Three-dimensional energetic ion sounding of the magnetopause using Cluster/RAPID

K. Oksavik[1], T. A. Fritz[2], Q.-G. Zong[2], F. Søraas[1], and B. Wilken[3,4]

Abstract. We present new results using energetic particles to remotely sound the high-latitude magnetopause in three-dimensions. Less than two gyro radii from an absorbing boundary a trapped particle distribution appears non-gyrotropic, as particles start to cross the boundary. Knowing the magnetic field and the particle mass and energy, it is possible to derive the direction and distance to the magnetopause just by examining the azimuthal distribution of locally mirroring particles. Combining observations from at least three spacecrafts gives a three-dimensional picture of the magnetopause surface. We have performed this analysis for a high-latitude boundary crossing on January 14, 2001. The very first results give a consistent overall picture of how the magnetopause boundary is coming towards, just passing, and then retreating away from the spacecrafts. This clearly illustrates that the magnetopause ion sounding technique can be used to remotely study the three-dimensional orientation and location of the magnetopause surface.

1. Introduction

In July and August 2000 the four Cluster spacecrafts were successfully launched into orbit. The tetrahedron formation of the spacecrafts provides the first real opportunities to study the physics of the magnetosphere in three dimensions as a function of time. Previous single or dual spacecraft missions have always had a problem separating temporal and spatial variations.

In this paper we present a new technique to remotely sense the magnetopause in three dimensions as a function of time. In one-dimension a single spacecraft technique was first established by *Fahnenstiel* [1981] to study standing waves at the magnetopause. Fahnenstiel used energetic > 24 keV ion distributions from the ISEE-2 spacecraft to remotely sound the ion trapping boundary at the dayside magnetopause. Later, *Fritz and Williams* [1984] used the same technique to study the structure and topology of the subsolar magnetopause. The same method has also been employed at data from other spacecrafts like the HEP-LD instrument onboard GEOTAIL [e.g. *Zong et al.*, 2000]. All these studies use the characteristics of the three-dimensional energetic particle distributions observed near the magnetopause [*Williams*, 1979; *Williams et al.*, 1979] to estimate the location, orientation and velocity of the magnetopause in a direction perpendicular to the magnetic field.

[1]Department of Physics, University of Bergen, Bergen, Norway.
[2]Center for Space Physics, Boston University, Boston, Massachusetts.
[3]Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, Germany.
[4]Deceased.

Paper number .
0094-8276/01/$5.00

2. Instrumentation

The present study uses data from three of the Cluster spacecrafts (Rumba, Samba, and Tango) during one of the first days of joint operation. The imaging energetic particle spectrometer RAPID (Research with Adaptive Particle Imaging Detectors) measures the velocity vector and energy of both electrons and ions. The current paper will, however, only focus on ion data. Different ion species are separated using a time-of-flight (T) vs. energy (E) telescope in front of a solid state detector. The atomic mass (A) of the detected particle is thus given as $A = ET^2$, where the energy range is from 50 to 1500 keV. RAPID is designed to cover 12 angular intervals over a 180° field-of-view with respect to the spacecraft spin axis. Furthermore, the spin plane of the spacecraft is divided into 16 sectors, giving 192 independent samples of the unit sphere in velocity space. A more detailed description of the instrument has been given by *Wilken et al.* [1997, 2001].

3. The Ion Sounding Technique

The energetic ion sounding technique uses the relatively large ion gyro radius for remote sensing of a scattering boundary like the magnetopause. On closed field lines and away from any scattering mechanisms the three-dimensional ion distribution is found to be trapped, with high fluxes of locally mirroring particles and two loss cones parallel to the magnetic field direction. In the upper left panel of Figure 1 an example of such a trapped ion distribution is shown. Note the high ion flux along the solid black line marking the 90° pitch angle region. If the spacecraft is less than two ion gyro radii away from the scattering mechanism, locally mirroring ions from some directions are prevented from performing a full gyration. This gives an asymmetric or non-gyrotropic distribution like in the upper middle panel of Figure 1. The longer the region of absent 90° ions (shown by the dotted line) is, the closer the spacecraft is to the scattering mechanism. The azimuthal location of ϕ_1 and ϕ_2 gives the rotation of the scattering boundary relative to the spacecraft coordinate system. If the spacecraft has crossed the scattering boundary, no significant locally mirroring ion fluxes will be seen at all, and one only observes a background distribution similar to the one in the upper right panel of Figure 1.

