SPACE PHYSICS
AURORA BOREALIS

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Introduction

Flickering curtains of dancing light against the dark skies, aurora borealis have inspired a great deal of mythology and superstition. These glowing, wavering lights have also been the subject of much scientific investigation.

Martin Connors, researcher in space physics, studies this beautiful phenomenon in Edmonton and Athabasca. Thanks to him, I learned a lot of things during my training period : Space pysics and aurora borealis, C language, Linux and gmt programs. So, in order to present my work during these three months, I will first introduce the laboratory for which I worked and its contexte then I will present the theory that I learned, necessary to finally explain our study on the plasma sheet.

Contents

Figure 1: Athabasca University Geophysical Observatory, Martin Connors

1 AU Geophysical Observatory, Athabasca University

Athabasca University (AU) is Canada's leading distance-education and online university: Canada's Open University. They currently serve about 32,000 students per year, following a period of rapid growth which has seen student numbers double over a six-year period. Some 260,000 students have registered in AU's individualized courses and programs since the University was created by the Government of Alberta in 1970.

The Athabasca University Geophysical Observatory (Fig 1), the most modern and comprehensive auroral observatory in Canada, has been making a major contribution to the growing understanding of auroras borealis. The AUGO has been built to know what triggers auroral substorms and how they cause magnetic field changes. In fact, the AUGOs northern, rural location allows the Northern Lights to be seen to their best advantage. Construction of the AUGO, funded by the Canadian Foundation for Innovation, began in 2002, just before Athabasca University physics professor Martin Connors received the Canada Research Chair in Space Science, Instrumentation and Networking. Connors studies outbursts of auroral activity and space weather to improve understanding of these phenomena and their effects on communication, pipeline function and other activities on earth. Early in 2004, Connors installed the AUGOs principal instrument of observation, a KEO Consultants multi-spectral camera, one of only a few in the world. This camera photographs light from the auroras with precise colour measurement. It is part of the University of Calgary NORSTAR network, a network of 10 cameras placed across western Canada that photograph the auroras with unprecedented resolution. Over the years, the AUGO has attracted a growing collection of international instruments and research partners. One of the other cameras hosted by the observatory is a THEMIS white light camera from the University of California at Berkeley. AUGO assists the University of Calgary in THEMIS, one of the largest auroral research projects ever undertaken. NASA launched five satellites on February 16 of this year that will track disturbances in the magnetosphere. The satellite data will be compared with observations from the ground data at AUGO, one of 20 such observatories all equipped with automated, all-sky cameras linked directly to the University of Calgary. The ground stations will be taking images of the auroras every three seconds over the two-year mission, for a total of 140 million pictures.

Athabsaca University has also an office in Edmonton and Martin Connors, has a lot of summer students at this place. I worked in Edmonton, with Roxane Sauve et Rob Lerner , two other summers students. We were three students working together on aurora borealis for Martin Connors. That was a very good experience to work with a researcher, to learn this type of research and also, to work with other students because we formed a real team.

My first work during my training period was to learn about space physics. Indeed, I learned a lot with M. Barthelemy about aurora borealis but I had to learn more about space physics theory to understand well what Martin Connors does. In order to do that, I read the very good book "Introduction to space physics", Margaret G. Kivelson and Christopher T. Russel. So, the following paragraphs focus on what I learned and they are necessary to understand our study.

2 What's happening above our head ?

2.1 The solar wind

The solar wind is a stream of charged particles (i.e., a plasma) which is ejected from the upper atmosphere of the sun. The composition of the solar wind is approximately 95% protons (H+), 4% alpha particles (He++) and 1% minor ions, of which carbon, nitrogen, oxygen, neon, magnesium, silicon and iron are the most abundant. Figure 2 illustrates some properties of the solar wind near the Earth from the spacecraft ACE, for the day September 21, 2002.

Solar wind velocity when measured in the ecliptic plane is normally in the range from 300 to 600 km^{-}1, but under some conditions can exceed 1000 km^{-}1. A typical value would be 450 km^{-}1.

The density of this plasma is about 10 particles/cm^3 and the temperature associated with the random motion of the particles is about 10^5 Kelvin. This temperature corresponds to a particle thermal energy of 10 eV, while the ki-

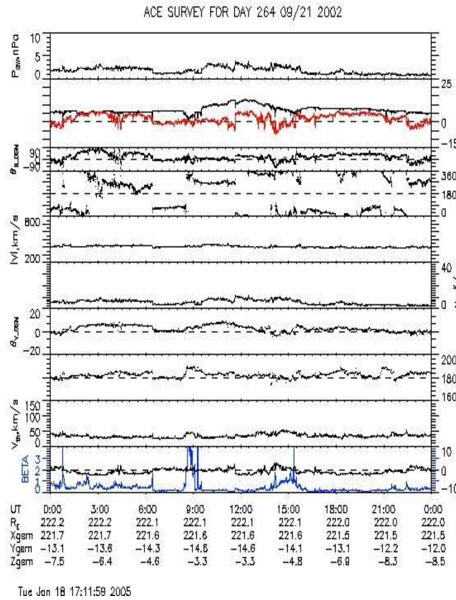

Figure 2: Solar wind properties, ACE, on Spetember 21^{rd}, 2002

netic energy associated with ion bulk flow is about 1 keV per particle. In this way, dynamic pressure exceeds thermal pressure in this flow.The thermal speed as it shown on the picture, is about 50 km^{-}1, less than the bulk flow. The solar wind is a supersonic flow.

The magnetic field associated with the solar wind is usually referred to as the interplanetary magnetic field called IMF. Near the Earth, it's variable and 5 nT is a typical value. Again, the dynamic pressure dominates due to the low magnetic field value. A typical value for the dynamic pressure is 4 nPa.

Usually, the magnetic pressure is less than the thermal pressure. They are both in the range of 10 $^{-}$11 Pa. But sometimes, the magnetic pressure can increase and dominate the thermal pressure. The β number which is the ratio of thermal to magnetic pressure indicates which one exceeds.

The solar wind will spend 4 days to reach our Earth, especially its protection ; the magnetosphere.

