

# Project Fys3600

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## 1 Introduction

As society moves towards more automatization, accurate, globally available navigational tools are coming in demand. A solution to this is using satellites. There are some problems however. Satellites (and in some cases even earthbound equipment) are susceptible to bad space weather. Having your self-driving car suddenly acting up is not desirable. Predicting when equipment will be in danger of getting hit by high energy particles is therefore of interest.

In this report, we will be looking at data from several instruments measuring properties of the solar wind and the interplanetary magnetic field (IMF) along with auroras and some ionospheric currents from 06.01.2011. We will also be looking at some potential consequences of the measurements.

## 1.1 Theory

### 1.1.1 The Sun:

The root of all our problems is the star in the center of our solar system: the sun.

#### IMF

The sun, like the earth, has a magnetic field. This magnetic field stretches throughout the solar system, and has fittingly been dubbed the interplanetary magnetic field. What causes this magnetic field is beyond the scope of this report, but it is seemingly quite erratic, changing sign and field strength often.

Something more constant about the imf is the general direction of the field lines. Due to the rotation of the sun, the magnetic field lines end up looking like archimedian spirals (or a ballerina skirt in 3 dimensions).

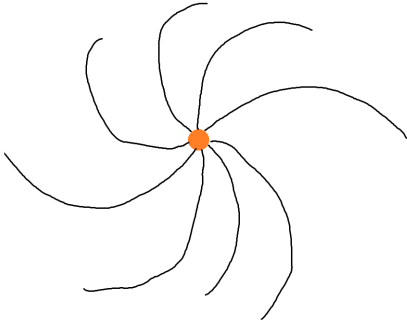


Figure 1: An artistic rendition of the interplanetary magnetic field. With the sun in the middle and rotating, the magnetic field lines end up forming archimedean spirals.

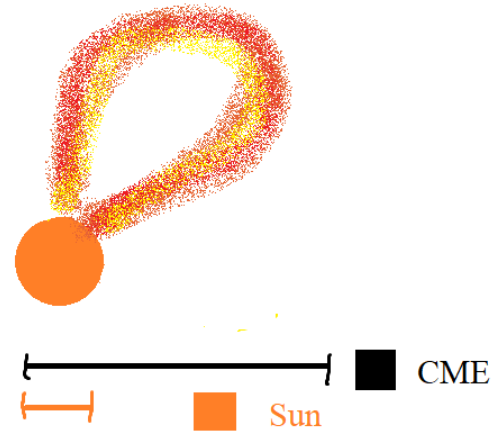


Figure 2: Artistic size comparison between the sun and a possible cme. As one can see, the cme can be many times larger in size than the sun.

### Solar Wind

Accompanying the magnetic field lines is plasma streams. Ejected from the sun's corona, these plasma streams of varying velocity and density can also be drawn like figure 1.

Carrying large amount of highly energized ionized particles, the solar wind is of great interest to us. Knowing the density and velocity of the solar wind is necessary in understanding the consequences of its interactions with earth and its satellites.

### Coronal mass ejection and solar flares

There are events where the sun sends out relatively huge amounts of plasma and radiation.

One such event is a solar flare. A solar flare is a massive outburst of radiation happening in the lower corona. Being composed of mostly photons, a solar flare does not follow the magnetic field lines. Another such event is a coronal mass ejection (CME). During times of magnetic unrest, the sun might eject massive amounts of mass from its corona. Such outbursts are sometimes several times larger than the sun in diameter. The mass ejected follows the magnetic field lines, and ends up causing a spike in the solar wind density, something that can be harmful to instruments on earth.

### 1.1.2 The Magnetosphere:

Like the sun, the earth also has a magnetic field.

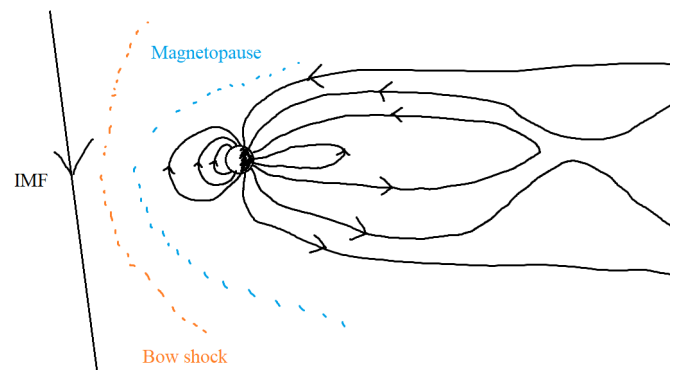


Figure 3: The earth's magnetosphere. Note that it looks a bit different when the IMF Z component has the same sign as earth's (in the figure, they are opposite).

