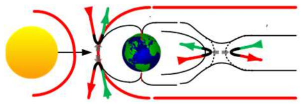
Solar & Geomagnetic Storms 23-24 March 2024

Whitham D. Reeve



Solar activity reached high levels during the early UTC morning on 23 March with an X1.1 x-ray flare first observed at 0058 and peaking at 0133 (figure 1). Associated with the flare were radio bursts over a very wide frequency range including a Type II slow radio sweep, which was detected between 30 and 75 MHz at the Cohoe Radio Observatory in Alaska in e-CALLISTO data at 0109 (figure 2). Type II sweeps and coronal mass ejections (CME) often go together. In this case, a halo CME was observed by the SOHO spacecraft during the same time period (figure 3). According to the Space Weather Prediction Center (SWPC) Forecast Discussion for 24 March at 0030, the CME signature *contained plasma from multiple sites on the Sun*.

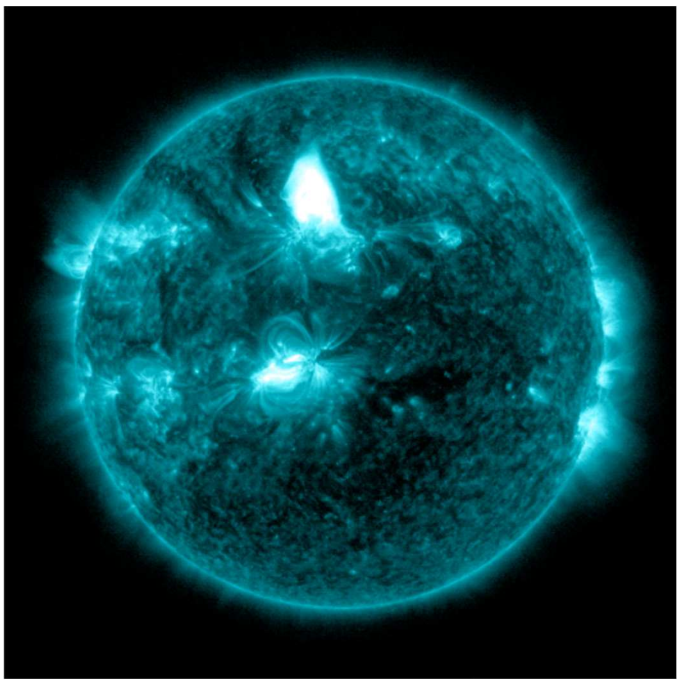


Figure 1 ~ Simultaneous x-ray flares early on 23 March from two different sites and pointed practically head-on toward Earth. This false-color image was produced by the SDO spacecraft using an extreme ultraviolet (EUV) sensor designed to highlight the extremely hot material in flares.

The flares produced a variety of radio bursts including Type VI (series of Type III fast sweep bursts over a period lasting more than 10 minutes and no period longer than 30 minutes without activity), long-lived broadband continuum over 3 octaves in the VHF band and Type II. Image credit: NASA/SDO

About 2.5 hours after the flare, at 0400, the 10 MeV proton flux measured by the GOES-18 spacecraft started to rise and reached the warning threshold of 10 particles $cm^{-2}\ s^{-1}\ sr^{-1}$ at about 0800 (figure 4). The average speed for these particles was about 16 700 km s^{-1} or 5.6% of the speed of light. The 50 MeV proton flux also increased but did not exceed the warning threshold. The high proton flux was able to penetrate the geomagnetosphere, causing a solar energetic particle (SEP) event. The SEP, in turn, increased the electron density in the high-latitude D-region ionosphere, which induced high levels of absorption in the HF band that lasted a few days (figure 5).

Transient CME effects were observed by the ACE spacecraft (1.5 million km from Earth along the Sun-Earth line) at 1411 on 24 March. The travel time from Sun to ACE was only 37 hours, giving an average speed of 1100 km s^{-1} for the plasma mass. The subsequent impact of the CME with Earth's magnetosphere 26 minutes later at 1437 rapidly compressed the magnetosphere and produced a sudden storm commencement (SSC) in the form of a sudden impulse. At the time of the shock, the solar wind speed measured at the ACE spacecraft was 800 km s^{-1}.

