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A study of magnetic drift motion of particles around the equatorial plasmapause by using the cluster observation

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Abstract

On August 7, 2003 the Cluster spacecraft moved through the dayside magnetosphere. The energetic particle spectrometer on board Cluster provided measurements of an extensive range of energy. Besides, satellite measurements of geomagnetic field showed a gradient magnetic field. It is known that an inhomogeneity of the magnetic field leads to a drift of charged particles. In this paper, the drift velocities including gradient drift and curvature drift have been calculated for an energy range from 0.1 to 300 keV via various pitch angles (about 6 to 9 UT). The pitch angles in the magnetic equator via the magnetic mirror location have been calculated near the magnetopause. Besides, the ratio of perpendicular particle energy over total particle energy as a function of equatorial pitch angle has been calculated. The drift velocities depending on the pitch angle for the low energy (0.1 kev) is about 0.01-0.07 km/s and for the higher energies of the particles (300 kev) is about 50-200 km/s between $L \approx 4$ to $L \approx 6$. The results show that particles with higher energies penetrate the deeper areas of the magnetosphere.

Keywords: magnetosphere, drift velocity, pitch angle, particle flux, plasmapause

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1 Introduction

On August 7, 2003, the Cluster spacecraft moved through the dayside magnetosphere. Darrouzet et al. (2006) analyzed the plasmasphere pass on August 7, 2003, at 14:00 LT and between -30° and +30° of magnetic latitude MLAT. Figure 1 illustrates an example of frequency-time spectrogram on August 7, 2003, by Cluster spacecraft. They analyzed a plasmasphere pass by Cluster to study the overall geometry of the plasmaspheric density structure, using gradient computation techniques. Kalaee and Katoh (2016) studied the effect of the angle between the magnetic field and the gradient density in detail on the radio window. Moreover, satellite measurements of the geomagnetic field show a gradient magnetic field.

It is known that an inhomogeneity of the magnetic field leads to a drift of charged particles. The gradient drift velocity is proportional to the perpendicular gyratory energy of the particle and also when the field lines are curved, a curvature drift appears. Vogiatzis et al. (2006) showed that the electrons with pitch angle around 90 degrees (subjected mainly to curvature drift) observed by Cluster are produced in a remote location duskward of the satellite location, due to the longitudinal and tail ward expansion of a current disruption region.

On the other hand, the RAPID spectrometer (Research with Adaptive Particle Imaging Detectors), is an advanced particle detector for the analysis of super thermal plasma distributions in the energy range from 20–400 keV for electrons, 30 keV–1500 keV for hydrogen (Wilken et al. 1997, 2001; Korth et al. 1997). Korth et al. (1997) showed that on the dayside magnetopause, the effect of density gradients is less obvious and the particle flux appears to be eroded by the growing size of the loss cones. Apatenkov et al. (2009) considered the injections of energetic electrons with a dispersion over energies, which were observed during substorm by the Cluster satellites near the midnight meridian. They determined the radial propagation of the injection front with a velocity of 100–150 km/s at a distance of 7-9 R_g.

Vogiatzis et al. (2006) showed that the perpendicular-peaked electron enhancements (electrons with pitch angle around 90 degrees, subjected mainly to curvature drift) observed by Cluster are produced in a remote location duskward of the satellite location, due to the longitudinal and tail ward expansion of a current disruption region.

The current study is based on the observational data obtained around the plasmapause region via the Cluster satellites. It is known that the velocity of drift motion is an important characteristic since the charge particle flux can be estimated from the drift velocity and the density. Details concerning the data analysis are given by Engwall et al. (2009) and André et al. (2015).

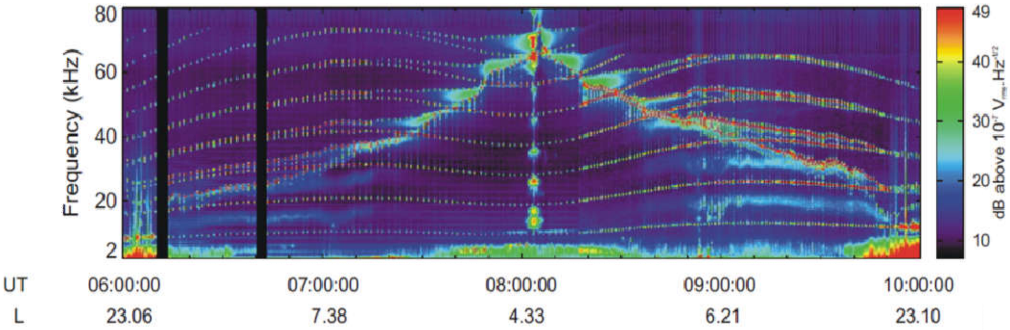


Figure 1. An example of frequency-time spectrogram on August 7, 2003, by Cluster spacecraft (Darrouzet et al., 2006).