To our knowledge the magnetopause ion sounding technique has so far only been applied at the low latitude magnetopause, where $\mathbf{B}$ is approximately parallel to the Z_{GSE} axis, see e.g. *Williams* [1979]. At low latitudes the vector $\mathbf{R}$ from the spacecraft to the magnetopause is given by

$$\mathbf{R} = R\sin(\beta)\mathbf{X}' + R\cos(\beta)\mathbf{Y}'$$

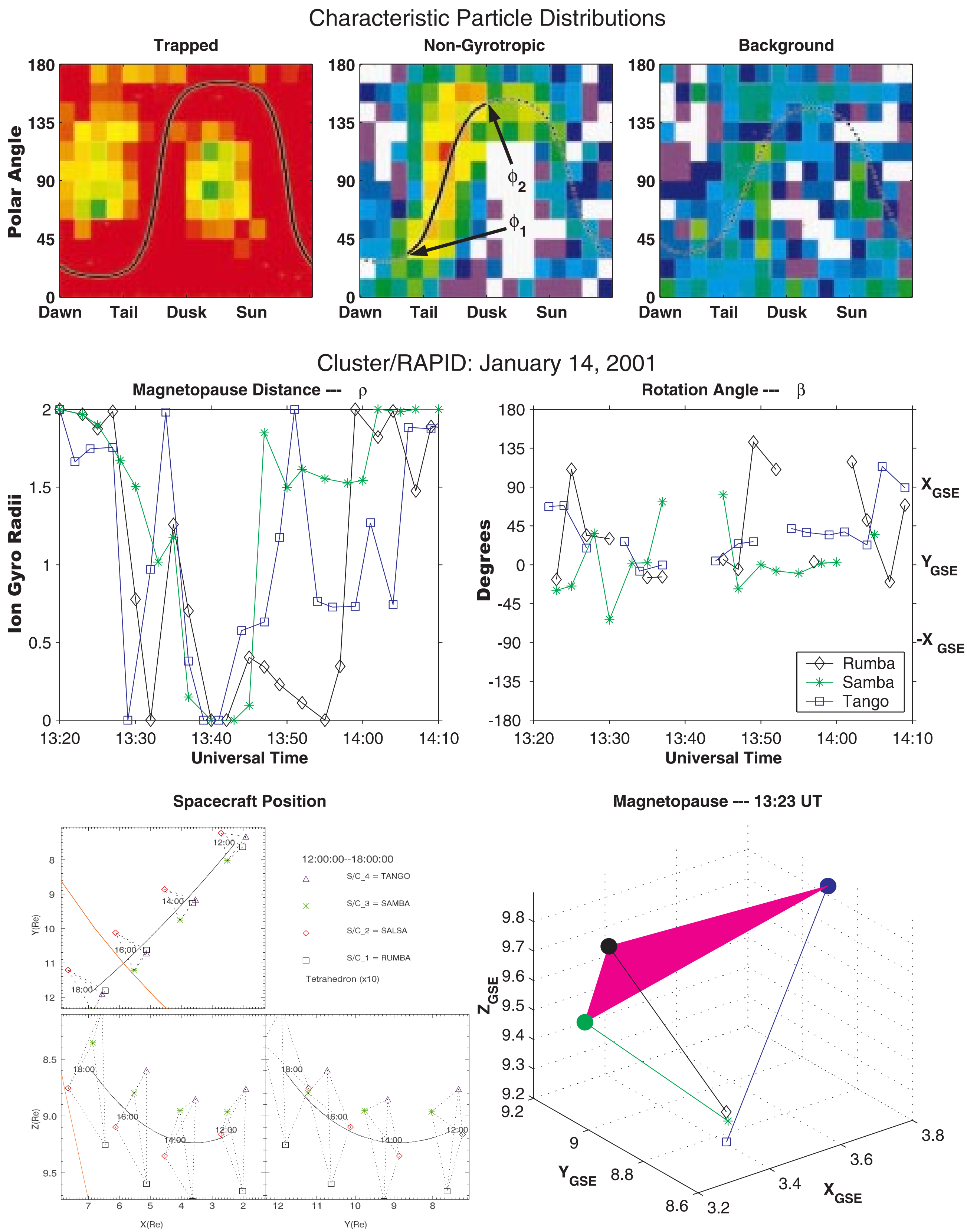

Figure 1. The first row gives three characteristic ion distributions; a trapped distribution on closed field lines, a non-gyrotropic distribution less than two ion gyro radii away from the magnetopause, and a background distribution found outside the magnetopause. The middle row gives the distance in ion gyro-radii from Cluster to the magnetopause and the magnetopause tilt angle, both derived using the energetic ion sounding technique and data from the RAPID instrument. The bottom row gives the position of the Cluster spacecrafts and a sketch of the magnetopause geometry at 13:23 UT. Here we have assumed that the ions are 60 keV protons.