The CME impact and associated relatively high solar wind speed directly affected the *auroral oval* and the *auroral electrojet*. The auroral oval, which maps the footprint on Earth of open magnetic field lines and along which aurora is produced, was significantly expanded and pushed equatorward by fast high solar wind (figure 6). The auroral electrojet is a huge current system that flows in the neighborhood of 90 to 150 km altitude (ionosphere's E-region) in the auroral oval. It is the only magnetospheric current system whose effects can be measured by ground magnetometers.

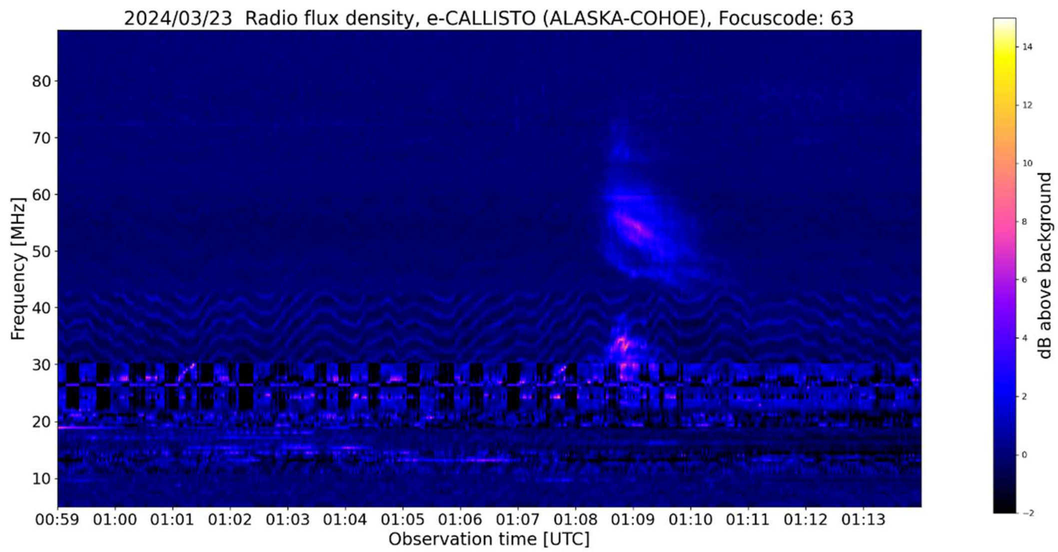


Figure 2 ~ Type II slow radio sweep between 25 and 75 MHz seen as two puffy features one of which is seen to sweep downward in frequency. The horizontal features below 30 MHz are shortwave stations. Image credit: FHNW Brugg/Windisch and IRSOL Locarno, Switzerland and W. Reeve