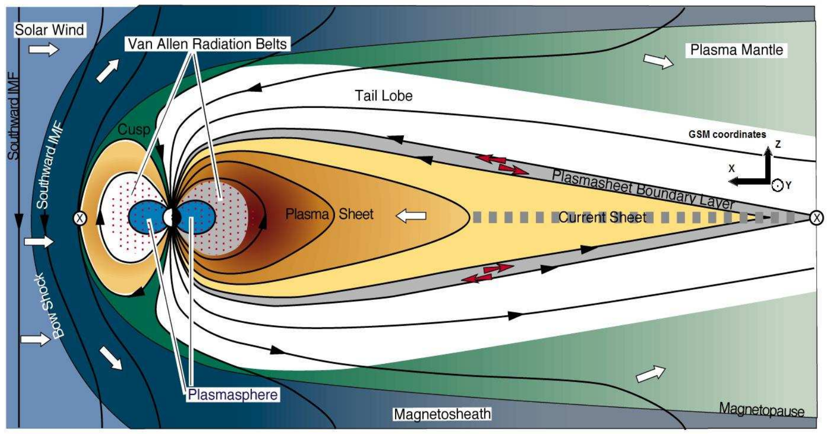

Figure 3: Magnetosphere in GMT coordinates system

	Plasma sheet : hot plasma	Tail lobes : cold plasma
density	3 cm-3	0.01 cm-3
thermal energy	4 keV	300 eV
magnetic field	10 nT	30 nT
β	β ~ 6	β ~ 0.003

Figure 4: Plasma sheet and Lobes characteristics

2.2 Magnetosphere

Earth is one of the planets that has a strong internal magnetic field. In the absence of external drivers, the geomagnetic field can be approximated by a dipole field. This dipole has an intensity of about 40 000 nT at the Earth's surface and diminishes like the inverse of the cube of the distance.

When the solar wind encounter the Earth's magnetic field, it slows down and flows around it leaving behind a cavity ; the magnetosphere. Figure 3 represents the magnetosphere with its different regions in a GSM coordinates system.The outer boundary of the magnetosphere is called the magnetopause. Solar wind modify the form of the magnetosphere by pushing it in the dayside and creating a long magnetotail in the night side. As a consequence, the distance of the magnetopause from the Earth is only 10 Earth's radius (1 Re = 6378 km) while the tail is more than 10 times longer. In front of the dayside magnetopause, another boundary called bow shock is formed because the solar wind is a supersonic flow. The region between the bow shock and the magnetopause is called the magnetosheath.

The magnetotail is mainly formed by tail lobes and the plasma sheet. These regions are very important because that's here that solar particles manage to enter in the magnetosphere due to the reconnection, phenomenon still bad un-

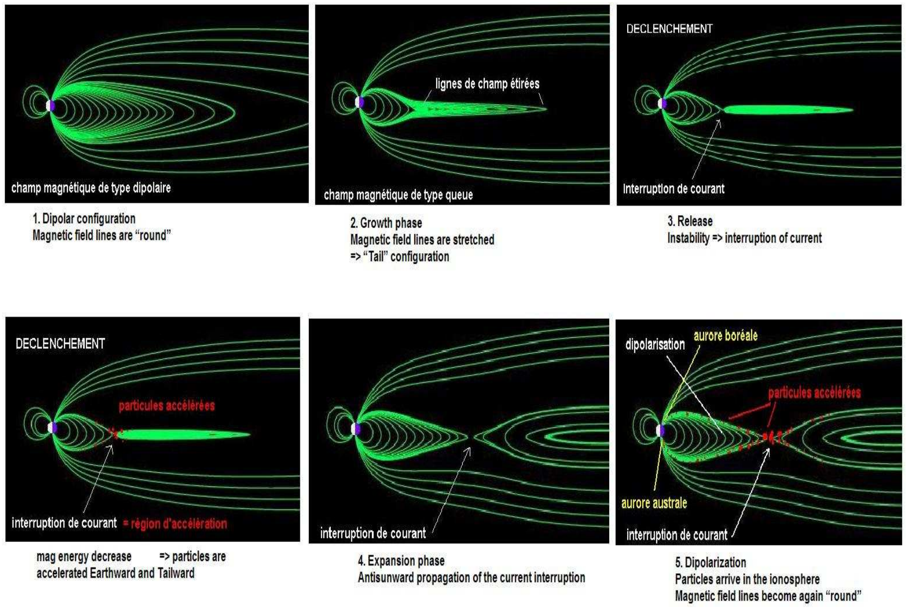

Figure 5: Substorm steps

derstood. Figure 4 represents some charateristics for the tail lobes and the plasma sheet. The tail lobes comprise the major part of the magnetotail, being found between the plasma sheet and the magnetopause. These are the regions where the magnetic field pressure is large and the plasma pressure is small. Indeed the magnetic density is very low (0.01 cm^3), whereas the magnetic field is relatively high (30 nT). Tail lobes are in pressure balance with the rest of the magnetosphere and the magnetic field is primarily directed parallel to the neutral sheet with only a relatively small northward component. The plasma sheet otherwise is the region with hot, relatively dense plasma that is found at the centre of the magnetotail. The plasma sheet is typically 4-8 Earth radius thick. Characterisitics plasma parameters are density about 3 cm^3, thermal energy about 4 eV. In this region, the magnetic pressure is dominated by the thermal pressure.

The plasma sheet is the scene of much geomagnetic activity, especially during substorms.

2.3 substorms and aurora borealis

2.3.1 substorms

Earth's magnetosphere is always in activity. The most important of these dynamic phenomena is called substorm. It lasts appromitately 1 hour, where a lot of energy is released in the magnetotail to cause aurora borealis on the Earth. This substorm can be decomposed in few stages. Fig 5 represents these differents steps.

1. First, during quiet times, magnetic field lines are pretty round. It's a dipolar configuration.

2. During the growth phase, magnetic field lines are streched, like an elastic that you strech. This is the tail configuration. Magnetic field is principally on the X component.

3. Nevertheless, this situation is not stable and an interruption of current occurs. The magnetic energy suddently decreases. Plasma particles acquire this energy and in this way, they are accelerated Earthward and Tailward, following magnetic field lines. Some particles manage to enter in the ionosphere to cause aurora borealis. Activation of these first bright aurora corresponds to the release of the substorm.

4. During the expansion phase, the region of the current interuption propagates tailward. The acceleration of particles still happens but in regions more far from the Earth. And, because the magnetic field lines far from the Earth corresponds to higher latitude ionospheric region, auroras occur at higher latitude. There is a northward aurora movement.

5. Then the dipolarization makes magnetic field lines become again round, like an elastic that you snap.

Finally, during the recovery phase, there is no more current interuption, auroras stop and everything return in the base statement, i.e. the dipolar configuration.

