

Energy Inversion Calculations for Vortical Structures on March 21 and March 22, 2026

The values for energy and energy flux in Table 1 are calculated using the absolute intensities of three auroral wavelengths measured by the all-sky imager at Poker Flat Research Range. The technique, based on Grubbs 2018 (and references therein), is described in Zhou and Hampton (2025) for the January 1, 2024, event, and the same analysis was applied to the March 21, 2025, event, shown in Figure S1. The event on March 22, 2025, involved diffuse aurora with much lower surface brightness and required closer scrutiny to avoid issues related to low signal-to-noise ratio (SNR) in the resulting images.

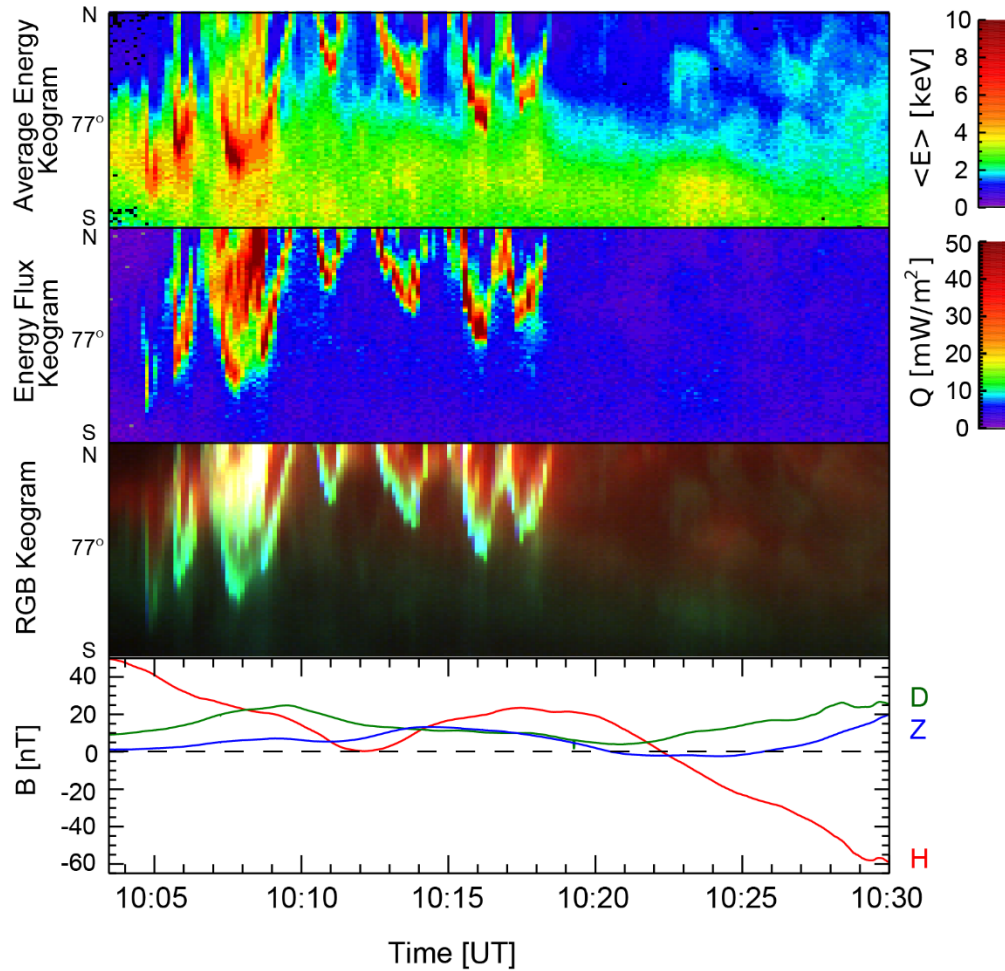


Figure S1. Keograms and the ground magnetogram of the vortex event on March 21, 2025. Keograms are N-S slices from 62° to 92° , from south to north, with the magnetic zenith at 77° at the center. The top two panels show the average

energy and energy flux, calculated using the method described in Zhou and Hampton (2025) and Grubbs et al (2018). The third panel shows the intensities of the red, green, and blue lines. The bottom panel shows the variation in local magnetic fields as measured by the Poker Flat magnetometer.