The earth's magnetic south pole is currently located on the north pole. This means that the magnetic field goes from the geographical south pole to the geographical north pole. In figure 3, this is indicated by arrows pointing along the field lines.

### Magnetic reconnection

We observe many magnetosphere-related events from earth, such as the aurora. As these are not happening all the time, something must happen to trigger them.

When the Z (north/south) direction of the IMF and earth's magnetic field points in opposite directions, field lines from earth and field lines from the IMF can break and recouple with each other. This phenomenon is known as magnetic reconnection.

When magnetic reconnection happens, the field lines "wrap around the earth" in an attempt to regain equilibrium. We can divide this process into different stages of what we call the Dungey cycle.

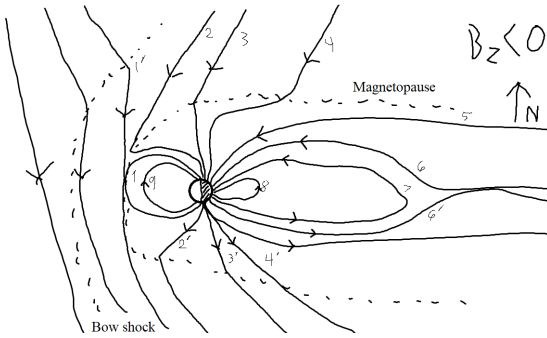


Figure 4: A figure explaining the Dungey cycle. The numbers indicate the stages of the cycle. The field lines start off with a reconnection on the day-side, then proceeds to wrap around to the night side. We then get another reconnection at 6, and the field lines settle down.

### 1.1.3 Ionospheric currents

The Dungey cycle is important, as magnetic reconnection is the main perpetrator in accelerating plasma into the polar cusps.

There are several plasma currents in the ionosphere ( $\approx 75\text{-}1000\text{km}$  above sea level).

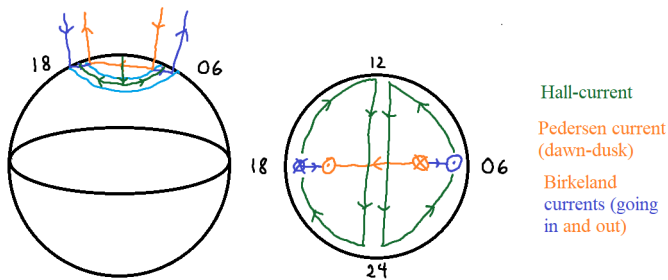


Figure 5: Some ionospheric currents. Here we see the Birkeland currents stretching out from the polar cusp, the Pedersen current going from dawn to dusk and Hall-currents going from day to night, and back around the cusp. The numbers indicate magnetic local time, with 12 being dayside and 06 being dawn.

One of these is the Birkeland currents which bring plasma in and out of the polar cusps. The cause of this is the interaction between the magnetosphere and the IMF.

As the charged particles in the Birkeland currents

approach earth, their density increases. This increases their collisions rate, which in turn causes the ions and electrons to drift apart (since they gyrate in opposite directions). This causes another current in the lower ionosphere: the Pedersen current (the orange and purple lines going along the earth in figure 5).

Since the Pedersen current includes a divition in charge, we also end up with an E field. This, along with the B field lines that point towards the polar cusp introduces another current through  $E \times B$  drift: the Hall-current which is depicted in green in figure 5.

Along with these current systems, we can also observe 630 nm (red) and 557 nm (green) light from the lower ionosphere as charged particles hit and excite oxygen. This is the phenomenon known as aurora borealis; the northern lights.

Since all these phenomenon are caused by interactions in the magnetosphere, we can use them to say something about the IMF and the other way around.

## 2 instruments

### 2.1 Ground based magnetometer; IMAGE

Knowing the B field at ground level is of interest. Luckily for us, there is a network of groundbased magnetometers known as the International Monitor for Auroral Geomagnetic Effects; IMAGE.

at a certain time.

## 2.3 All-Sky Camera

As the auroras emit very specific wavelengths, it is possible to measure the level of auroras by measuring the intensity of these wavelengths. On Svalbard, the University of Oslo have placed All-Sky Imagers that measure the intensity of these wavelengths for much of the night sky by using a fish-eye lens, filters and a photon counter. By slicing these circular pictures into lines going from low to high latitude and combining them, one can make a keogram that describes the development of the aurora over time.

One must be careful when reading keograms however, as they are prone to errors due to atmospheric conditions. For example, if there are clouds, they will block a lot of the light. Clouds tend to drift across the sky, so its possible to tell from a glance that a keogram has been affected by clouds if the light from the auroras also seem to drift.

