Links between the plasmapause and the radiation belts boundaries as observed by Cluster instruments

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1. ABSTRACT.

The **Cluster mission** offers the exceptional opportunity to study the **relations between the position of the plasmapause and the position of the radiation belt boundaries** with identical sensors on multiple spacecraft. We compare the positions of the radiation belt edges deduced from **CIS observations (electrons with energy larger than 2 MeV)** with the positions of the plasmapause derived from **WHISPER data (electron plasma frequency)**. In addition, we compare those results with the boundary positions determined from **RAPID observations (electrons with energy between 244.1 and 406.5 keV)**.

The period of **1 April 2007 to 31 March 2009** has been chosen for the analysis because at that time **Cluster's perigee** was located at lower radial distances than during the earlier part of the mission (as close as **2 R_E, deep inside the plasmasphere and the radiation belts**). This time period corresponds to a **long solar activity minimum**.

Differences are observed between the radiation belt boundary positions obtained from the two different instruments: The **radiation belt positions are related to the energy bands**. The **plasmapause position is more variable than the radiation belt boundary positions**, especially during small geomagnetic activity enhancements. A correspondence is observed between the **plasmapause position determined by WHISPER and the outer edge of the outer radiation belt of energetic electrons (> 2 MeV)** observed by CIS. There may be an apparent contradiction with previous studies that indicated a correlation between the inner edge of the outer radiation belt and the plasmapause. Radiation belt losses through plasmaspheric waves, however, occur on a longer time scale and are longitudinally averaged because of energetic particle drift motion, so the **radiation belt boundaries should not necessarily reflect the instantaneous plasmapause position at one particular local time**. Moreover, **during higher geomagnetic activity time periods, the plasmapause is located closer to the inner boundary of the outer radiation belt**.

2. GENERAL CONTEXT.

a) Inner Magnetosphere.

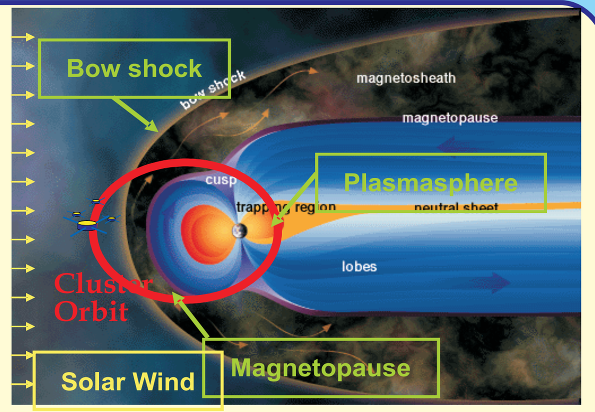

FIG. 1*: Sketch of the magnetosphere with the CLUSTER orbit and the regions crossed by the spacecraft (from ESA).*

♣ The **Earth's plasmasphere [FIG. 1]**:
- ♦ Toroidal region in Earth's magnetosphere, above ionosphere (≈1000 km).
- ♦ Extending up to equatorial distances of **4-8 R_E**.
- ♦ Outer boundary called **plasmapause**.
- ♦ Configuration, size, shape and plasma distribution depend sensitively on the **recent history of geomagnetic activity [REF. 1]**.

♣ The **Earth's radiation belts**:
- ♦ **Energetic protons and electrons** (>100 keV) trapped by magnetic field.
- ♦ **Inner belt** located typically between 1 and 2 R_E, and **relatively stable**, varying only during intense geomagnetic activity.
- ♦ **Outer belt** extended approximately from 4 to 7 R_E and **highly dynamic**, especially during geomagnetically active times.
- ♦ Outer and inner belts separated from each other by **a slot region**.

♣ **Radiation belt dynamics is strongly influenced** by the core plasmasphere distribution and **the plasmapause position**. All studies between radiation belt boundaries and plasmapause position have been done with different satellites and/or models. But **possible to study both regions with instruments onboard 1 unique mission**: Cluster.

b) Cluster Mission.