where R is the magnetopause distance, $\mathbf{X}' \approx \mathbf{X}_{GSE}$, and $\mathbf{Y}' \approx \mathbf{Y}_{GSE}$. The data set we present in this paper is from high-latitudes, which will further complicate our geometry, since the offset between the Z_{GSE} axis and the magnetic field vector (given by θ_X and θ_Y) must be taken into account. According to Figure 2 the transformation is given by:

$$\mathbf{X}' = \cos(\theta_X)\mathbf{X}_{GSE} + \sin(\theta_X)\mathbf{Z}_{GSE}$$

$$\mathbf{Y}' = \cos(\theta_Y)\mathbf{Y}_{GSE} + \sin(\theta_Y)\mathbf{Z}_{GSE}$$

where $\theta_X = \tan^{-1}(B_X/|B_Z|)$ and $\theta_Y = \tan^{-1}(B_Y/|B_Z|)$.

The magnetopause tilt angle β is found from the azimuthal distribution of the ions, by reading out the angles ϕ_1 and ϕ_2 of where the significant fluxes start and end respectively (see Figure 1). Both angles are measured clockwise

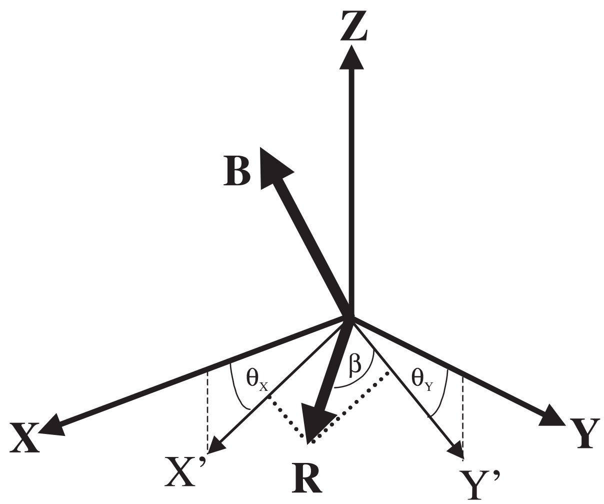

Figure 2. Geometry near the high-latitude magnetopause, showing the transformation from the local X'Y'B magnetic field coordinate system at the satellite to the fixed XYZ GSE system.

