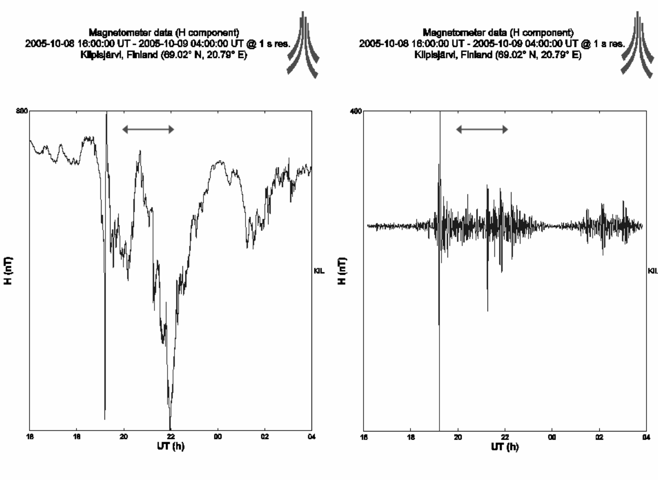

Fig. 1. SAMNET magnetometer data (left panel) showing the period when black auroras were observed (arrows). These data have been filtered to highlight Pi2 pulsations (right panel), indicating substorm onset prior to the onset of the black auroras.

conjunction with the ODIN night-vision TV camera. No evidence for ionospheric plasma depletion within the black aurora was found [11]. The first ever westward traveling black aurora was reported [12]. The black aurora drift speed had no relationship to the ionospheric F-region plasma drift [12]. However, significantly, the black aurora drift velocity was related to the characteristic energy of the precipitating particles within the adjacent diffuse aurora, as inferred from the EISCAT data [12, 13](ignoring the single westward observation). This result suggests that the black aurora are the result of a magnetospheric mechanism, as the eastward gradient-curvature drift velocity of magnetospheric electrons is energy-dependent.

4. New Results

In order to further address the relationship between the drift speed of the un-sheared black aurora and the precipitating particle energy in the adjacent diffuse aurora, bi-static optical observations in conjunction with the EISCAT radar were undertaken. The concept was to check whether the black aurora drift speed related to the height, and therefore the precipitating particle energy, of the diffuse background aurora. Here we report on the initial results.

On 8 October 2005, the DASI TV imager was located at the EISCAT radar site, recording in white-light with a $\approx 30°$field of view and pointing into the magnetic zenith. The ODIN TV imager was located 27 km away, also recording in white-light with a similar field of view and pointing into the common volume. The EISCAT UHF radar was performing a 7-position scan for an unrelated purpose, pointing into the magnetic zenith once every 5 minutes. Black auroras were observed in the interval 20-22 UT. Fig. 1 shows the unfiltered (left panel) and filtered (right panel) SAMNET magnetometer data for this event from Kilpisjärvi, Finland. It is clear that the black aurora not only occurred during a negative bay (left panel), but the Pi2 activity (right panel) indicates a substorm onset ≈ 40 minutes prior, which is consistent with the black aurora appearing in substorm recovery phase.

Fig. 2 (top row of panels) shows optical data from DASI, clearly showing evidence of un-sheared black auroras. The blue dot indicates the EISCAT UHF radar pointing direction along the magnetic field direction. Fig. 2 (middle row of panels) shows the electron density profile from EISCAT. The red dot indicates the mean altitude of the surrounding diffuse aurora, inferred from bi-static triangulation of the black aurora. The altitude is in the range $\approx 110-115$ km, consistent with [9]. Fig. 2 (bottom row of panels) shows the precipitating particle energy spectrum, inferred from the EISCAT data [13]. There is a peak in the spectrum around 3-6 keV, which is consistent with the inferred altitude.

Fig. 3 shows an example of the bi-static tomographic inversion from 22:24:19 UT. The retrieval of the volume emission rates was a simplified version of [14] where we use the DASI images for the column emission rate and then search for the best fit between images from both DASI and ODIN. The top panels show the raw white light data, with red intensity contours overlaid, for DASI (left) and ODIN (right). The black aurora arc is seen diagonally bottom-left to top-right in the DASI image and in the bottom left quadrant of the ODIN image. The bottom panels show, in false colour, horizontal (left) and vertical (right) cuts through the diffuse aurora layer, which include the black aurora. Again, the black aurora is clearly seen diagonally top-left to bottom-right in the horizontal cut and in the bottom left quadrant of the vertical cut.

5. Conclusion

The evidence to date suggests that sheared black auroras (vortex streets) are associated with space charge, downward field-aligned currents and thermal plasma depletion, whereas the un-sheared black auroras (arc segments) are not. Since black auroras always seem to occur post-substorm, are clearly regions devoid of particle precipitation, and their drift velocity appears to be energy-dependent, it is proposed that the black auroras are "images" of small-scale flux tubes of stably trapped particles within the magnetosphere [15], which occur as a result of substorm activity. The mechanism remains unknown.