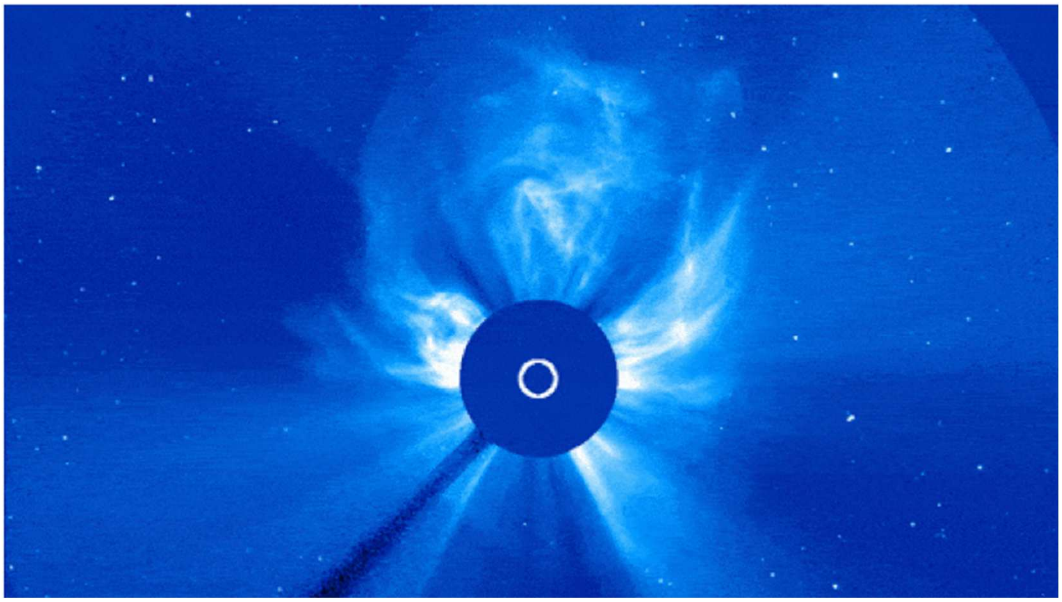


Figure 3 ~ Halo CME resulting from the flares on 23 March. The dark-blue occulting disk is designed to block the bright Sun from the SOHO spacecraft coronagraph so it can image the relatively dim CME structures. The Sun is represented to scale by the white circle. Image credit: NASA/SOHO

The open magnetic field lines, with footprints on Earth below the auroral oval, opened a gap in the magnetosphere and allowed precipitation of solar energetic particles into the upper atmosphere where they collided with atoms and molecules. The collisions increased the ionization and, thus, the electron density and conductivity in the region. Charge imbalances in the region produced strong horizontal electric fields, which along with the high conductivity caused large variations the electrojet current.

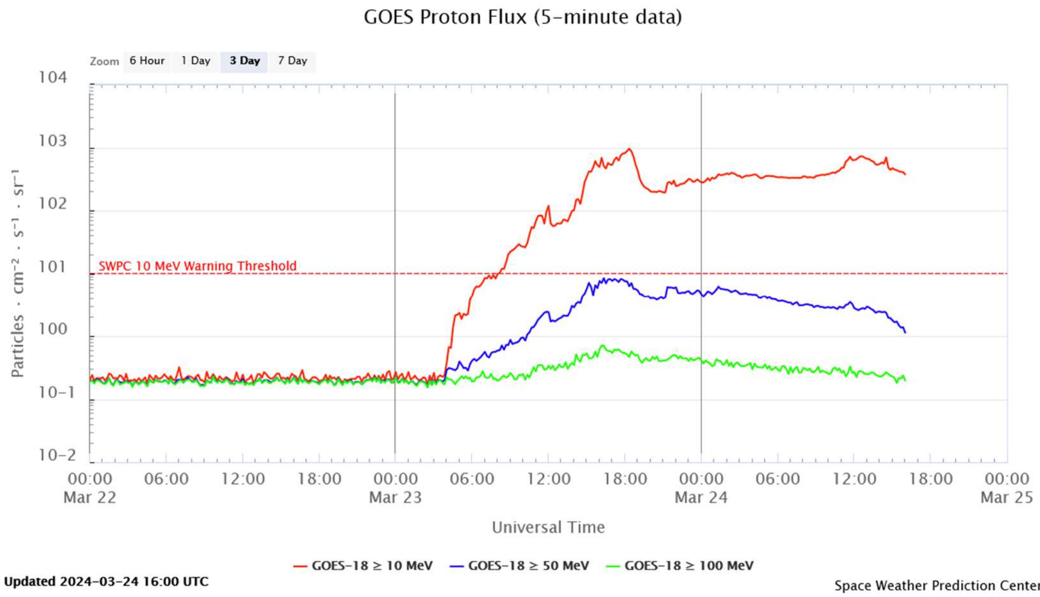


Figure 4 ~ 3-day GOES-18 Proton Flux plot showing 10, 50 and 100 MeV measurements. The flux began to rise at 0400 on 23 March giving 2.5 hour time of flight from Sun to spacecraft and an average speed of 5.6% speed of light. Image credit: NOAA/SWPC