In this work, it is considered that the magnetic field strength, the gradient magnetic field and a wide range of particle energies from 0.1 to 300 keV. Further, the pitch angles in the magnetic equator via the magnetic mirror location have been calculated near the magnetopause. Besides, the ratio of perpendicular particle energy over total particle energy as a function of equatorial pitch angle has been calculated.

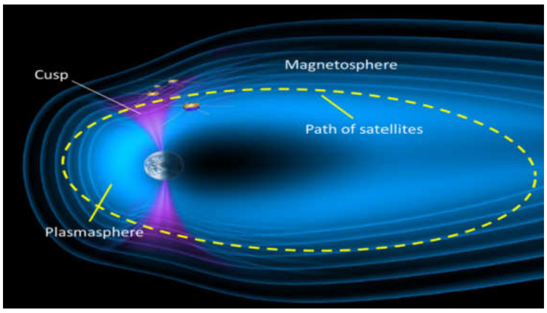


Figure 2. Sketch of the magnetosphere with the Cluster orbit. Image adapted from the ESA.

2 Dataset and Observations

The Cluster satellite system includes four spacecrafts with a polar elliptical orbit. Figure 2 shows a sketch of the magnetosphere with the Cluster orbit. The passage of the four Cluster spacecraft is considered through the inner magnetosphere on August 7, 2003, from 06:00–9:00 UT when the Cluster satellites were in the dayside magnetosphere close to perigee (4RE). A subinterval of this passage has been studied earlier by Darrouzet et al. (2006) and De Keyser et al. (2007). They focused on the gradients of the magnetic field strength |B| and of the electron density. Figure 3 shows a projection of the Cluster orbit onto the XZ GSE plane on August 7, 2003. The satellites cross the inner magnetosphere from the south to the north.

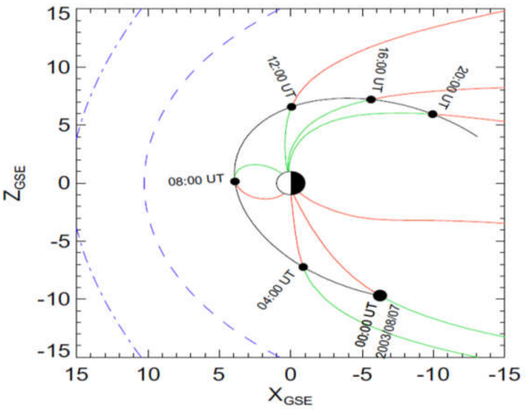


Figure 3. Projection of the Cluster orbit onto the XZ GSE plane.

3 Discussion and results

In this paper, the energetic electron behavior in the low latitude magnetospheric region has been considered. A consideration of the plasmasphere crossing on August 7, 2003, between 07:00 and 09:00 UT, at 14:00 LT and between 30 and +30 of MLAT has been analyzed by Darrouzet et al. (2006). Figure 4 shows the magnetic field strength (black curve) and the angle between the magnetic field and the gradient magnetic field (red curve) as a function of time on August 7, 2003, at the magnetic equator $\theta = 90°$ with a magnetic field strength about 332 nT. Figure 4 shows that |B| reaches a local minimum around perigee, at a geocentric distance of about 4.53RE. The perigee is around 08:05 UT. The variation of the magnetic field strength along the field lines is faster, except for closeness to the magnetic equator.

Spacecraft detectors cover the energy range from several eV to hundreds of keV. The energetic particle spectrometer on board Cluster provided measurements of an extensive range of energy. A wide range of particle energies from 0.1 to 300 keV are considered. It is known that the total magnetic drift velocity (sum of gradient and curvature drifts) (Baunmjohann and Treumann, 2012) in the Earth's inner magnetosphere is:

$$\mathrm{v}_{drift} = \mathrm{v}_R + \mathrm{v}_\nabla = (v_\parallel^2 + \frac{1}{2}v_\perp^2)\frac{\mathbf{B}\times\nabla B}{\omega_c \mathrm{B}^2}, \qquad (1)$$

where ω_c is the cyclotron frequency, $v_\perp$ and $v_\parallel$ are the transverse and the field-aligned components of the particle velocity, **B** and ∇B are the magnetic field and the magnetic field gradient respectively.