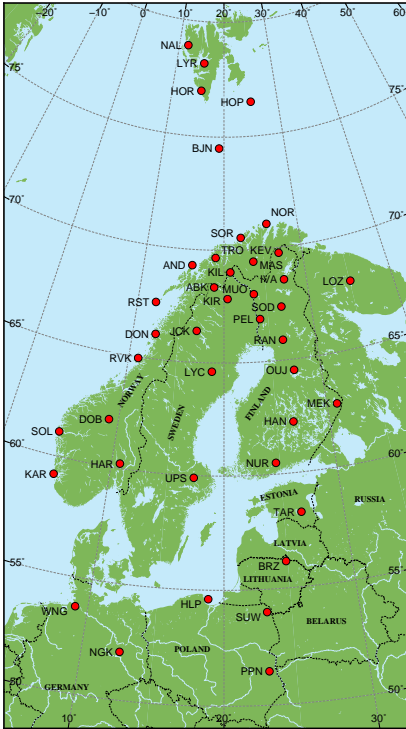


Figure 6: A map showing the IMAGE stations. Source: <http://space.fmi.fi/image/www/index.php?page=maps>

When charged particles start flowing in the ionosphere, it creates a B field in accordance with Ampere's law. For example, if we have a dawn-dusk current inside the polar circle, we can notice it by measuring the B field perpendicular to it.

Knowing the coordinate system used by IMAGE is important when reading its data. IMAGE operates using 3 coordinates: X, Y and Z.

The X coordinate always points towards the north pole from the magnetometer, akin to latitude. The Y coordinate always points towards the east, akin to longitude. The Z coordinate points towards the sky, perpendicular to the earth from where the magnetometer is.

## 2.2 Super Dual Auroral Radar Network; SuperDARN

SuperDARN is a network of radars used to measure plasma flow in the ionosphere. By using data from SuperDARN, one can make a convection flow chart that tells us what the Hall-current looks like

## 2.4 Advanced Composition Explorer (ACE)

In this project we are using data from a heliospheric satellite called ACE, which stands for Advanced Composition Explorer. ACE is a NASA satellite that gives us info about the solar wind. It is positioned in the L1 libration point, about 1.5 million km from the Earth. The instrumentation on the satellite includes an Electron, Proton and Alpha Monitor (EPAM) from Johns Hopkins University Applied Physics Laboratory. Magnetic Field (MAG) from the University of Delaware Bartol Research Institute and subsequently University of New Hampshire. Solar Isotope Spectrometer (SIS) California Institute of Technology. Solar Wind Electron Proton and Alpha Monitor (SWEPAM) Los Alamos National Laboratory. We will be using the MAG and the SEWPAM.

The MAG can give us the B-field magnitude and the magnetic field vector in different coordinate systems, such as GSM, GSE and RTN. The SWEPAM gives us information about the solar wind (SW) proton number density, the SW bulk speed, alpha to proton density ratio, the SW velocity in the same coordinate systems as the MAG and

also the position of ACE.

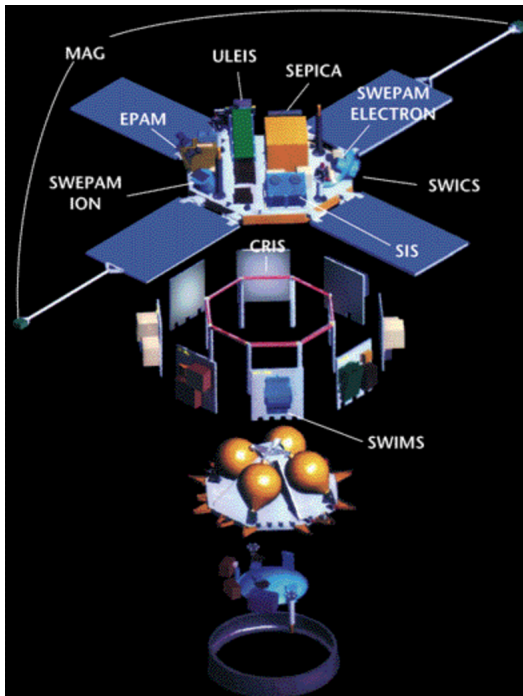


Figure 7: Exploded view of the ACE satellite, here we can see the two instruments we will be using. Source: [http://www.srl.caltech.edu/ACE/ace\\_mission.html](http://www.srl.caltech.edu/ACE/ace_mission.html)

## 2.5 Indices

### 2.5.1 Dst (Disturbance storm time)

With the Dst we can observe geomagnetic storms. The Dst is a quantification of the ring current and is an hourly scaling of the horizontal magnetic variation. Since the current flows in the equatorial magnetosphere, it is best sensed at low-latitude stations. These stations are sufficiently far from the equatorial electrojet so it is not disturbed by those ionospheric currents have little effect on the magnetic field variations. The auroral currents also have little effect. They use the quiet days to establish the benchmark or background levels of the magnetic field and the average minimum ring current. This is then subtracted from the records so the disturbance is the important part. The world average is called the Dst.