2.3.2 aurora borealis

Substorms cause the particles acceleration Earthward. Some of these particles manage to enter in our atmosphere. In this way, these particles coming from the tail collide with gas molecule in our atmosphere, especially oxygen and nitrogen. Due to this collision, molecules are excited, i.e. their electron circle the nucleus in a higher orbit. But because this situation is not stable, the electrons come back in their first statement, emitting a photon. Naked eyes need 100 billions photons to see light.

The emitted photon has a wavelenght related to the nature of the atom and also to the energy provided by the tail particles. This wavelenght will give the colour. Usually, we see green and red colors and sometimes blue and purple. We can note that molecules emit in the IR and the UV but we can't see that.

Aurora borealis are the manifestation of geomagnetic activity in the magnetosphere. A lot of spacecrafts in the space are used in order to see the parameters that reveals this activity, like the magnetic or the electric field. During my intership I used the data from the spacecraft Cluster. It reveals to be an excellent tool for my work, to study plasma sheet behavior.

3 Cluster Mission

There are a lot of spacecrafts to study the magnetosphere, but Cluster with its 4 spacecrafts in a 3 dimensionnal configuration at variable distances, represent a good measurement.

This mission consists of 4 identical spacecrafts flying in a tetrahedral formation between 4 and 20 Earth radius above the Earth. Each cluster spacecrafts carries an identical set of 11 instruments. These are designed to detect electric and magnetic fields, current and particles behaviour.

3.1 Orbit

Figure 6 represents the orbit of Cluster during one year. On the right, it shows the orbit of Cluster during winter and spring of each year and on the left, the orbit a half year later because the Earth had turn around the Sun. During summer and fall, Cluster spends a lot of time in the tail. Our study focused on this region, so we worked with the Cluster data especially during this period.

Cluster is a very good tool. At the beginning of my training period, I had to learn how to use Cluster and see how data from this spacecraft can verify the characteritics of the magnetosphere. It was very useful to me to understand well what's happening into the magnetosphere. In order to do that, I looked on the Cluster website and I also took data from the website CDAWEB ($http://cdaweb.gsfc.nasa.gov/istp_public/$). Here, a lot of data from many spacecrafts are available. So first, in order to make a good and an effective work, I learned the C language and some gmt programs.

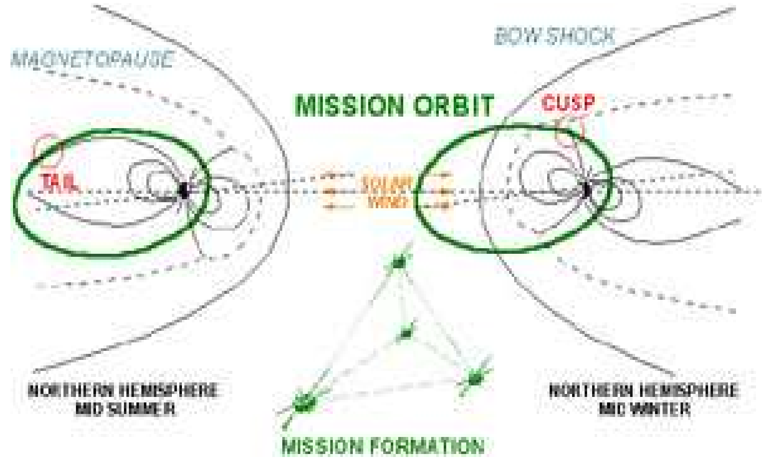

Figure 6: Cluster Orbit, on the left orbit during summer and fall, on the right orbit during winter and spring

Because all my c and gmt programs are nearly the same, I am just going to present an example for each one.

3.2 C and gmt programs

3.2.1 Data use : C program

A lot of data are available from many spacecrafts in ASCII format. Nevertheless, we nedeed to extract the data in txt format and sometimes make some operations to find some important values like the pressure for example. Here is an example of a typical c programs that I made (obtenir_nTB.c). This one is written to extract the density, the temperature, the three components of the magnetic field, and to calculate the total magnetic field.

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>

main()
{
Int i,hour,min;
float dx,dy,dz,d,UT,sec,BX,BY,BZ,B,n,T;
FILE *magfile,*protfile;
magfile=fopen(”BxByBz.txt”,”r”);
```

```
protfile=fopen("nT.txt","r");

for(i=0;i<72;i++) while(fgetc(magfile)!='\n') ;
for(i=0;i<68;i++) while(fgetc(protfile)!='\n') ;

for(;;)
{fscanf(magfile,"%*s %2d%*c%2d%*c%f %f %f %f",&hour,&min,&sec,&BX,&BY,&BZ);
fscanf(protfile,"%*s %2d%*c%2d%*c%f %f %f",&hour,&min,&sec,&n,&T);

if(feof(magfile))break;
if(feof(protfile))break;

UT=hour+min/60.+sec/3600.;
B=sqrt(BX*BX+BY*BY+BZ*BZ);

printf("%f %f %f %f %f %f ",UT,n,T,BX,BY,BZ);
printf("%f\n",B);
}
}
```

After the compilation of this program, we were able to run it and put the data in a txt file (nTB.txt) :

```
cc -o obtenir_nTB obtenir_nTB.c
./obtenir_nTB > nTB.txt
```

The c language is very useful for this type of work who requires a lot of data. I worked under Linux to make all these programs, and I quickly realised that Linux is very powerful and fast for our work. A lot of data can be treated in few seconds. Also, from txt files, we were able to plot these data thanks to gmt programs.

3.2.2 data plots : gmt program

Here is an exemple of a gmt program, written to plot the x component of the magnetic field versus time, for each Cluster spacecraft on august second, 2002.

```
#!/bin/sh
# magnetogram

gmtset LABEL_FONT_SIZE 12
gmtset HEADER_FONT_SIZE 18
gmtset MEASURE_UNIT cm
```

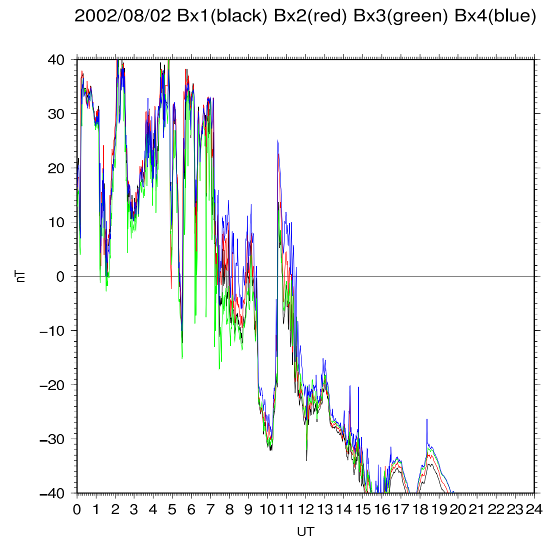

Figure 7: X magnetic field component for each spacecrafts, on august second, 2002