The method for determining both the energy and energy flux is the same as for the active aurora. The energy flux is proportional to the brightness of the (0,1) band of the N_2^+ first negative series at 427.8 nm (blue line) for average energies above 1 keV. We use a conversion factor of 245 [R / (mW/m²)] to produce energy fluxes from the images [Grubbs et al. 2018, Strickland et al., 1989]. The average energy is determined by examining the ratio of the O (¹D) red-line emission at 630.0 nm to the O (¹S) green-line emission at 557.7 nm. Due to the long lifetime of the forbidden transition of the O (¹D), the emission is heavily quenched by collisions at lower altitudes. Therefore, the brightness vs energy curve has a negative slope. The green line intensity increases with electron energy. Therefore, the ratio of the red to green lines is a strong function of the average energy of the precipitating electrons. This relationship is estimated using an electron transport code (GLOW, Solomon, 2001) for Maxwellian electron distributions ($N(E) dE = N_0 \exp(-E/a) dE$ [e⁻ / cm² / s² / eV], where a is the energy at the peak of the distribution, i.e. the characteristic energy) to produce profiles of the volume emission rates of several emissions including the red, green and blue used here. The column-integrated volume emission rates are converted to surface intensities in units of Rayleighs (mega-photons / cm² / s). Tables of red-to-green ratios are created over a range of characteristic energies and energy fluxes, similar to those seen in Grubbs et al. (2018), Figure 3 (who used the 844.6 to 557.7 ratio).

For bright, active, and breakup auroras, intensities are typically several thousand Rayleighs (R), with signal-to-noise ratios well above 100, as on January 1, 2024 (see Zhou and Hampton 2025), and March 21, 2025. For March 22, the surface brightness of the diffuse aurora is on the order of

1000 R for the green line, and 200 to 500 R for the red and blue lines. This corresponds to SNRs below 10 for most of the region of interest. Unlike the profile plots in Zhou and Hampton (2025), profiles along single columns of pixels largely show random noise, which makes them difficult to interpret. Co-adding multiple columns helps reduce random noise, but the structure of interest in the bottom row of Figure 2 is small enough that co-adding columns would smear out the structure we want to examine. We found that examining the energy parameters in image form was more illuminating.