The drift velocity of particles with energies: 0.1, 1, 10, 20, 30, 50, 100 and 300 keV are calculated for different pitch angles from 0 to 90 degrees. The pitch angle, α of a charged particle in the magnetosphere is defined as:

$$\alpha = \tan^{-1}\left(\frac{v_\parallel}{v_\perp}\right). \qquad (2)$$

Figures 5 and 6 show the drift velocities as a function of time, between 06:00 to 09:00 UT. The bottom scale gives the L-shell position of the center of the Cluster.

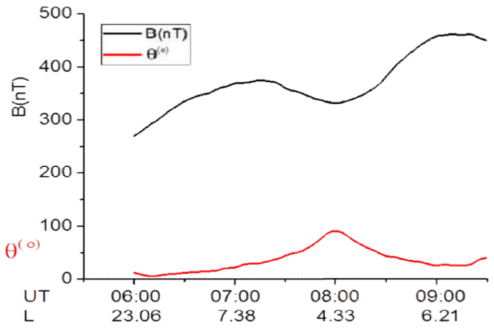


Figure 4. The magnetic field strength (black curve) and the angle between the magnetic field and the gradient magnetic field (red curve) as a function of time. The bottom scale gives the L-shell position of the center of the Cluster.

The gradient drift velocity is proportional to the perpendicular gyratory energy of particles, more energetic particles drift faster since they have a larger gyroradius and experience more inhomogeneity of the field. The curvature drift velocity is proportional to the parallel particle energy and perpendicular to the magnetic field and its curvature. Figures 5 and 6 show the drift velocities take their maximum values in the magnetic equator (L ≈ 4.5). The drift velocities depending on the pitch angle for the low energy (0.1 kev) is about 0.01–0.07 km/s and for the higher energies of the particles (300 kev) is about 50–200 km/s between L ≈ 4 to L ≈ 6. Results for the drift velocities (the minimum and the maximum value) of particle energies in the near magnetic equator are listed in Table 1.

Table 1. The minimum and the maximum values (depending on the pitch angle) of drift velocities via the energy of the particle.

Energy of particle (keV)	Drift velocity (km/s)
0.1	0.03-0.07
1.0	0.3-0.7
10	3.2-7.0
20	6.0-14
30	10-20
50	15-35
100	30-70
300	100-200

The motion of trapped particles in the plasmasphere is a combination of gyro motion, bounce motion, and gradient and curvature drifts. The bounce motion is determined by the mirror points and the equatorial pitch angle. Incidentally, not all particles participate in the bounce motion. Particles with a mirror point below about 100 km heights will be absorbed in the atmosphere through collisions with the neutral atmosphere.

In the next step, the magnetic mirror, the latitude of the magnetic mirror and the equatorial pitch angle, α_{equ} are considered. L ≈ 4.54 approximation is considered at the plasmapause. The mirror magnetic field and its location on the meridian related to L ≈ 4.54 are calculated. The mirror points correspond to $v_\parallel = 0$. The equation of the equatorial pitch angle, α_{equ} related to the mirror latitude of the particle is:

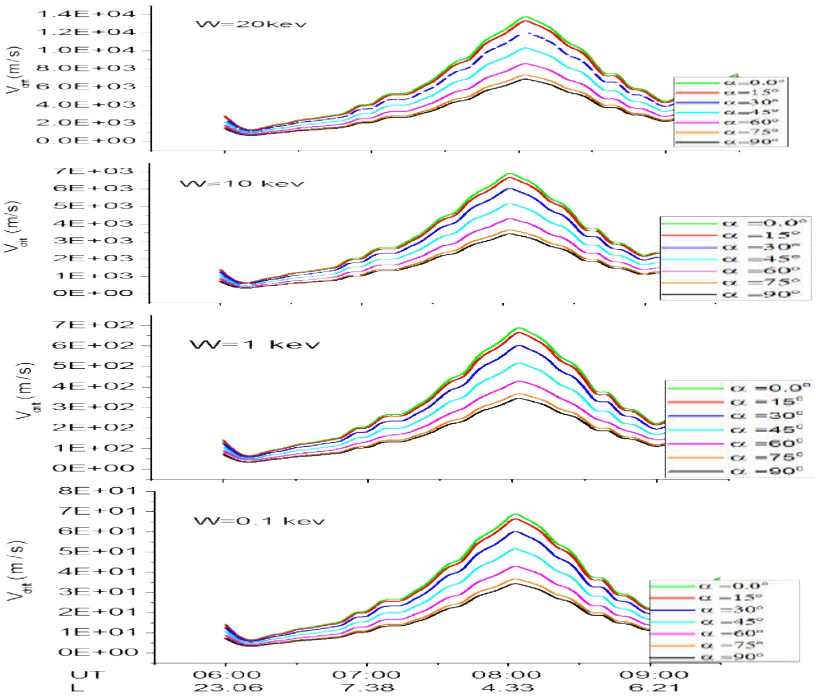


Figure 5. The drift velocity (including the gradient drift and the curvature drift) for different particle energies and with the different pitch angles (α°). The bottom scale gives the L-shell position of the center of the Cluster.