### 2.5.2 Auroral Electrojet (AE) Index

Using the AE index we can observe substorms. The AE index measures the strength of the auroral current systems. These current are at low alti-

tudes (near 100 km) and high latitudes (near  $70^\circ$ ). There are 12 stations that measure this. The AE is comprised of AU (upper envelope, eastward auroral electrojet) and AL (lower envelope, westward auroral electrojet), so  $AE = AU - AL$  which gives us the overall activity of the electrojets

### 2.5.3 Kp index

The Kp index is yet another way to monitor geomagnetic disturbances from the ground. There are 13 subauroral stations that record the disturbance of the two horizontal magnetic field components. The mean value of this makes the Global Kp index. It is given with three hour intervals at values from 0 to 9 according to a quasi-logarithmic scale, and this is then divided into 28 values on the form  $00, 0+, 1-, 10, 1+, 2-, 20, 2+ \dots 80, 8+, 9-, 90$ . This then represents the magnitude of the geomagnetic storm.

## 3 Observations

### 3.1 IMAGE data

Here is the IMAGE data from the sixth of January 2011. As we can see, things are relatively quiet until around 10 pm.



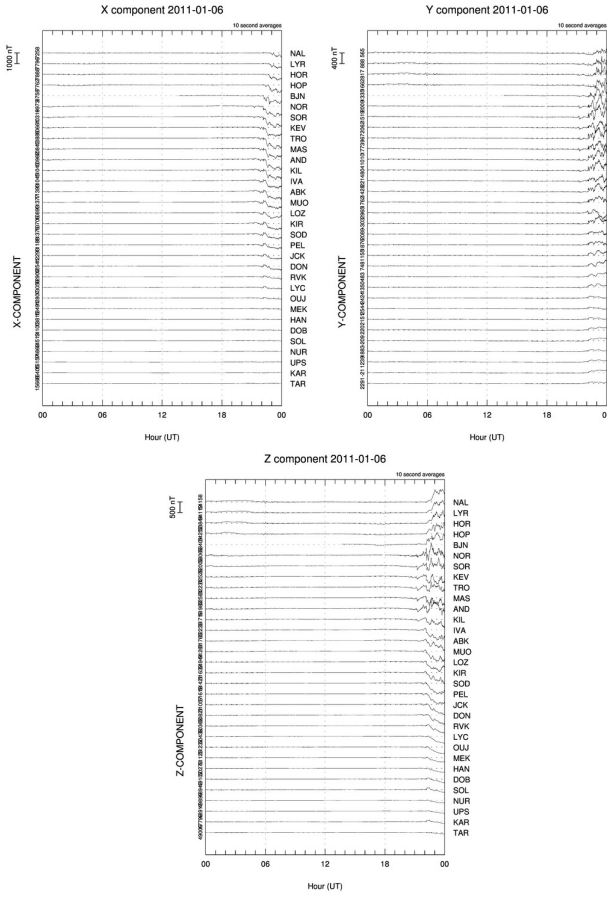


Figure 8: IMAGE data. The letters on the side refer to stations seen in figure 6. Source: <http://space.fmi.fi/image/www/index.php?page=home>

### 3.2 SuperDARN data

Here is some of the data from SuperDARN for the sixth of January 2011. We have chosen to include data for times that indicate the development of the ionospheric currents over time.