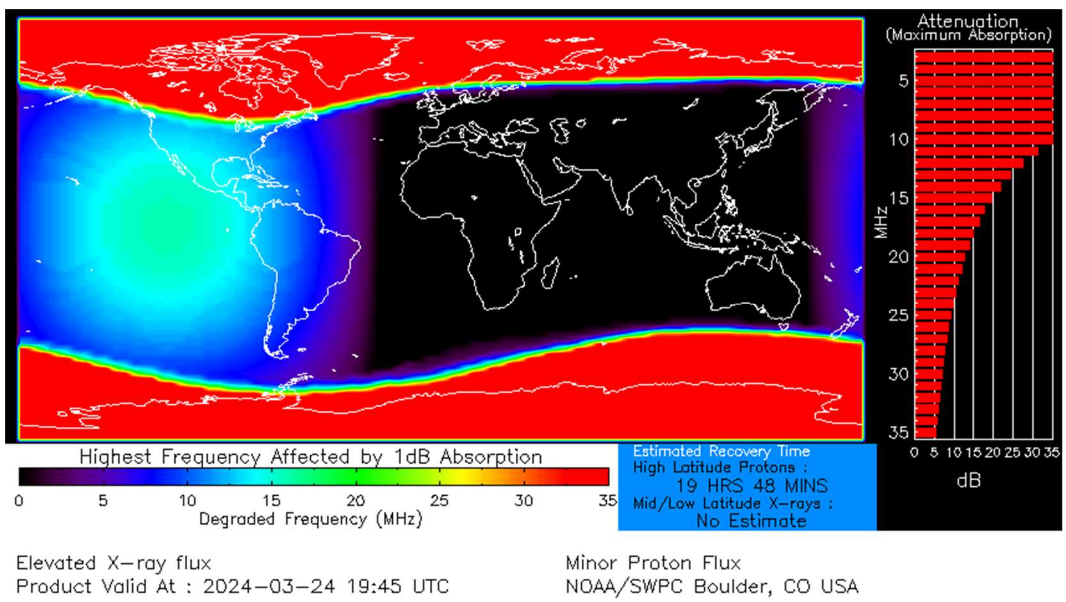


Figure 5 ~ D-region absorption prediction at 1945 on 24 March showing heavy absorption, which are indicated by the red bands at high latitudes. This plot shows that absorption was still at elevated levels almost 2 days after the x-ray flares on 23 March and was expected to continue for another 20 hours. Note the very high levels of absorption at lower frequencies indicated on the right-side bar graph. The elevated absorption likely led to radio blackouts on HF radio propagation paths within the red areas. The green-blue round feature over the Pacific Ocean west of Panama is the predicted effect of a relatively low level flare about 1 hour earlier. Image credit: NOAA/SWPC

The auroral electrojet effects are characterized by the AE index, which is composed of the AU, AL, AE and AO indices (figure 7). The AU and AL define the upper and lower envelopes of magnetic measurements from selected northern hemisphere high-latitude stations and express the strongest current intensity of the eastward and westward auroral electrojets, respectively, at any given time.

AE is the difference between AU and AL and AO is the average of AU and AL at any given time. Thus, AE represents the overall or peak-to-peak activity of the electrojets and is always positive. AO provides a measure of the equivalent current flows and may be positive or negative at any given time. AO was primarily negative during the disturbance on 24 March, indicating a westward current flow in the auroral oval. Both AE and AO ran off-scale at about 1600.

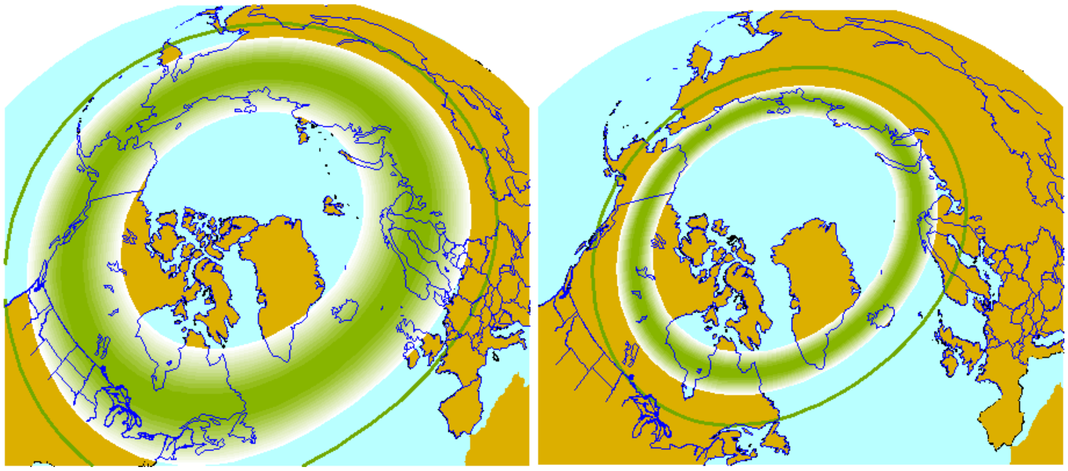


Figure 6 ~ Left: Prediction of the northern hemisphere Auroral Oval, shown by the green belt, for the time period following the solar flares of 23 March. The thinner green line circling the oval shows the boundary of the auroral zone, above which aurora may be observed. Right: Magnetically quiet day for comparison. Image credit: University of Alaska Fairbanks Geophysical Institute.

