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

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[1] 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 spacecraft 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 spacecraft. 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. *INDEX TERMS:* 2720 Magnetospheric Physics: Energetic particles, trapped; 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2731 Magnetospheric Physics: Magnetosphere—outer; 2794 Magnetospheric Physics: Instruments and techniques

1. Introduction

[2] In July and August 2000 the four Cluster spacecraft were successfully launched into orbit. The tetrahedron formation of the spacecraft 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.

[3] In this paper we present a new technique to remotely sense the magnetopause in three dimensions as a function of time. An ion moving perpendicular to a uniform magnetic field will due to the Lorentz force term qvB perform a circular motion, where q is the ion charge, v is the particle velocity, and B is the magnetic field intensity. The ion gyro radius of this motion is given as $\sqrt{2mE}/qB$, where m and E are the ion mass and energy, respectively. However, if the magnetic field contains a sharp scattering boundary, the ion will not be able to perform its original circular motion. This leads to a net loss of initially trapped ions across the boundary, which will create a distinct signature in the ion distribution.

[4] Such studies use these characteristics of three-dimensional energetic particle distributions observed near the magnetopause

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[*Williams*, 1979; *Williams et al.*, 1979] to estimate the location, orientation and velocity of the magnetopause in a direction perpendicular to the magnetic field. *Fahnenstiel* [1981] used energetic > 24 keV ion distributions from the ISEE-2 spacecraft to remotely sound the ion trapping boundary and to study standing waves 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 to data from other spacecraft such as the HEP-LD instrument onboard GEOTAIL [e.g. *Zong et al.*, 2000].

2. Instrumentation

[5] The present study uses data from three of the Cluster spacecraft (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 $A \propto ET^2$, where the energy range is from 50 to 1500 keV. The RAPID ion sensor 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

[6] 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. Significant fluxes of ions are only observed along the solid contour between ϕ_1 and ϕ_2 (to be defined below). The dotted part of the contour shows that 90° ions are absent. The longer this dotted line is, the closer the spacecraft is to the scattering mechanism. The azimuthal location of ϕ_1 and ϕ_2 gives the rotation β of the scattering boundary relative to the spacecraft coordinate system. However, if the spacecraft itself 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.

[7] To our knowledge the magnetopause ion sounding technique has so far only been applied at the low latitude magnetopause,