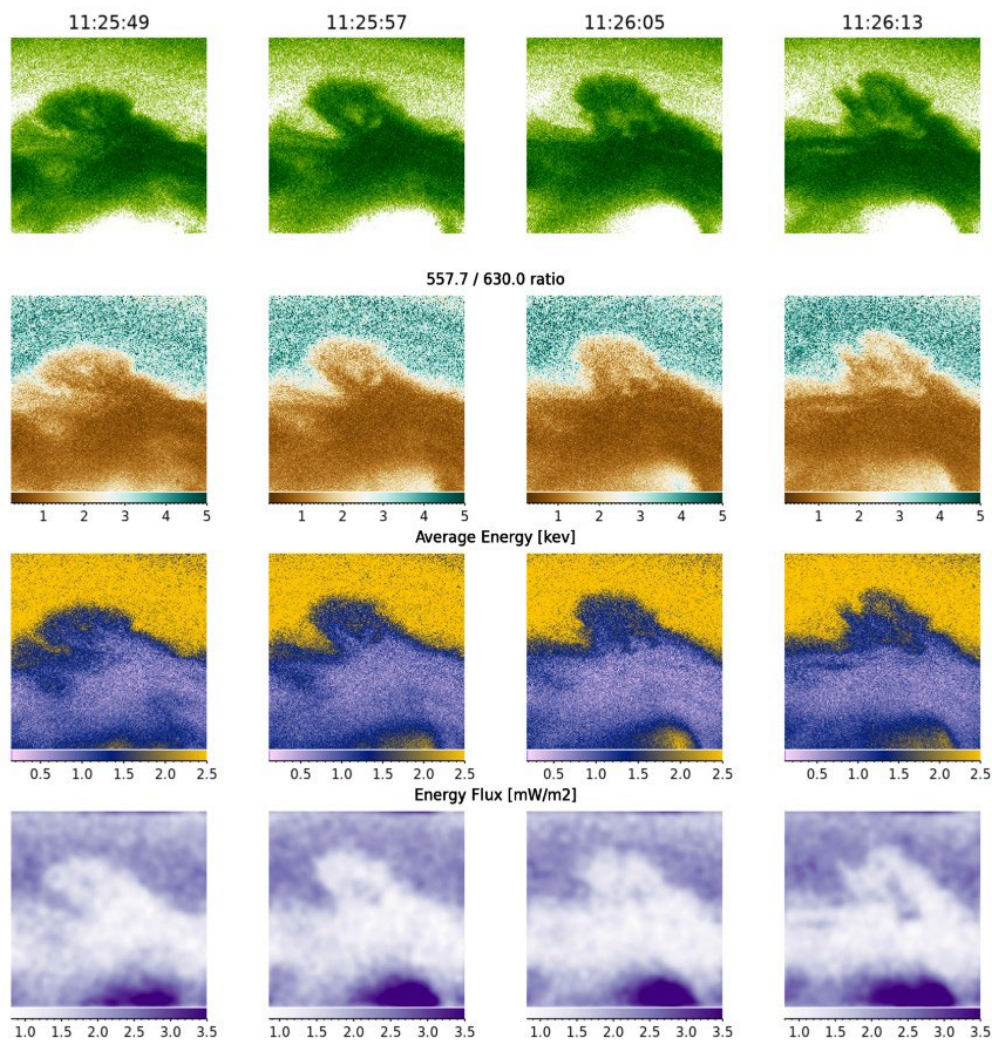
Care was taken to find the correct background level by subtracting the camera background outside of the all-sky field of view and the signal level in the low-intensity gap between the diffuse aurora and discrete aurora seen in Figure 2 and Figure S2. This ensured that the energy calculations were based on emission intensities produced by electron precipitation, rather than any background illumination (airglow or light pollution).

From the top to bottom row, Figure S2 shows the green-line intensity, the green-to-red ratio, the average energy, and the energy flux at four times during the development of the black vortex on March 22, 2025, between 11:25:49 and 11:26:13 UT. The 427.8 nm blue images (not shown here or in the paper) had the lowest signal-to-noise, and the resulting energy flux calculation showed largely random noise. We applied a low-pass filter to the image to reduce the random noise, which enabled us to see the mid-sized structures associated with the black vortex. The image orientation is the same as in Figure 2, with S at the top and E to the right.

These sub-images show three areas of interest. At the top (to the south) is a region of uniform diffuse aurora, which often develops after midnight. The energy flux is about 2 to 2.5 mW/m², and the average energy is uniformly 2 to 2.5 keV. The dark gap between the southern diffuse and northern discrete auroras in the green-line images shows essentially no energy flux when

59 examining the blue-line emission and correspondingly low average energy. The area of particular
 60 interest is the region of enhanced intensity in the center of the black vortex. This shows slightly
 61 lower energy flux and significantly lower average energy than the diffuse aurora.

62 The difference in average energy hints that this central spot is not just an island of diffuse aurora
 63 and argues that its source differs from that of the diffuse aurora. We suggest that a possible source
 64 could be the upward field-aligned current as illustrated on the left of Figure 1b.



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 66 Figure S2. Analyzed images from the black auroral vortex event on March 22, 2025, showing the intensity of the green
 67 line emission (top row), the ratio of the green line emission to the red line emission (2nd row), the average energy

68 calculated from that ratio (3rd row), and the energy flux determined by the blue line emission (bottom row). South is
69 at the top of the images, and East is to the right (as if an observer is facing N and looking up at the sky). During the
70 calculation, the blue line emission images were smoothed to reduce the high level of random noise (due to low SNR).

References:

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