```
t1=0
t2=24
y1=-40
y2=40
xlabel=”UT”
ylabel=”nT”
title=”02 august 2002 Bx_T”

# sec, hour, X, Y, Z, dx1, dy1, dz1, dx2, dy2, dz2, dx3, dy3, dz3, dx4, dy4,
dz4, Bx1, By1, Bz1, Bx2, By2, Bz2, Bx3, By3, Bz3, Bx4, By4, Bz4, Jx, Jy, Jz,
Div, Curl, cond

# give ability to use identifiers of variables based on first line comment
for parn in 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
27 28 29 30 31 32 33 34 35 36 do
export ‘head -1 /home/geraldine/cluster/cluster-60sec/020802.txt | tr ”,” ” ” |
awk ’print $’$parn’”=”’$parn’-1’‘ done

tail –lines=+2 /home/geraldine/cluster/cluster-60sec/020802.txt | awk ’print
$’$hour’,$’$Bx1’’
| psxy -R$t1/$t2/$y1/$y2 -JX15/16 \
-B:.”$title”:a1f0.1g0:”$xlabel”:/a10f1g100:”$ylabel”:WSne \
-W1/0/0/0 -P -X5 -Y5 -K > plot.ps
```

```
tail –lines=+2 /home/geraldine/cluster/cluster-60sec/020802.txt | awk 'print
$'$hour',$'$Bx2''
| psxy -R$t1/$t2/$y1/$y2 -JX15/16 \
-W1/255/0/0 -P -O -K >> plot.ps

tail –lines=+2 /home/geraldine/cluster/cluster-60sec/020802.txt | awk 'print
$'$hour',$'$Bx3''
| psxy -R$t1/$t2/$y1/$y2 -JX15/16 \
-W1/0/255/0 -P -O -K >> plot.ps