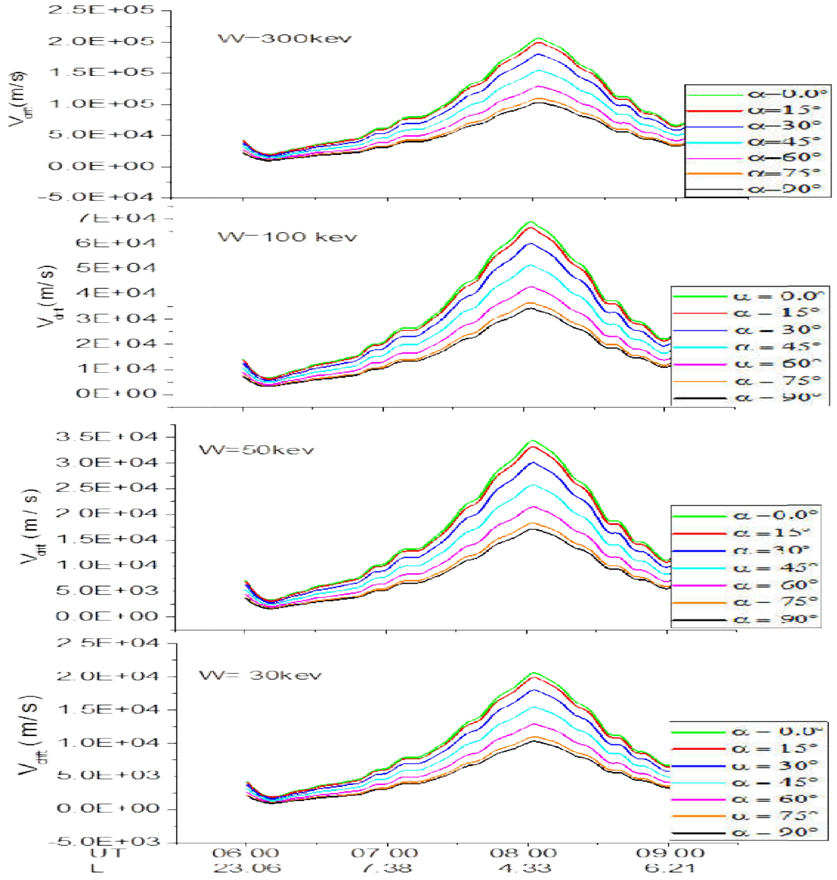


Figure 6. The same as Figure 5 but for a higher range of particle energies.

$$\sin^2\alpha_{equ} = \frac{B_{equ}}{B_m} = \frac{\cos^6\theta_m}{\left(1+3\sin^2\theta_m\right)^{1/2}}, \qquad (3)$$

where B_{equ}, B_m and θ_m are the equatorial magnetic field strength, the mirror magnetic field strength and the latitude of the mirror point, respectively.

The mirror magnetic field strength as a function of the latitude of the mirror point on the meridian related to L ≈ 4.54 is shown in Figure 7. As expected, the magnetic field strength increases with the increase in the latitude of mirror point. At the latitude of ≈ 60°, a dipole field line of given L ≈ 4.54 intersects the Earth's surface. In Figure 8, the pitch angle equator as a function of the magnetic mirror point latitude is shown. The equatorial pitch angle depends on the latitude where a particle is reflected. The latitude of mirror point decreases with the increase of the equatorial pitch angle. With increasing equatorial pitch angles, the mirror points move to more equatorial latitudes and the particles mirror close to the equatorial plane. Figure 9 shows the ratio of the perpendicular energy particle and energy particle as a function of a) the pitch angle equator, and b) the latitude of the mirror point. Particles with small equatorial pitch angles have large parallel velocities, and their mirror points are at high latitudes.