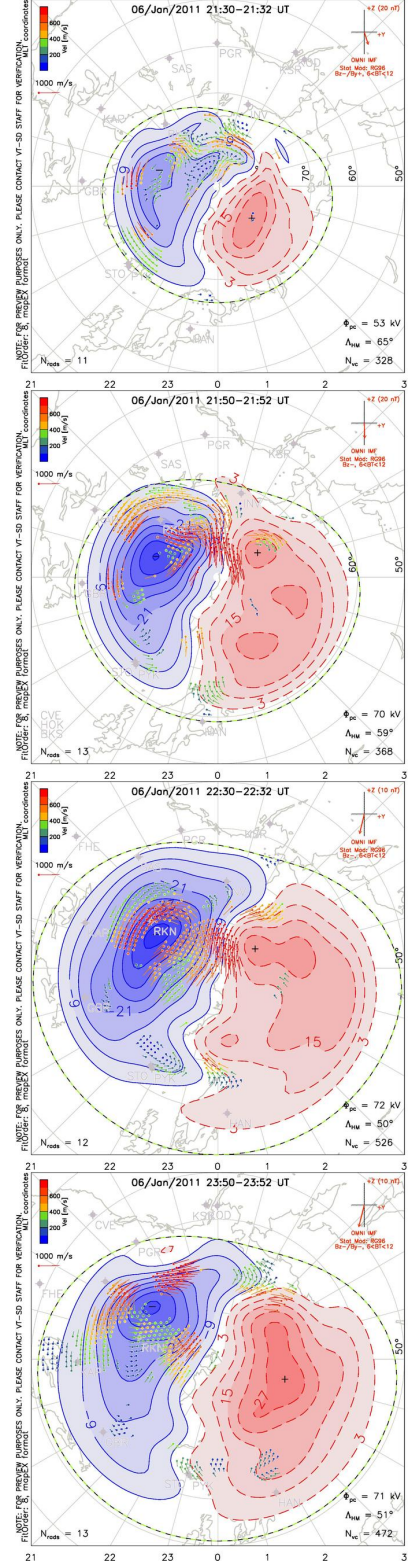


Figure 9: Convection maps derived from SuperDARN data. The vector arrows indicate measured data, while the streamlines indicate derived plasma flow. Source: <http://vt.superdarn.org/tiki-index.php>

### 3.3 All-sky Camera data

Here we have 2 keograms from the sixth of January 2011. The 2 keograms depict the development of auroras over time by measuring the intensity of 557 nm and 630 nm light.

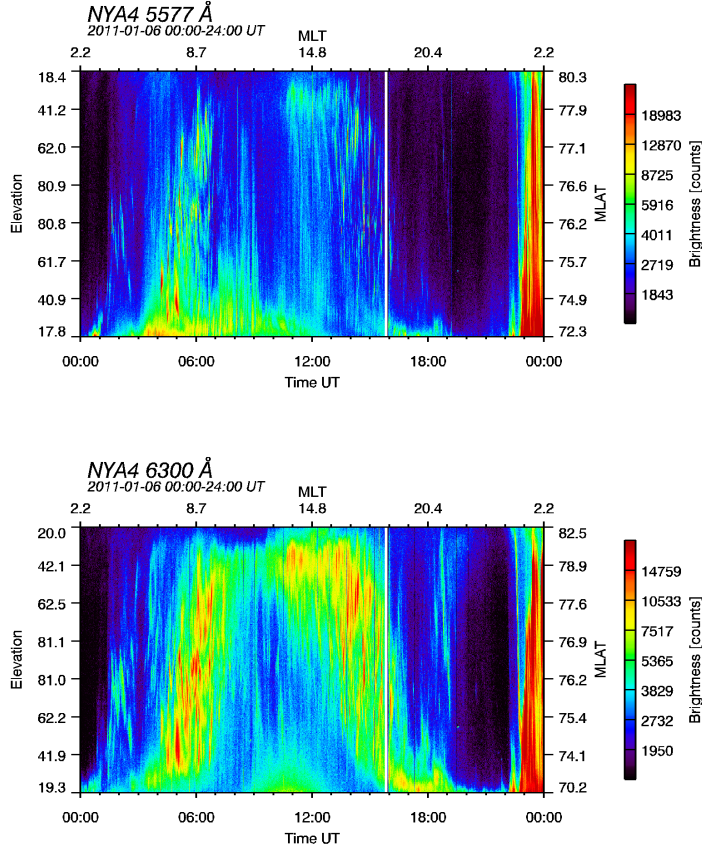


Figure 10: Keograms showing development of aurora over Ny Ålesund the sixth of January 2011. Source: <http://tid.uio.no/plasma/aurora/>

### 3.4 ACE data

#### ACE MAG

First we will begin with the ACE data from the MAG instrument. The thing of interest is the IMF Bz component of the magnetic field. From midnight to about 17 the Bz is fluctuating slowly and calmly around 0 nT. After 17 and until 20 the Bz becomes more erratic, with bigger movements. At around 20, there is a sudden jump in Bz up to around 10 nT, after which it plummets to about  $-15\text{ nT}$ . What follows is a negative Bz almost all the way to midnight, except for a positive spike a little after 21.

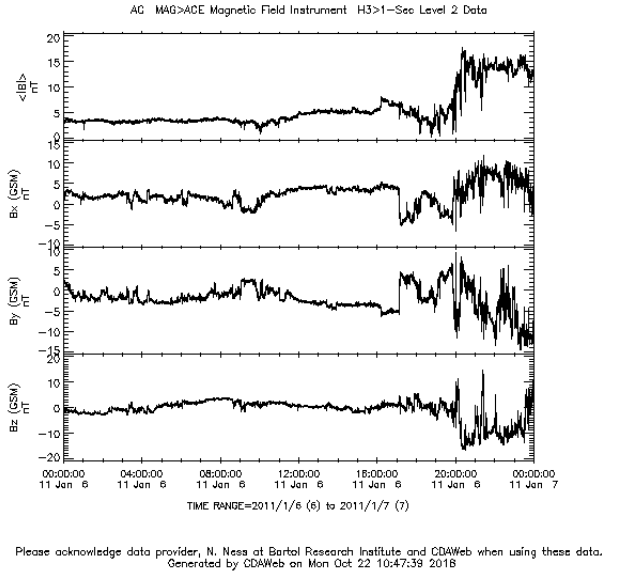


Figure 11: Data from the MAG instrument showing the magnetic field in GSM coordinates and the magnitude. Source: [http://cdaweb.gsfc.nasa.gov/cdaweb/istp\\_public/](http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/)