tail –lines=+2 /home/geraldine/cluster/cluster-60sec/020802.txt | awk 'print
$'$hour',$'$Bx4''
| psxy -R$t1/$t2/$y1/$y2 -JX15/16 \
-W1/0/0/255 -P -O >> plot.ps
```

First, in a terminal : sh plot.gmt
Then, you can see the graphic thanks to the evince command: evince plot.ps
Fig 7 shows this plot.

I learned a lot about c and gmt programs. It revealed very useful for my study, and every day I used these programs. So, because I was able to use data from spacecrafts especially Cluster, I tried to see and verify some characteristics of the magnetosphere, in order to be accustomed with what's happening in the space, and also to see why Cluster is a good tool.

3.3 Cluster : magnetosphere characteristics

During this step of my training period, I spent quite a long time to learn about Cluster and its use to study the magnetosphere. Here are two examples that represents the kind of work that I did. First, the detection of the magnetopause, then, the verification of the pressure balance between lobes and plasma sheet.

3.3.1 Magnetopause detection

Thanks to the Cluster website and the data from Cluster, I was able to see when the spacecrafts crossed the magnetopause and see some characteristics of these regions. Fig 8 represents this crossing on February, 12^{th}, 2003, that I plotted from the Cluster data. First, because Cluster is near the Earth, the magnetic field (B_z) is high. Then, near 14 UT, it becomes very low and it's changing north-south that reveals the IMF. So these observations make conclude that the spacecrafts crossed the magnetopause at about 14.20 UT. It is

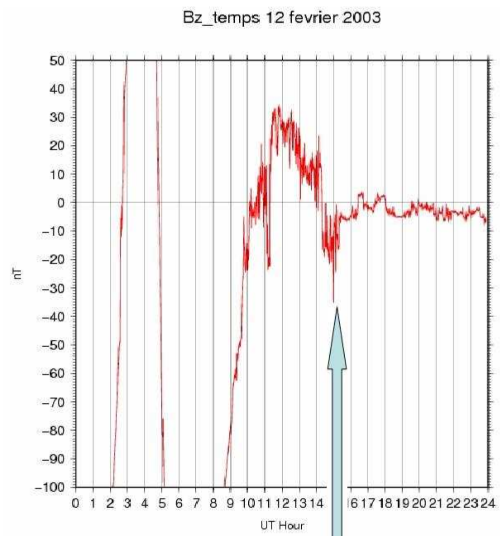

Figure 8: Magnetopause crossing on February 12^{th}, 2003

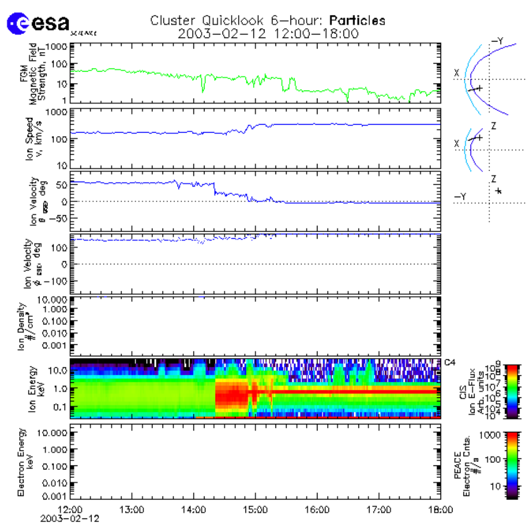

Figure 9: Magnetopause crossing from Cluster website on February 12^{th}, 2003

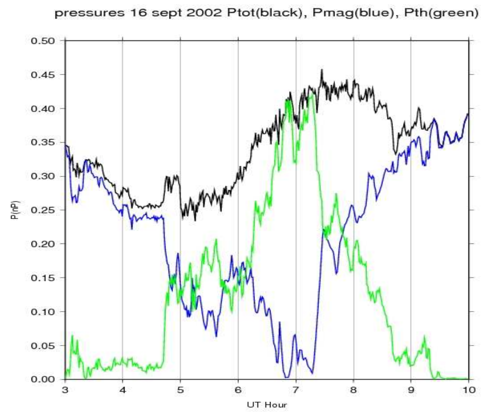

Figure 10: Thermal, magnetic and total pressure during a plasma sheet crossing on September 16^{th}, 2002

possible to verify this thanks to the fig 9 which represents the same crossing from the Cluster website. First, on the right, the position of the spacecrafts in the space shows that Cluster is crossing the magnetopause after 14 UT. Then, the increase of 1 keV ion energy and also the decrease of the absolute value of the magnetic field near 14.20 UT, reveal both that Cluster is going through the magnetosphere to arrive in the magnetosheath, where the characteristics are nearly the same than in the solar wind.

Thanks to Cluster, it was possible to verify and "see" what I learned on the magnetopause. I looked a lot of these data to know well the magnetosphere structure. Also, after these observations of the magnetosphere geography, I tried to verify some important properties that I learned like the pressure balance between the lobes and the plasma sheet.

3.3.2 Pressure balance between lobes and plasma sheet

The definition of the total pressure is the addition of three pressures : the thermal, the magnetic and the dynamic pressure. But because particles in the magnetotail don't have high velocities, the total pressure can be approximate by the addition of the two other pressures.

So, in the magnetotail :

$$P_{tot} = P_{th} + P_{mag} \quad (1)$$

with,

$$P_{th} = 2nk_BT$$

n = protons density, we assumed that electrons have the same and that's the reason of "2n"

$$P_{mag} = \frac{B^2}{2\mu_0}$$

Moreover, as we saw (section 2.2), the pressure in the lobes is dominated by the magnetic pressure whereas in the plasma sheet it's the thermal pressure that dominates.

In the lobes :

$$P_{lobes} \approx \frac{B^2}{2\mu_0} \quad (2)$$

In the plasma sheet :

$$P_{ps} \approx 2nk_BT \quad (3)$$

In order to verify the pressure balance between lobes and plasma sheet, I used the Cluster data (protons density, protons temperature, magnetic field) and during a plasma sheet crossing, I plotted each pressure and the total pressure thanks to a c and gmt programs. Fig 10 represents these three pressures (magnetic, thermal and total pressure). Some good conclusions can be done.

First, the total pressure seems to remain constant during the crossing with a typical value of 0.35 nPa.

Indeed,

$B \approx 30.10^{-9}\ nT$
$2\mu_0 \approx 3.10^{-6}\ m.kg.s^{-2}A^{-2}$

So,

$$P_{mag} \approx 10^{16-6} \approx 10^{-10}\ nPa$$

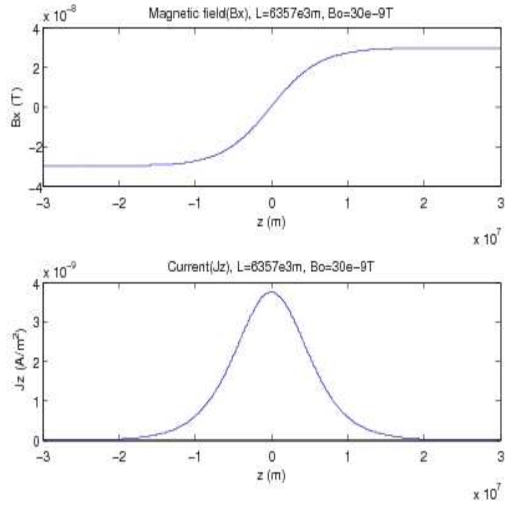

Figure 11: Harris model $B_x(z)$ and $J_y(z)$

Then, a good symmetry between the magnetic and the thermal pressure seems to appear in order to balance the total pressure. Moreover, that confirms the hypothesis of a low thermal pressure in the lobes, a low magnetic pressure in the plasma sheet and in this way the expressions (2) and (3).

During my study on Cluster and the magnetosphere, I quickly realised that this spacecraft is a very good tool and we can do a lot of study. The recent research focuses on the magnetotail behavior, especially the plasma sheet. We made first some few research about this region. And finally, because we found that very interesting, we decided to continue in this way : the plasma sheet study.