Characteristic Particle Distributions
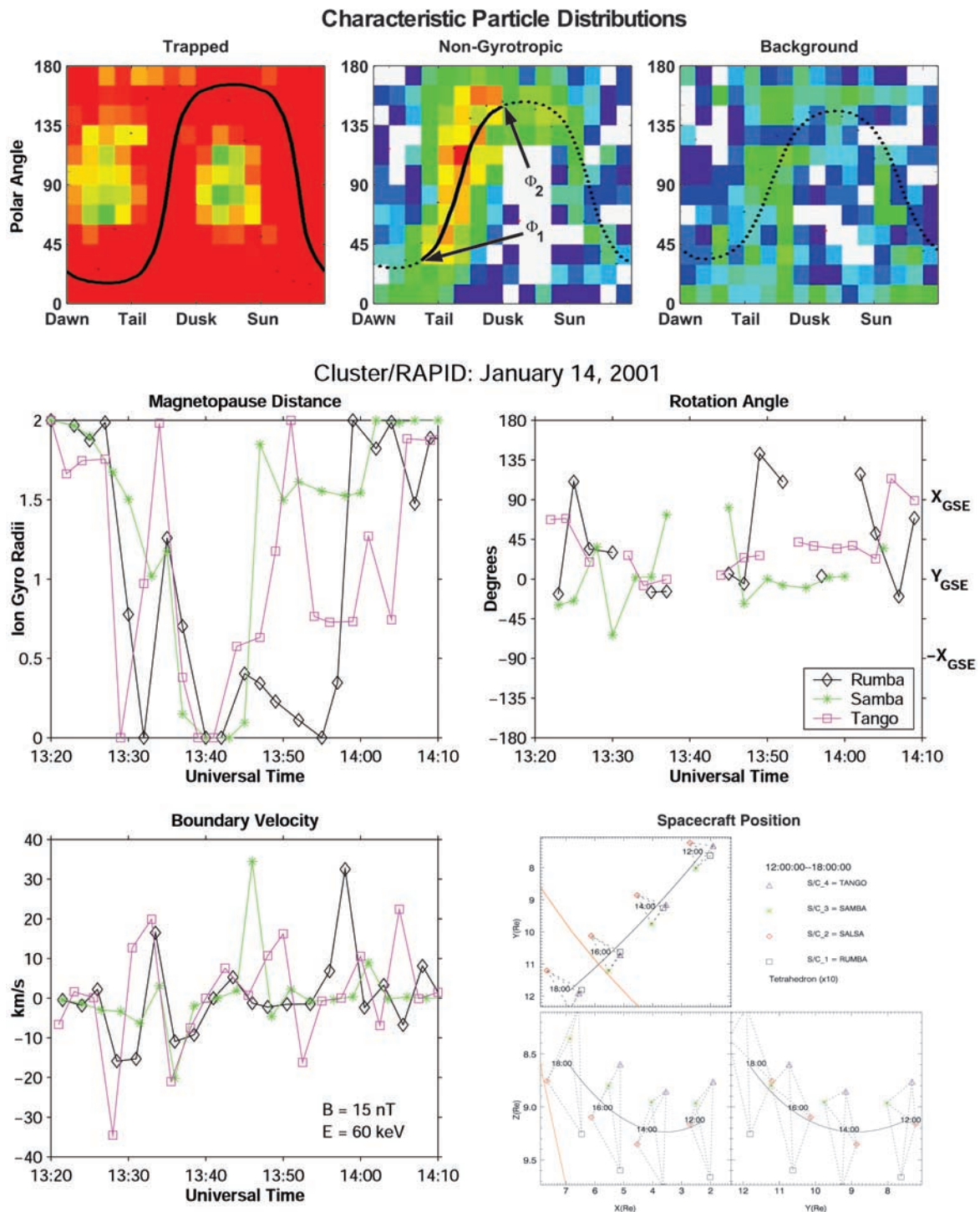

Cluster/RAPID: January 14, 2001

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 R in ion gyro-radii from Cluster to the magnetopause and the magnetopause tilt angle β, both derived using the energetic ion sounding technique and data from the RAPID instrument. The bottom row gives the corresponding boundary velocities (assuming that our sounding ions are 60 keV protons in a 15 nT field) and the position of the Cluster spacecraft on January 14, 2001.

see e.g. *Williams* [1979]. The vector **R** from the spacecraft to the magnetopause is given by

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

where R is the distance from the spacecraft to the magnetopause. At low latitudes $\mathbf{X}' \approx \mathbf{X}_{GSE}$ and $\mathbf{Y}' \approx \mathbf{Y}_{GSE}$, since **B** is approximately parallel to the $\mathbf{Z}_{GSE}$ axis. However, the data set we present in this paper is from high-latitudes, which will further complicate our geometry. The offset between the $\mathbf{Z}_{GSE}$ axis and the magnetic field vector must be taken into account, and we define a new coordinate system $\mathbf{X}'\mathbf{Y}'\mathbf{Z}'$ or $\mathbf{X}'\mathbf{Y}'\mathbf{B}$, since the $\mathbf{Z}'$ axis is chosen to be parallel to the magnetic field. Furthermore, we define the $\mathbf{X}'$ axis to be perpendicular to **B**, located in the $\mathbf{XZ}_{GSE}$ plane, and rotated an angle θ_X relative to the $\mathbf{X}_{GSE}$ axis. Finally, the $\mathbf{Y}'$ axis is chosen so that the $\mathbf{X}'\mathbf{Y}'\mathbf{B}$ system is orthogonal. According to Figure 2 the transformation is then given by:

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

$$\mathbf{Y}' = \frac{\mathbf{B}}{B} \times \mathbf{X}' = -\frac{B_Y}{B}\sin(\theta_X)\mathbf{X}_{GSE}$$
$$+ \left[\frac{B_Z}{B}\cos(\theta_X) + \frac{B_X}{B}\sin(\theta_X)\right]\mathbf{Y}_{GSE} - \frac{B_Y}{B}\cos(\theta_X)\mathbf{Z}_{GSE}$$