#### SWEPAM proton density

If we look at the data from SWEPAM and start with the Proton density, Figure 12, we see that it is stable at 10 protons per cubic centimeter until 16:00 hours, where it makes a jump up and keeps climbing and reaches a maximum at 70/cc at right before 20:00 hours. After this it drops down to around 20/cc for the rest of the day.

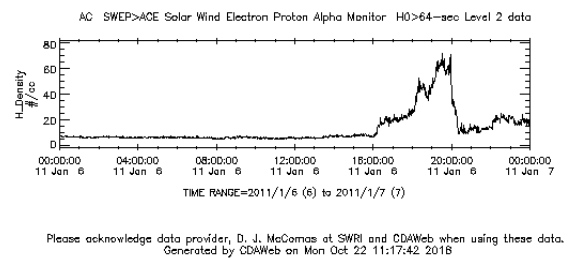


Figure 12: Data from SWEPAM showing the solar wind proton number density. Source: [http://cdaweb.gsfc.nasa.gov/cdaweb/istp\\_public/](http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/)

#### SWEPAM radial proton temperature

The radial temperature of the protons is at a stable value around  $5.0 \times 10^4 \text{ K}$  from midnight to 20:00. Here it rises until  $t \approx 21:30$  and settles at  $T \approx 2.0 \times 10^5 \text{ K}$



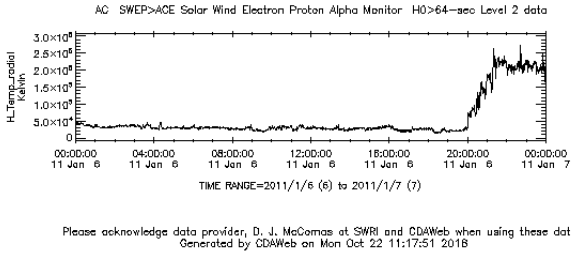


Figure 13: Data from SWEAPAM showing the radial component of the proton temperature. Source: [http://cdaweb.gsfc.nasa.gov/cdaweb/istp\\_public/](http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/)

### SWEAPAM alpha/proton ratio

The alpha/proton ration starts off at 0.06 and drops down to approximately 0.005. It is at its lowest in the time between 16 and 20. After  $t = 20$  the graph disappears.

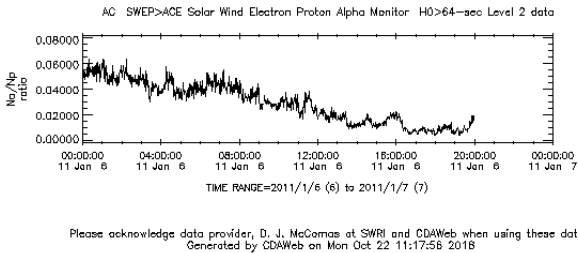


Figure 14: Data from SWEAPAM showing the alpha to proton density ration. Source: [http://cdaweb.gsfc.nasa.gov/cdaweb/istp\\_public/](http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/)

### Solar wind velocity

The solar wind has a velocity along the X axis at negative 350 km/s, which means towards the earth, until  $t \approx 20H$ . After that it increases to 450 km/s. The Y-component of the the wind starts at postitive 50 km/s, drops down to -40 km/s at  $t = 20H$ , after which it increases to 100km/s in positive y-direction. In the z direction it is stable until 8 pm, and then it jumps up and down.

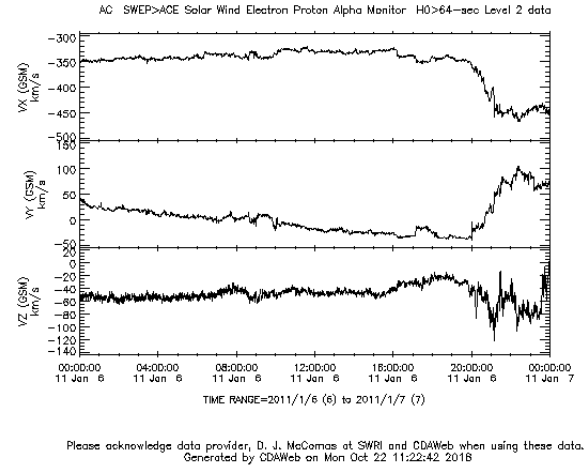


Figure 15: Data from SWEAPAM showing the solar wind velocity in GSM coordinates. Source: [http://cdaweb.gsfc.nasa.gov/cdaweb/istp\\_public/](http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/)

### Solar wind bulk speed

We can see from Figure 16 the bulk speed is at a stable level until 8 pm after which it increases to 450 km/s.