4 Plasma sheet study

4.1 Harris model

The current structure in the magnetotail is often approximated by using the analytic expression referred to as the 'Harris neutral sheet' that represents the component of the magnetic field along the EarthSun direction as :

$$B_x(z) = B_0 tanh(\frac{z - z_0}{L}) \tag{4}$$

where B_0 is the magnitude of the magnetic field x-component in the northern lobe (Harris, 1962). Here, z_0 represents the position of the center of the current sheet and L is the scale of the plasmasheet thickness. We assumed that $B_y = B_z = 0$ and $B_0 = cste$.

Correspondingly, the cross-tail current density, derived from $\mu_0 J = curl(B)$, is :

$$J_y(z) = (\frac{B_0}{\mu_0 L}) sech^2(\frac{z - z_0}{L}) \tag{5}$$

where $J_x = J_z = 0$

This Harris Model come from a simple magnetohydrodynamics (MHD) model of the magnetotail. The plasma density (mass density) and temperature used in this model are :

$$\rho_m(x, y, z) = \rho_0$$

$$T(z) = T_0 sech^2(\frac{z - z_0}{L})$$

Where ρ_0 and T_0 are constants. A magnetic tail described by the above equations is a stable MHD configuration.

Fig 11 represents respectively $B_x(z)$ and $J_y(z)$ in this model, with z_0=0. This form can be easy explain and visualized. Indeed, when z is positive (in the north lobes), the magnetic field is pretty high with a typical value of 30 nT and remains constant. If z decrease until enter in the plasma sheet where the magnetic field is low, B_x should decrease and reach 0 in the center of the plasma sheet. Then, if z continues to decrease and in this way, become negative, the x component of the magnetic field becomes negative and as z decreases until exit the plasma sheet and reach the south lobes, B_x should decrease until reach $B_0 = -30$ nT (lobes typical value).
For the current, it's the opposite : the maximum is situated at the center of

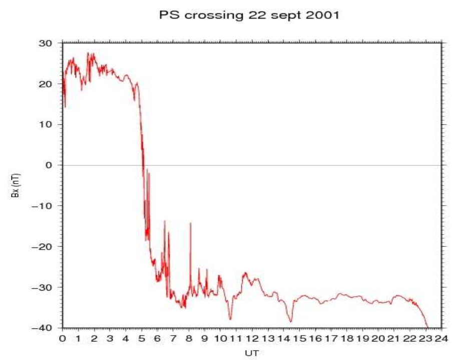

Figure 12: Plasma sheet crossing on September 22^{th}, 2001

the plasma sheet and decrease when the spacecrafts are more far from current sheet, until zero (in the lobes).

With Cluster, we measured Bx, and we tried to see if the x component of the magnetic field looks like the Harris model, during plasma sheet crossing.

4.2 Plasma sheet crossing and Cluster

Fig 12 represents the x component of the magnetic field (B_x) versus time on September 22^{th}, 2001.
When we looked at this graphic, it appears that the B_x corresponds to the model. We can verify in detail what's happening thanks to the orbit of Cluster versus time on the Cluster website (Fig 13). The spacecrafts are primarily in the positive z that why in fig 12 B_x is first positive with a value of about 25 nT. Then when the spacecrafts go through the plasma sheet (the crossing seems to be near 5 UT), we can see that B_x reach 0. Finally, because they are located in the south lobes (negative z), B_x=-30 nT.

This result seems to be very interesting. Because we found some good events like that, we tried to fit this crossing in order to obtain some parameters that can define this region. Martin Connors made a c program to do this fit. It can give the magnetic field in the lobes (B_0), the thickness of the plasma sheet (L) and its position (z_0).

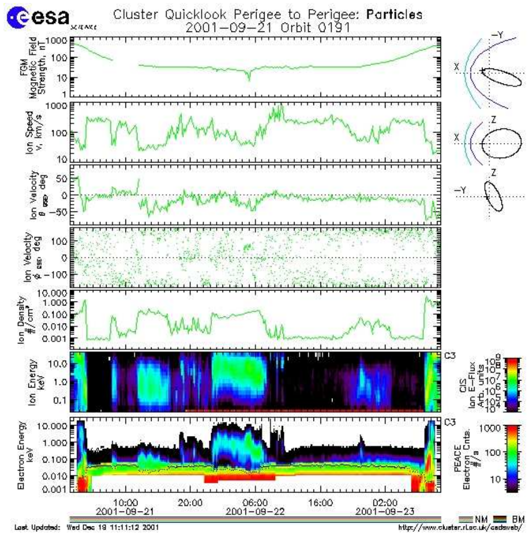

Figure 13: Plasma sheet crossing from Cluster website on September 22^{th}, 2001

4.3 Harris fit

Cluster data are available from 2001 to 2003, so we tried to fit the plasma sheet crossings for this period. But Cluster spends its time in the magnetotail from july to october, and because it makes one orbit in approximately 2.375 days, that makes 152 crossings to fit that is not a lot. Moreover, sometimes the fit can't be done for some reasons like the lack of data. So we obtained only 71 crossing fits. Fig 14 represents one of them on August 3^{rd}, 2002. For this event, we obtained $B_0 = 26.788$ nT, $Z_0 = -1.6435R_e$ (1 Earth radius R_e=6378 km) and $L = 0.632426R_e$.

The lobes magnetic field appears realist and really good. The z_0 value, different from zero, means that the plasma sheet is not centred (z axis). And because another fits gave different z_0, we can conclude that the plasma sheet makes some movement in the z direction. We also observed suddently z motions that we call flapping. The plasma sheet is flapping.

So, from these good observations, we can wonder if these three parameters are related and if there something that influence them, like the solar wind.

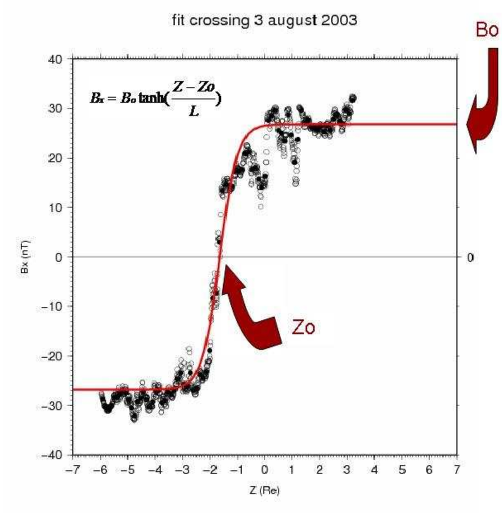

Figure 14: Harris fit on August 3^{rd}, 2003

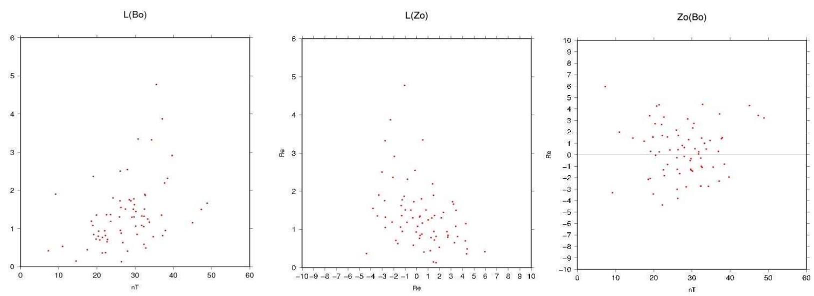

Figure 15: L(B_0), L(z_0) and z(B_0) for 2001, 2002, 2003

4.3.1 Tail parameters