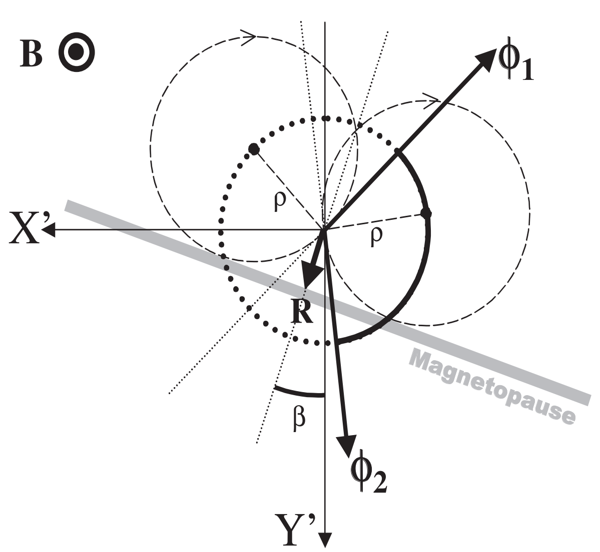

Figure 3. Geometry near the magnetopause, showing how the non-gyrotropic ion distribution from a single spacecraft (upper middle panel of Figure 1) can be used together with the ion gyroradius to find the distance **R** to the magnetopause and the magnetopause tilt angle β.

from the the X' axis, and are calculated in the following way:

$$\phi_1 = C_1/C_T \times 360^\circ + 60.167^\circ$$

$$\phi_2 = C_2/C_T \times 360^\circ + 60.167^\circ$$

where C_1 and C_2 are the positions of ϕ_1 and ϕ_2, respectively, measured along the 90° contour, and C_T is the total length of this contour. The last term adjusts for an offset relative to Sun-Earth line of the first azimuth sector of the RAPID instrument. From Figure 3 symmetry ($\phi_1 - 90^\circ - \beta = 270^\circ - \phi_2 + \beta$) gives the magnetopause tilt angle relative to the Y' axis:

$$\beta = (\phi_1 + \phi_2)/2 - 180^\circ$$

The magnetopause distance, R, is expressed by the gyroradius ρ (see Figure 3) and is given as :

$$R = \rho - \rho sin(\delta)$$

where

$$\delta = 90^\circ + (\phi_1 - \phi_2)/2$$

4. January 14, 2001

January 14, 2001, was one of the first days when the Cluster spacecrafts were in full operation. Several papers [e.g. *Moen et al.*, 2001; *Opgennorth et al.*, 2001; *Zong et al.*, 2001] have been published and present data from this date, believed to be the first real Cluster magnetospheric cusp encounter. We would like to go a step further and study the dynamics of the magnetopause during that boundary layer crossing, as deduced from energetic ion observations from the RAPID instrument.

The two middle panels of Figure 1 gives the magnetopause distance R in ion gyro-radii and the magnetopause tilt angle β for the three Cluster spacecrafts Rumba, Samba, and Tango. To indicate whether the spacecraft is inside or outside the magnetopause, we have set $R = 0$ when the spacecraft is outside and $R = 2$ when the spacecraft is more than two ion gyro-radii inside the absorbing boundary assumed to be the magnetopause. The magnetopause is seen to be in constant motion, as seen by all three spacecrafts. The overall magnetopause distances and the fact that the magnetopause is observed duskward of all spacecrafts, are consistent with the Cluster spacecrafts being near the dusk terminator.

Before 13:20 UT all three spacecrafts observed fully trapped distributions. Hence, all three spacecrafts were inside the magnetopause and more than two ion gyro-radii away from the magnetopause. At 13:23 UT all three spacecrafts start to see non-gyrotropic distributions, and the magnetopause now is less than two gyroradii away. At 13:25 UT there is a change in the tilt angle of the local magnetopause, but the magnetopause distance is almost unchanged. At 13:28 UT the local magnetopause starts to move quickly inwards, and within the next two-three minutes both Tango and Rumba cross the magnetopause for the first time. The magnetopause retreats, however, quickly again outwards around 13:35 UT. Samba does not cross the magnetopause before 13:40 UT. At that time the magnetopause migrates rapidly inwards and overtakes all three spacecrafts, and only background distributions are observed. Cluster is now in the magnetosheath for four to five minutes. At 13:45 UT the magnetopause moves rapidly away from Samba and Tango, while Rumba stays near the magnetopause until 13:57 UT. This latter time interval also nicely demonstrates that even if the spacecraft separation is quite small compared to the ion gyro-radius during this early part of the Cluster mission, the RAPID instruments still provide different (though consistent) observations. After 14:00 UT the magnetopause moved away from all three spacecrafts, and from 14:10 UT only fully trapped distributions were observed.