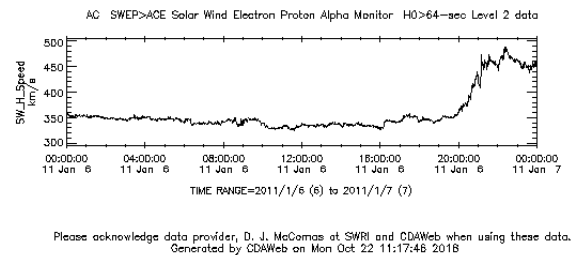


Figure 16: Data from SWEAPAM showing the solar wind bulk speed. Source: [http://cdaweb.gsfc.nasa.gov/cdaweb/istp\\_public/](http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/)

### ACE position

ACE moves in the normal way it moves

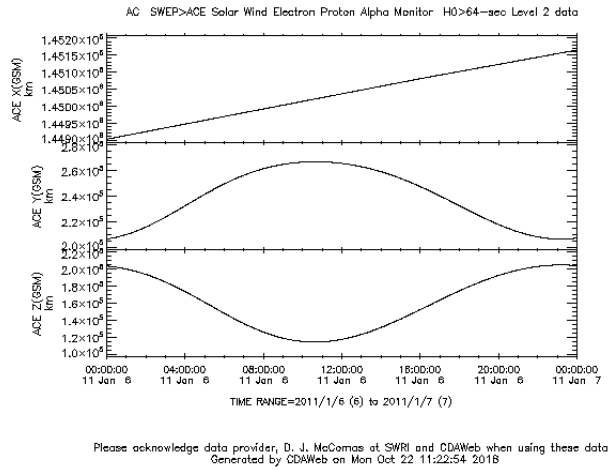


Figure 17: Data from SWEPAM showing the satellite position in GSM coordinates. Source: [http://cdaweb.gsfc.nasa.gov/cdaweb/istp\\_public/](http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/)

### 3.5 Dst data

Figure 18 shows both a graphic representation of the Dst, and the value of the first 10 days. In the graph we see a little bump and drop around the transition from the 6th of January to the 7th. This is also shown in the values. On the 6th at 18/19 UT the value rises and peaks at 24 nT at 21UT, after which it quickly drops to -18nT at 24UT

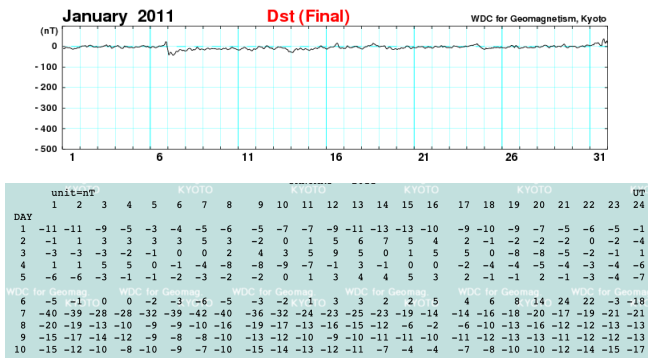


Figure 18: The Dst index of January 2011, with values for the 1st to the 10th. source: [http://wdc.kugi.kyoto-u.ac.jp/dst\\_final/201101/index.html](http://wdc.kugi.kyoto-u.ac.jp/dst_final/201101/index.html)

### 3.6 AE Index data

The AE index is relatively quiet until about 2130UT at which point there is activity in the lower envelope to a maximum value around -600nT