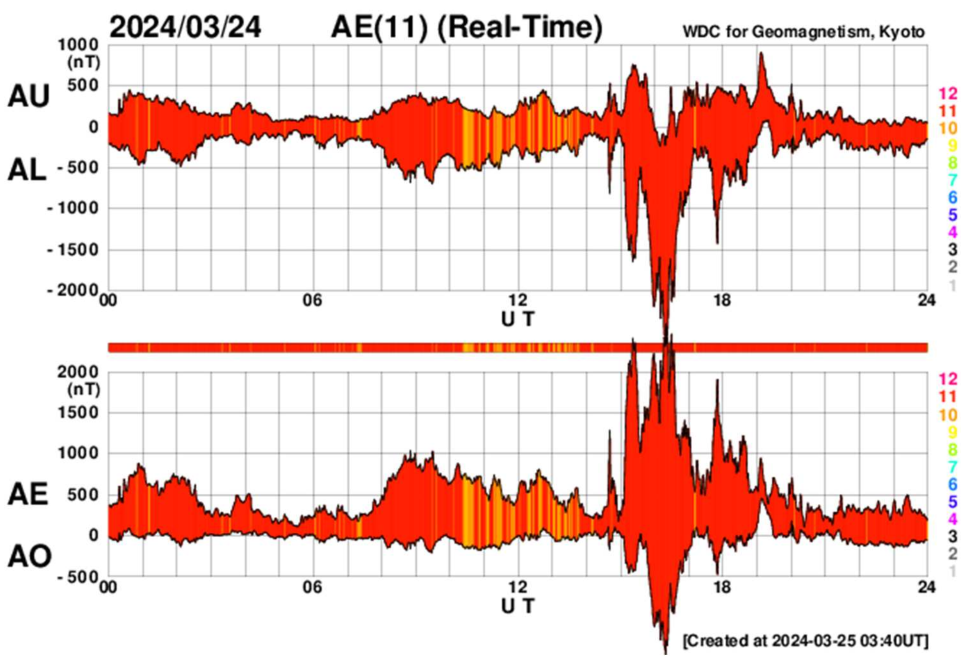


Figure 7 ~ Auroral Electrojet Indices AU, AL, AE and AO (see text). Image credit: World Data Center for Geomagnetism, Kyoto

The westward current flow produced a magnetic field that opposed Earth's internal magnetic field measured on the ground at Anchorage and HAARP (figure 8). The opposition manifested as a decrease (bay) in the horizontal component of the geomagnetic field that may be directly compared to the AE index plots. During the 1500 to 1800 UTC synoptic period, the SAM-III magnetograms at Anchorage Radio Observatory and HAARP Radio Observatory in Alaska both displayed the highest possible K-index of K9. The K-index provides a 3-hour summary of peak-to-peak magnetic activity. It generally is designed to represent the horizontal (H-) component of the magnetic field, but the SAM-III reports a pseudo-index for each of the three magnetic components, X, Y and Z.

As seen in the Anchorage and HAARP magnetograms, the X- (east-west) and Y- (north-south) components of the magnetic field were reduced from the baseline by 1750 and 750 nT, respectively, at Anchorage and 2000 and 1850 nT, respectively, at HAARP. The reductions in the east-west component represent roughly 50% of the steady-state east-west magnetic flux densities measured on the ground. For the north-south component, the reductions represent roughly 5% at Anchorage and 14% at HAARP of the steady-state magnetic flux densities. These changes highlight the immensity of the enhanced current flow during the geomagnetic storm.