In this initial analysis we have not considered the different energy channels and ion species which RAPID provides. Still our results clearly illustrates how energetic ions can be used to remotely sense the local magnetopause in three-dimensions, when a spacecraft is within two ion gyro-radii from a scattering boundary like the magnetopause. In the bottom right panel of Figure 1 we show a sketch of what will be the topic of an upcoming paper. Knowing the local magnetic field, our method gives one point and tilt angle at the magnetopause for each spacecraft, each ion species (H, He, CNO), and each ion energy. Making some assumption about the shape of the magnetopause, it is possible to remotely sense the motion and direction of the three-dimensional local magnetopause surface within two ion gyro-radii from the Cluster spacecrafts, only limited by the time resolution of the RAPID instrument (128 seconds).

Acknowledgments. Financial support has been provided by Norwegian Research Council (University of Bergen) and NASA Grant NAG5-10108 (Boston University).

References

Fahnenstiel, S. C., Standing waves observed at the dayside magnetopause, *Geophys. Res. Lett., 8*, 1155, 1981.

Fritz, T. A., and D. J. Williams, Energetic particle sounding at the magnetopause and implications for magnetic reconnection, *Proc. Conf. Achievements of the IMS, 26-28 June 1984, Graz, Austria, ESA SP-217*, 131, 1984.

Moen, J., et al., Cluster boundary-layer measurements and optical observations at magnetically conjugate sites, *Ann. Geophysicae, 19*, in press, 2001.

Opgennorth, H., et al., Coordinated ground-based and CLUSTER observations on global and local scales, during a transient postnoon sector excursion of the magnetospheric cusp in response to solar wind variations, *Ann. Geophysicae, 19*, in press, 2001.

Wilken, B, et al., RAPID the imaging energetic particle spectromenter on Cluster, *Space Sci. Rev., 79*, 399, 1997.

Wilken, B, et al., First results from the RAPID imaging energetic particle spectrometer onboard CLUSTER, *Ann. Geophysicae, 19*, in press, 2001.

Williams, D. J., Magnetopause characteristics inferred from three-dimensional energetic particle distributions, *J. Geophys. Res., 84*, 101, 1979.

Williams, D. J., T. A. Fritz, B. Wilken, and E. Keppler, An ernergetic particle perspective of the magnetopause, *J. Geophys. Res., 84*, 6385, 1979.

Zong, Q.-G., B. Wilken, S. Y. Fu, and Z.-Y. Pu, Energetic oxygen ions sounding the magnetopause, *Proc. Cluster-II Workshop on Multiscale/Multipoint Plasma Measurements, London, 22-24 September 1999, ESA SP-449*, 379, 2000.

Zong, Q.-G., T. A. Fritz, B. Wilken, and P. Daly, Energetic ions in the high latitude boundary layer of the magnetosphere - RAPID/CLUSTER observation, Submitted to AGU Monograph on *The Low-Latitude Boundary Layer And Its Interaction with the Solar Wind and Magnetosphere*, 2001.

T. A. Fritz, and Q.-G. Zong, Center for Space Physics, Boston University, Boston, MA 02215, USA. (fritz@bu.edu; zong@bu.edu)

K. Oksavik, and F. Søraas, Department of Physics, University of Bergen, Allégaten 55, N-5007 Bergen, Norway. (kjellmar.oksavik@fi.uib.no; finn.soraas@uib.no)

(Received ________________.)