♣ The **Cluster** mission is composed by **4 identical spacecraft** (C1, C2, C3, C4), launched in Summer 2000 **[REF. 2]**. The 4 spacecraft cross the **plasmasphere near perigee**, from Southern to Northern Hemisphere **[FIG. 2]**. The orbit of the tetrahedron formed by the 4 satellites is elliptic (orbital period = 57 h):
♦ Apogee = 19.6 R_E ♦ Initial perigee = 4 R_E ♦ Perigee after 2007 = 2 R_E

♣ **11 identical instruments**, measuring fields, waves and particles; 3 used here:
- ♦ Sounder and wave analyzer: **WHISPER** (Waves of HIgh frequency and Sounder for Probing Electron density by Relaxation).
- ♦ Ion spectrometer: **CIS** (Cluster Ion Spectrometry).
- ♦ High energy particles detector: **RAPID** (Research with Adaptive Particle Imaging Detectors).

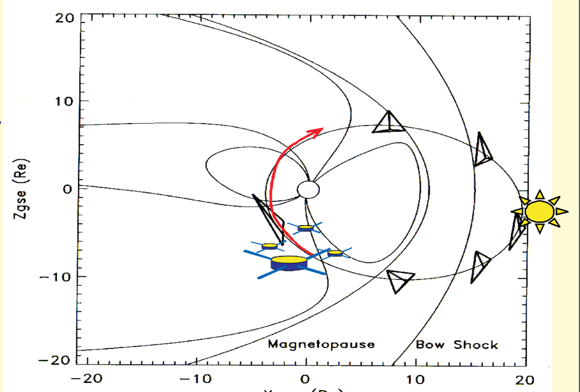

FIG. 2*: Sketch of the magnetosphere with the CLUSTER spacecraft configuration along the orbit (from ESA).*

REFERENCES

[1] Darrouzet, F., J. De Keyser, and V. Pierrard (Eds.), The Earth's Plasmasphere: A Cluster and Image perspective, *Springer*, 296 pp., ISBN 978-1-4419-1322-7, **2009**
[2] Escoubet, C. P., C. T.Russell, and R. Schmidt (Eds.), The Cluster and Phoenix Missions, *Kluwer*, 658 pp., ISBN 0-7923-4411-1, **1997**
[3] Darrouzet, F., et al., Links between the plasmapause and the radiation belts boundaries as observed by the instruments CIS, RAPID and WHISPER onboard Cluster, *J. Geophys. Res.*, 118, 4176-4188, **2013**
[4] Ganushkina, N. Y., et al., Locations of boundaries of outer and inner radiation belts as observed by Cluster and Double Star, *J. Geophys. Res.*, 116, A09234, **2011**
[5] Pierrard, V., F. Darrouzet, K. Borremans, and G. L. Rosson, Space weather effects in the inner magnetosphere: Plasmasphere and radiation belts dynamics during geomagnetic storms, 1st URSI Atlantic Radio Science Conference, doi:10.1109/URSI-AT-RASC.2015.7303154, **2015**
[6] Pierrard, V. et al., Recent progress in physics-based models of the plasmasphere, *Space Sci. Rev.*, 145, 193-229, **2009**
[7] Movie of plasmapause - radiation belts links: http://sci.esa.int/cluster/52802-cluster-shows-plasmasphere-interacting-with-van-allen-belts/

3. DATA ANALYSIS.

a) Plasmapause Position: WHISPER Data.