After doing all the 71 fits, I tried to see if the parameters could be related together, but as we can see on the fig 15, there is nothing really interesting. In fact, the thickness of the plasma sheet seems to be related to Bo and also a little bit to z_0. But, if we agree with that, it means that L increase with B_0 and it should not. Indeed, theory especially substorms theory implies the opposite : the increase of the magnetic field in the lobes makes the plasma sheet streched and in this way, thinner. Moreover, we suppose that this parameter, given by the fit is false. During many crossings, we observed a lot of flaps. These flaps appear suddently, it's the plasma sheet that enter in the tetrahedral formation of the spacecrafts. And because it occurs during the long crossing by Cluster, it modifies the thickness parameter obtained from the fit. So we can conclude

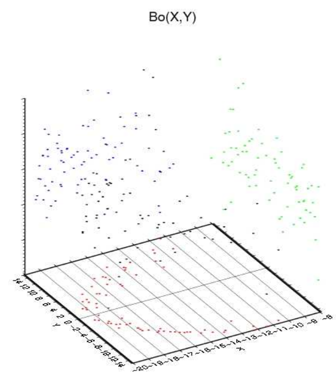

Figure 16: B_0 versus X,Y,Z with projections

that we should not take in account the L parameter because it must be false. There is no relation that appears between z_0 and B_0, so we can say that the parameters are not related.

Fig 16, represents the parameter B_0 versus the positions (X,Y,Z and the projections) in the tail. It's clear that the magnetic field in the lobes is not depending on the position. We were surprising because some research shew that the magnetic field decreases with the absolute value of X position in the tail. But, it can be explain by our short scale. So, because nothing appeared we tried to find a relation with the solar wind parameters.

4.3.2 solar wind influence

The principal parameters of the solar wind that can influence on the magnetotail behavior are the velocity (V_x), the z component of the magnetic field (especially when it's south, B_z), the y component of the electric field ($E_y = v \otimes B$), and the pressure (P). B_0 seems to be the best parameter that the fit gave, so we tried to see if B_0 can be a function of V_x, B_z, E_y or P. We took the data from the spacecraft Ace, which spends all its time in the solar wind. Fig 17 represents respectively $B_0(B_z)$, $B_0(E_y)$, $B_0(P)$, and $B_0(V_x)$.

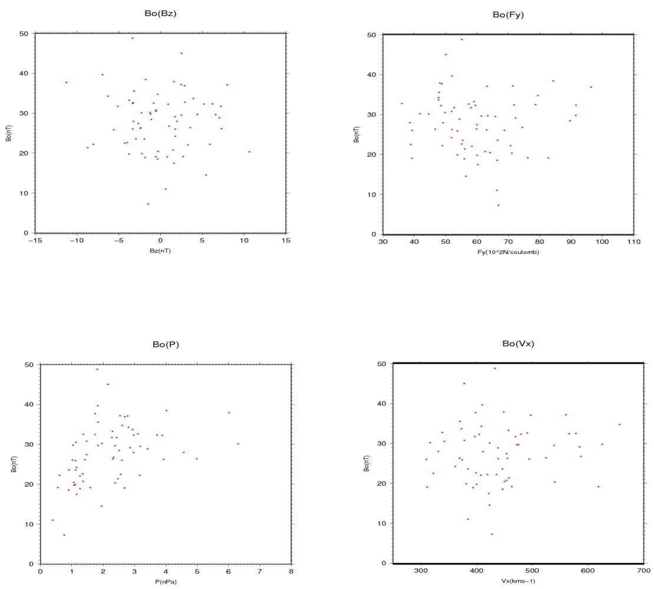

Figure 17: B_0 as a function of respectively B_z, E_y, P, V_x

It's quite clear that B_0 is not a function of V_x, B_z and E_y. Nevertheless, B_0 seems to be related to the pressure. At this point it could be very interesting to fit this and find which function can relate this two parameters, but we first have to check if nobody already found this result and then, we need more data. So, also because I had no more time for my training period, we didn't try, but it can be very good to do that in the future.

This Harris fit revealed to be very good unless for the plasma sheet thickness because of the flapping. Nevertheless, this observation made us thinking that we can use this motion. Indeed, plasma sheet crossing by Cluster takes to much of time, and some properties in the magnetotail can change during this long period. Flapping are very fast, as it said below, it's the plasma sheet that goes through the four spacecrafts very fast. So we can hope that during this short time, characteristics remain constant. It is possible and easy to verify this, thanks to the pressure during flapping.

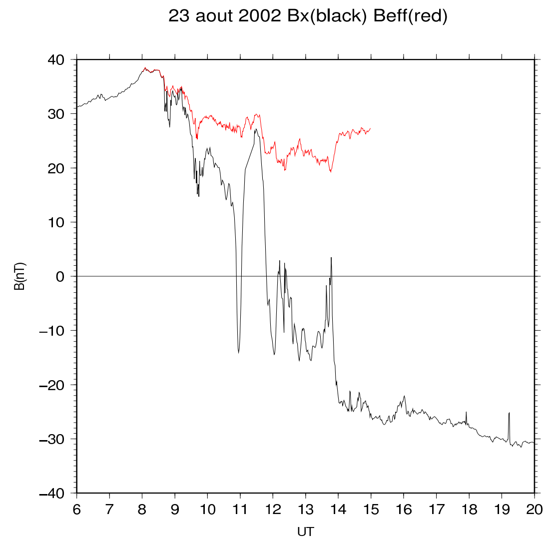

Figure 18: B_{eff} during a flap on August 23^{rd}, 2002

4.4 flapping study

4.4.1 pressure during flapping

One possibility to see if the magnetotail characteristics remain constant during a flapping is to see if the lobes magnetic field is constant.

In the lobes :

$$P_{lobes} = \frac{B^2}{2\mu_0} \tag{6}$$

Here we assume that the thermal pressure is negligeable.

In the plasma sheet :

$$P_{ps} = \frac{B^2}{2\mu_0} + 1.16nk_BT \tag{7}$$

We made some changes, and now it seems better to take 1.16 instead of 2.

We define B_{eff} as the lobes magnetic field during flaps. Because the pressure is in balance between the lobes and the plasma sheet,

$$P_{lobes} = P_{ps} = P$$

.

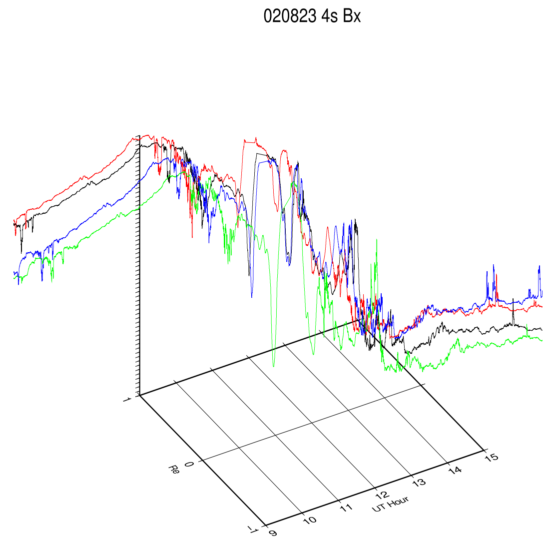

Figure 19: Magnetic field X component during a plasma sheet crossing with flapping on August 23^{rd}, 2002

In this way,

$$\frac{B_{eff}^2}{2\mu_0} = P$$

and

$$B_{eff} = \sqrt{2\mu_0 P} \tag{8}$$

So, we took the data from Cluster and thanks to a c and gmt programs, we plotted the $B_e ff$ during a flap. Fig 18 represents the magnetic field from Cluster (black) and B_{eff} calculated from Cluster data (red)on August 23^{rd}, 2002. It seems that B_{eff} remains constant during the flap, there are no big or suddently changes. In this way, we can assume that the magnetotail characteristics don't change during plasma sheet flapping.

4.4.2 Flapping Harris fit

At this point of my training period, we tried to fit the plasma sheet crossing but this time, using flapping motions. In order to do that, we made a c program that takes in account the z separation of the spacecraft rather than the z motion over time. The lobe magnetic field is a known parameter. Indeed, we assumed that the previous fit gave us a real good B_0 value. We also assumed