The un-sheared black auroras often give the impression of turbulence, similar to smoke rising from a fire. This analogy suggests an association between the black auroras and post-substorm plasma turbulence, which may be due to the intermingling of hot electron fluxes with the cold background plasma population.

In addition, the radar observations described for un-sheared black aurora arc segments, compared to the satellite observations described for observed or inferred black vortex streets, suggests that the black aurora has at least two different mechanisms associated with it.

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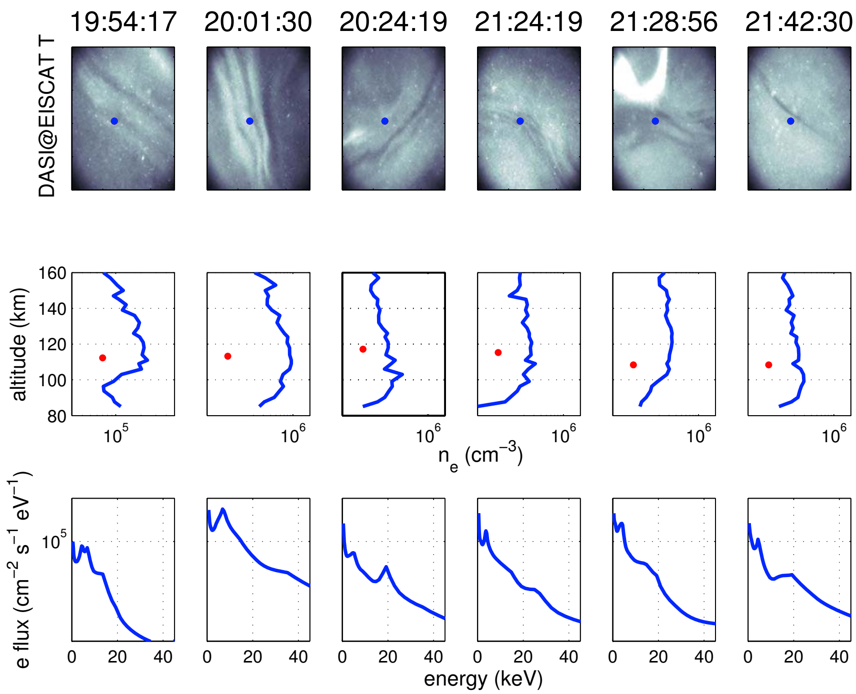

Fig. 2. Data from the 8 October 2005 campaign taken at Tromsø, Norway. The top row of panels show white-light optical data from DASI with a $\approx 30°$field of view, clearly showing evidence of black auroras. The blue dot indicates the EISCAT UHF radar pointing direction along the magnetic field direction. The middle row of panels show the electron density profile from EISCAT. The red dot indicates the mean altitude of the black aurora, inferred from bi-static triangulation. The bottom row of panels show the precipitating particle energy spectrum, inferred from the EISCAT data.

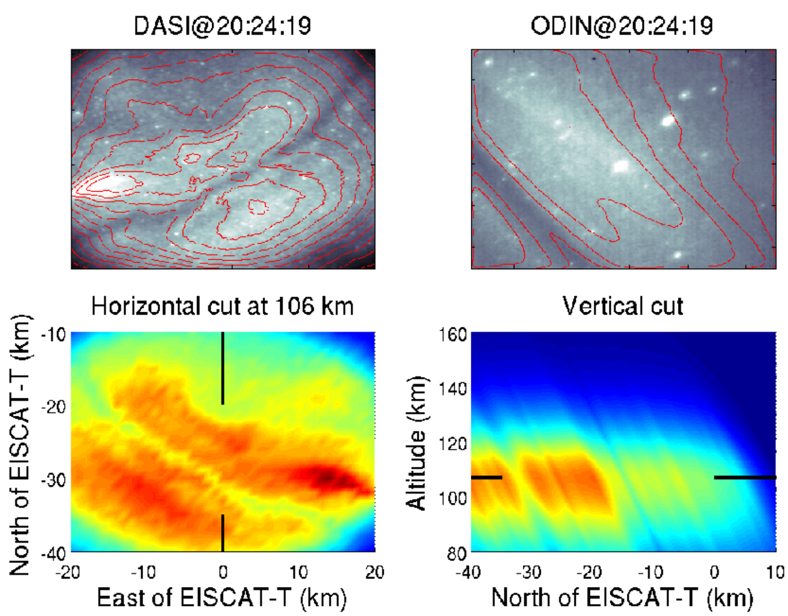

Fig. 3. Bi-static white-light recordings of the black aurora on 8 October 2005 (top panels) with intensity contours (red lines). The same black auroral "arc" is seen in both images. False-colour horizontal and vertical cuts through the tomographic reconstruction of the black aurora (bottom panels).

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