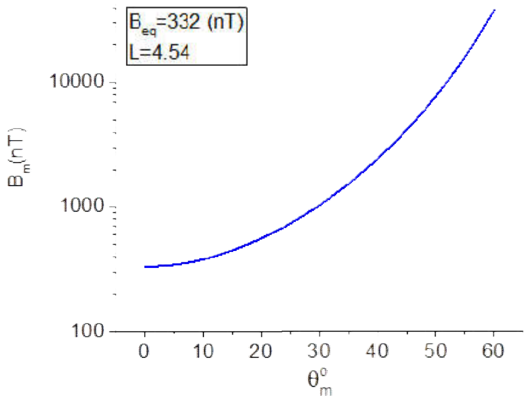


Figure 7. The mirror magnetic field strength as a function of the latitude of the mirror point.

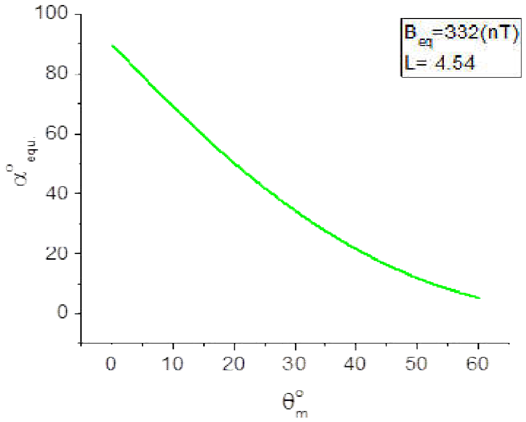
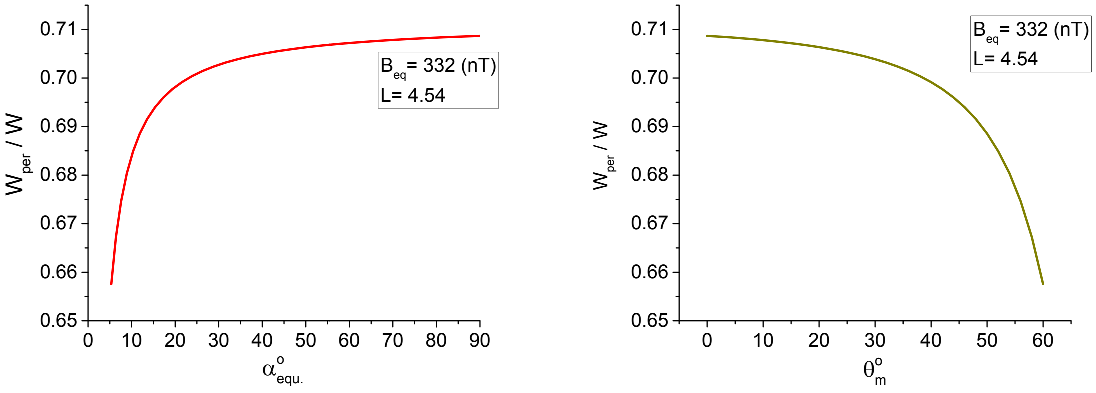


Figure 8. The pitch angle equator as a function of the magnetic mirror point latitude.



(a) (b)

Figure 9. The ratio of the perpendicular energy particle and energy particle as a function of a) the pitch angle equatorial, and b) the latitude of the mirror point.

4 Conclusions

It is known that the drift velocities of particles are very important quantities since the charged particle flux can be estimated from the drift velocity and the density. The observational data obtained around the plasmapause region by the Cluster satellites, on August 7, 2003, from 06:00–9:00 UT are used when Cluster spacecrafts went through the inner magnetosphere. The focus was on the gradients of the magnetic field strength |**B**| and particle energies for calculating drift velocities. The drift velocities including gradient drift and curvature drift have been calculated for an energy range from 0.1 to 300 keV via various pitch angles (about 6 to 9 UT). The drift velocities depending on the pitch angle for the low energy (0.1 kev) is about 0.01–0.07 km/s and for the higher energies of the particles (300 kev) is about 50–200 km/s between L ≈ 4 to L ≈ 6. Note that energies' electrons and ions precess around the Earth with about the same drift velocity, only in opposite directions, because there is no explicit mass dependence in Equation (1). By using the 3D PIC code, Esmaeili and Kalaee (2017) showed that particles with higher energies penetrate the deeper areas of the magnetosphere. Besides, the ratio of perpendicular particle energy over total particle energy as a function of equatorial pitch angle and mirror point has been calculated on the meridian related to L ≈ 4.54. The results show that the latitude of mirror point decreases with the increase of the equatorial pitch angle.

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