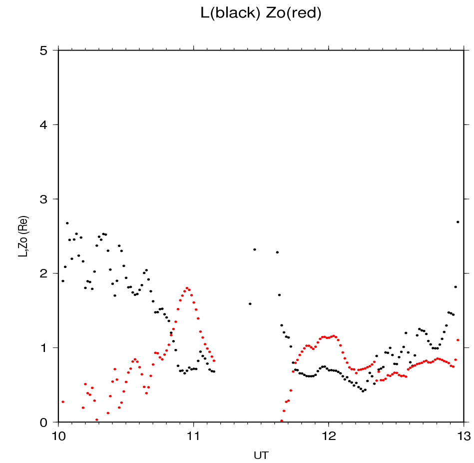

Figure 20: parameters L and z_0 obtained from Harris fit during a flap

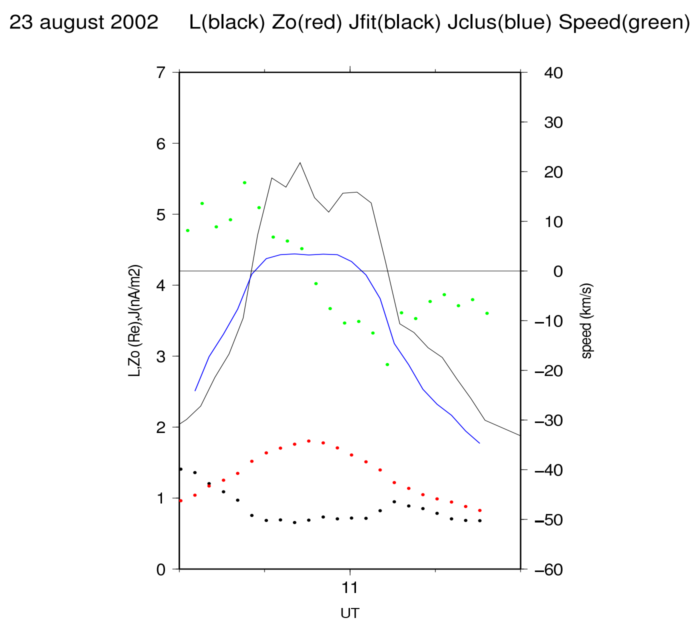

Figure 21: parameters L, z_0, v_z, J_{fit} deduced from Harris fit and J_{clu} obtained from Cluster, during a flap

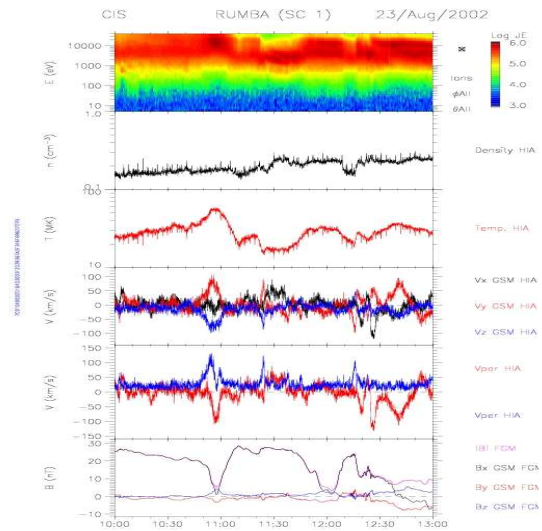

Figure 22: x, y ,z component of ions velocity from Cluster, on August 23^{rd}, 2002

that the flapping motions are only in the z direction and that during this event, the plasma sheet caracteristics remain constant. So with this program, we can obtain the thickness (L) and the position of the center of the current sheet (z_0). We hoped to find a constant L and a z_0 as a function of time which represents the movement of the flapping in the z component.

Fig 19 represents the x magnetic field component during a plasma sheet crossing and fig 20 shows the L and z_0 obtained from our fit. Fig 19 is showing well the plasma sheet flapping especially the one we chose to do our fit near 11 UT.
On the other picture (fig 20), our hypothesis seem to be confirmed. Indeed, thanks to z_0, we can see clearly the motion of the plasma sheet in the z direction, and recognize the two flaps. Also, during these flaps, L remain constant and the value (about 0.893328 Re) seems to be realist. So, at this point of the study, we can hope that what we did it's pretty good. But, we have to check with data from Cluster if our results are good and coherent.

Thanks to the parameter z_0, which represents the position of the plasma sheet during time, it's easy to determine the z component of the plasma sheet velocity and compared this value to the velocity measured by Cluster. Moreover, with the current Harris model, we can deduce the current sheet and do the same comparison in order to confirm our study. Fig 21 represents L, z_0, v_z, J_{fit} deduced from our fit and J_{clu} obtained from Cluster and fig 22 , shows the ions velocity in the plasma sheet in the three directions which represent the movement of this region. Good and bad conclusions can be done. If we look at the current, it seems to be realist compared to the Cluster data. Even if Cluster detected something little bit higher, the form is respected. Nevertheless, the velocity appears really bad for two reasons. The first one is that the z component is higher for Cluster than what we found. Indeed, with our fit we found something near 20 km.s^{-1} whereas the spacecrafts detected a velocity of about 80 km.s^{-1}. Then the second reason is related to our hypothesis that we made about the motion of the plasma sheet. We assumed that flapping is only in the z direction, but here, with the Cluster data it's clear that it's not true. The other components and especially the y component are in the same scale than the z one. So the plasma sheet has a three dimensional motion.

In this way, we can't confirm our work. We have to consider the three directions, and consequently our fit needs some changes.

5 Results summary

Our study on the plasma sheet is totally new, using flapping for a Harris fit with Cluster data. The results that we obtained are pretty good even if we have to improve our fit.

First, we saw thanks to the pressure and the plasma sheet thickness, that using flapping is better because the characteristics of the magnetotail remain constant during these fast events. Then, our method for the fit gives good results for the lobes magnetic field, the plasma sheet thickness, the z_0 evolution and also the current. Finally, with a previous study, we found that B_0 can be related to the solar wind pressure but we need more data and we have to find the good equation that can be long and complicated.

Nevertheless, our hypothesis of an only z motion of the plasma sheet is false. Its moving especially in the Z and Y direction. We have to improve our fit. We need a c program that can do a three dimensional fit. Martin Connors is going to do this program assuming that the plasma sheet is tilted in the X and Y component. And if it works we can do this study for a lot of cases to something really interesting about plasma sheet behavior to advance research.

Conclusion

Space physics and Aurora Borealis hide a lot of secrets, and research in this field is really interesting. I think that we will discover a lot about this beautiful phenomena. We are just at the beginning.

During this training period I learned so much: Space physics, C and gmt programs, working with a real team and what is the scientific research job. Moreover, I had the chance to do that in another country, learning also another culture. So I want to thank Martin Connors for all that he has taught me as well for giving me the passion for scientific research. And now, I hope that he will find something thanks to our work.