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

[8] 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 from the the $\mathbf{X}'$ axis, and are calculated in the following way:

$$\phi_1 = C_1/C_T \times 360° + 60.167°$$

$$\phi_2 = C_2/C_T \times 360° + 60.167°$$

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
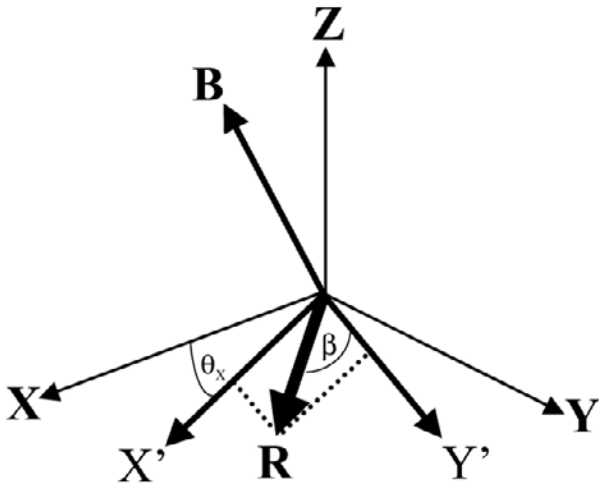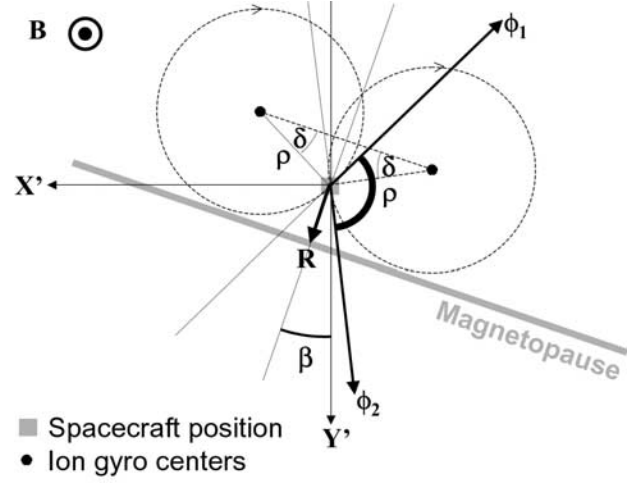

Figure 3. Geometry near the magnetopause, showing how the non-gyrotropic ion distribution from a single spacecraft (upper middle panel of Figure 1) can be used together with the ion gyroradius to find the distance **R** to the magnetopause and the magnetopause tilt angle β.

Figure 3 symmetry ($\phi_1 - 90° - \beta = 270° - \phi_2 + \beta$) gives the magnetopause tilt angle relative to the Y' axis:

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

The distance from the spacecraft to the magnetopause, R, is expressed by the gyro-radius ρ (see Figure 3) and is given as:

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

where

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

4. January 14, 2001

[9] January 14, 2001, was one of the first days when the Cluster spacecraft were in full operation. Several papers have been published from this date, believed to be the first real Cluster magnetospheric cusp encounter. *Opgennorth et al.* [2001] give a nice review of the large scale geophysical context (solar wind, Cluster observations, low-altitude spacecraft data, and ground-based instrumentation). *Moen et al.* [2001] present ground-based all-sky images from Svalbard. *Zong et al.* [2001] provide an overview of the RAPID observations. In this paper we would like to go a step further and study the dynamics of the magnetopause during this boundary layer crossing, as deduced from energetic ion observations from the RAPID instrument.

[10] The two middle panels of Figure 1 give the magnetopause distance R in ion gyro-radii and the magnetopause tilt angle β for the three Cluster spacecraft 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 spacecraft. The overall magnetopause distances and the fact that the magnetopause is observed duskward of all spacecraft, are consistent with the Cluster spacecraft being near the dusk terminator.

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

[11] Before 13:20 UT all three spacecraft observed fully trapped distributions. Hence, all three spacecraft were inside the magnetopause and more than two ion gyro-radii away from the magnetopause. At 13:23 UT all three spacecraft 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 spacecraft, 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 (500–600 km) is quite small compared to the ion gyro-radius (2400 km, for 60 keV protons in a 15 nT field) 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 spacecraft, and from 14:10 UT only fully trapped distributions were observed.

[12] In the bottom left panel of Figure 1 we have derived the velocity of the boundary, assuming the observed ions are 60 keV H ions in a 15 nT field. Please note that 40 km/s is an upper limit for the boundary velocities we can observe with these assumptions, corresponding to a boundary motion of two ion gyro radii in 128 seconds. It is obvious that time aliasing may be a problem, and the assumption of a well defined planar standing boundary may break down if the boundary is changing its orientation too rapidly. This may also explain some of the large changes of β in Figure 1. Furthermore, in this initial analysis we have not considered the different energy channels and ion species. We have just assumed 60 keV protons for the paper. Still our results clearly illustrates how these energetic ions can be used to remotely sense the local magnetopause in three-dimensions, reproducing gross patterns from the three spacecraft. In principle, knowing the local magnetic field, our method will give 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 spacecraft.

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