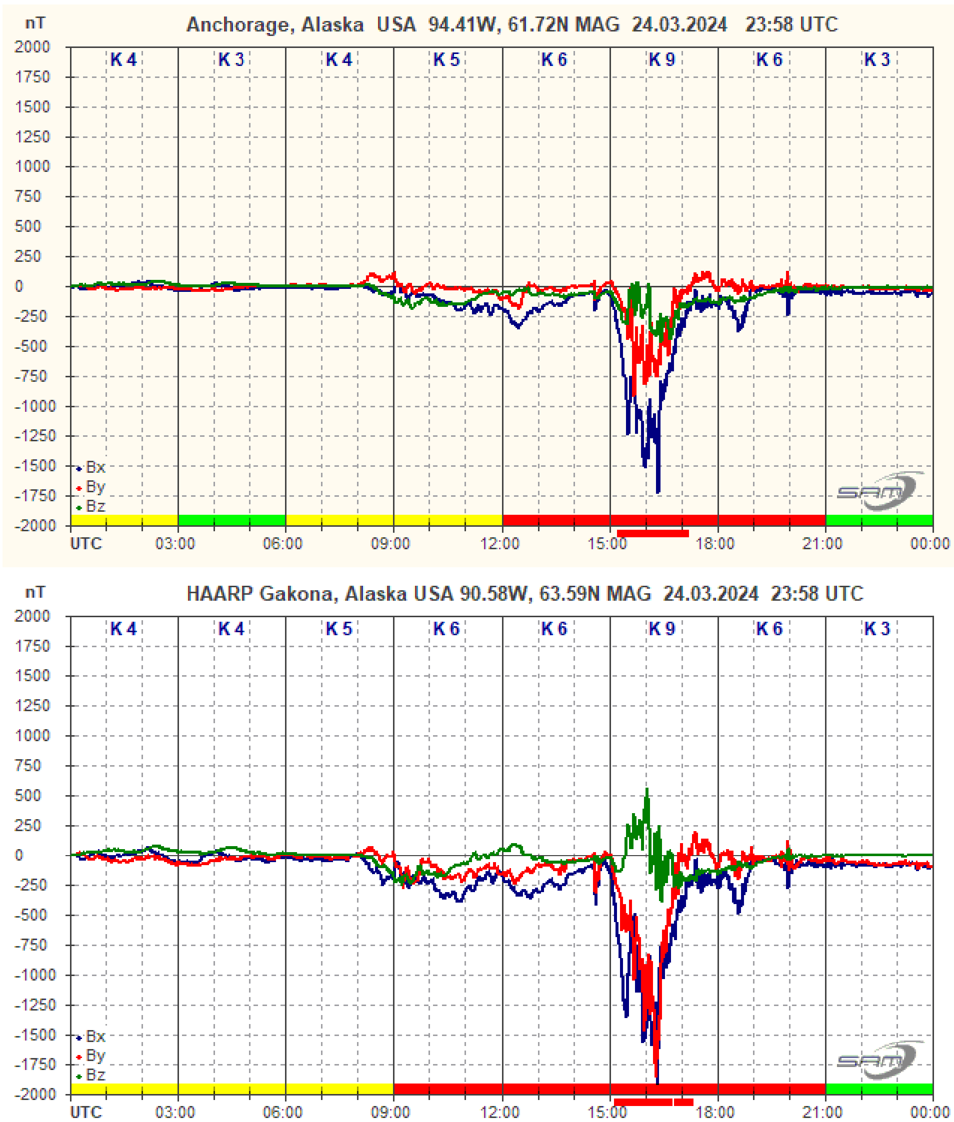


Figure 8 ~ Magnetic field measurements at Anchorage Radio Observatory (upper) and HAARP Radio Observatory (lower) for 24 March. The sudden impulse is clearly identifiable as the downward pulse between 1400 and 1500 UTC at both locations. The sudden impulse amplitude at Anchorage, approximately 200 nT, is one-half the amplitude as at HAARP but still considered quite strong. The reductions in the X- and Y-components around 1620 UTC are a significant percentage of Earth's internal magnetic field (see text). Image credit: © 2024 W. Reeve

Author: Whitham D. Reeve, Anchorage, Alaska USA

Revision: 0.0 (Initial draft, 24 Mar 2024)
0.1 (Substantial updates and added images, 29 Mar 2024)
0.2 (Reformatted images in tables, 30 Mar 2024)
0.3 (Edits for clarity, 31 Mar 2024)

Word count: 1450
File size (bytes): 5303438