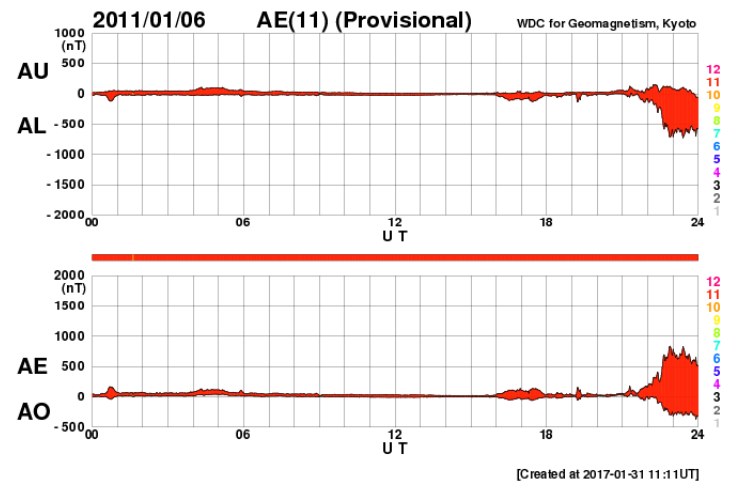


Figure 19: The Provisional AE index of January 6, 2011. Source: [http://wdc.kugi.kyoto-u.ac.jp/ae\\_provisional/201101/index\\_20110106.html](http://wdc.kugi.kyoto-u.ac.jp/ae_provisional/201101/index_20110106.html)

### 3.7 Kp Index

Date	Kp three-hourly							
	1	2	3	4	5	6	7	8
2011/01/06	1+	0+	0	0+	0+	1	2	4+

Table 1: The Kp index for the chosen date. Source: <http://wdc.kugi.kyoto-u.ac.jp/kp/index.html>

## 4 Discussion

We can start analysing the data in a somewhat chronological order, in other words we will analyse the data in the order of how early we see some interesting developments. This starts us off at ACE.

Beginning with some of the most important part of the data, the IMF, we see in the subsection 3.4 and from Figure 11 that the IMF Bz becomes negative at 20UT. This is great, because we know that when the IMF Bz is negative then reconnection can happen, which gives us a lot of fun physical processes. We notice that all the other measurements have an equivalent reaction. Such as the solar wind velocity has big changes with the bulk speed increasing from 350 km/s to 450km/s.

The radial proton temperature increases quite a bit just as the proton density drops down dramatically. All this suggests that there has been some sort of ejection from the sun some time before, which is just now hitting ACE.

Based on this we expect to see it hitting the Earth

after an hour due to the velocity and the distance. Since the IMF  $B_z$  is negative we expect reconnection which has several effects on the Earth's magnetic field and we can study these effects with indices such as Dst, AE and Kp.

The sudden spike in the Dst is the sudden commencement of a geomagnetic storm. Following is a massive drop in the horizontal magnetic field as the ring current builds up. It will rapidly have a partial recovery while the rest of the recovery will be slow and take several days as the ring current decays over the next week.

This can also be seen in the AE index. around 21:30 UT the substorm starts and begins to grow. It reaches the expansion phase and a maximum just before midnight. This means that there is a strong electrojet westwards. The magnitude of this geomagnetic storm is represented by the Kp index which has a value of 4+, which makes it a moderate storm.

### IMAGE

As we have a solar ejection hitting the earth with a negative IMF  $B_z$ , we expect to see an influx of ionospheric currents after some time. One way this would be measured would be using IMAGE. If the magnetic reconnection caused a dawn-dusk current, we would see a negative  $B_x$ . If we got a Hall-current, we would see a positive  $B_y$ .

From Figure 8 we see that this is exactly what happens. Approximately 2 hours after ACE measured the solar ejection, about 1 hour after it would have hit Earth, both the X and Y components see a spike. We also see the Z component spiking, which, together with the X component data, supports what we are reading from Dst and AE.

### SuperDARN

Much like IMAGE, we would expect SuperDARN readings to increase during times of magnetic reconnection.

From 9 we can see that the Hall-current increases massively at around 21:50 UT, which is at the same

time as the IMAGE data kicks in. We can also see that the polar cusp expands as the substorm commences.

### ASI

As we are experiencing a solar ejection with a negative IMF  $B_z$ , we can expect there to be auroras some time after the solar wind passes ACE. As there seemed to be little activity beforehand, we would also expect there to be little to no aurora before the ejection hits earth.

From figure 10 there would at first glance seem to be some activity in the time before the incidents occur. However, the intensity seems to be moving longitudinal in a way that indicates a cloudy sky, meaning that the data is bad. In other words, we can't really say anything about what the keogram is showing before things really escalate around 22-23 UT. At that point, the whole keogram seems to turn an intense red, indicating large auroral activity in both wavelengths. Again, this supports the other data which is pointing towards ionospheric activity after around 22 UT.

## 5 Conclusion

The data from ACE shows IMF  $B_z$  becoming negative and the solar wind velocity increasing, which point to some sort of solar ejection that has passed the satellite and is headed towards the earth. Upon arrival it causes a geomagnetic substorm which is observed on the Dst, AE and Kp indices. It also creates an influx of ionospheric currents which we can see with IMAGE and SuperDARN. Before it culminates with a display of Aurora Borealis.

## 6 References

Russel C.T, et.al(2016) Space Physics An Introduction.  
Cambridge:Cambridge University Press