♣ Use WHISPER data to derive the plasmapause position:
WHISPER spectrograms ⇒ Plasma frequency F_{pe} ⇒ **Electron density N_e** from: F_{pe} [kHz] = $9(N_e[cm^{-3}])^{1/2}$
⇒ Density profiles along trajectory during plasmasphere crossing
Search of largest jump of N_e
⇒ Derivation of **average innermost position of plasmapause [REF. 3]**

♣ Statistical analysis of WHISPER data on C3, **April 2007 to March 2009** (only inbound crossings because the outbound one is not as clear due to the presence of many waves): **205 plasmapause crossings [FIG. 3]**
- ♦ **All MLT sectors covered** except around midnight.
- ♦ L-position of the plasmapause: 3.5 - 7.5 R_E, and **mainly 5 - 7 R_E** (quite far from the Earth, due to the low geomagnetic activity during this period).
- ♦ Density values observed by WHISPER are low due to instrumental limits (maximum electron density = 80 cm^{-3})

⇒ Plasmapause position derived by WHISPER corresponds more to the **outer edge of the plasmapause boundary layer** than to the inner edge. When the plasmapause is not very sharp, this can lead to significant differences in the determination of the plasmapause position, so that the actual plasmapause position could be at **lower L values** than the values deduced from this WHISPER analysis.

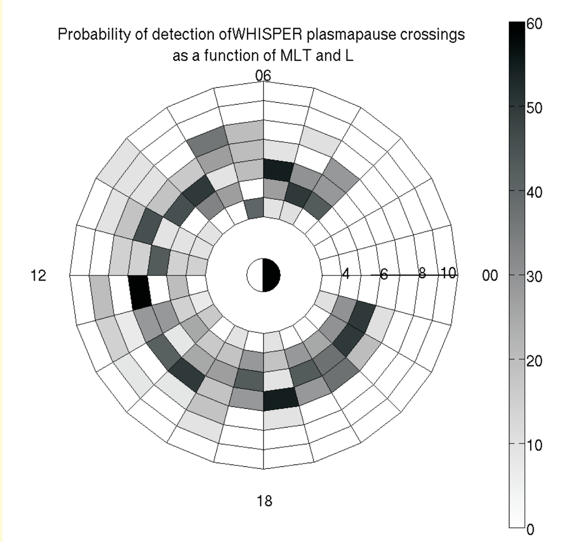

FIG. 3*: L–MLT probability of occurrence of the plasmapause inferred from inbound crossings and determined by WHISPER onboard C3 from 1 April 2007 to 31 March 2009*

b) Radiation Belt Boundary Position: CIS Data.

♣ **Boundaries of the outer and inner radiation belts** can be clearly identified by using background counts of the CIS instrument (due to **particles with energy E > 2 MeV**).

♣ Statistical analysis of CIS data on C3, April 2007 - March 2009 (**220 radiation belt crossings**) **[REF. 4]**:
- ♦ **Outer boundary of outer belt : L = 5-7 R_E [FIG. 4]**.
- ♦ Inner boundary of outer belt : L = 3-4 R_E.
- ♦ Outer boundary of inner belt : L = 2-3 R_E.
- ♦ Note that we do not have lots of data around midnight MLT sector for the outer boundary of the outer radiation belt during those 2 years of data. This is due to an **impossibility to determine this boundary from CIS** measurements and spacecraft eclipses.

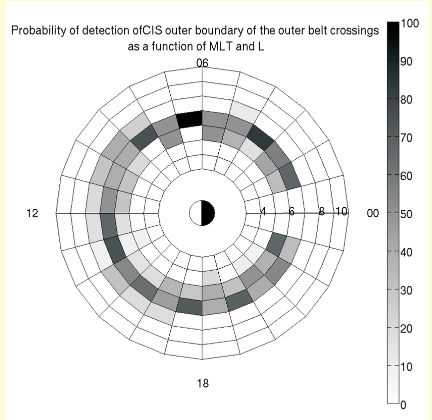

FIG. 4*: L–MLT probability of occurrence of the outer boundary of the outer radiation belt as inferred from inbound crossings and determined by CIS onboard C3 from 1 April 2007 to 31 March 2009.*

c) Radiation Belt Boundary Position: RAPID Data.

♣ **RAPID experiment**:
- ♦ Measures 3-D energetic electron and ion fluxes in energy range > ~ 30 keV.
- ♦ **2 sets of imaging spectrometers**, 1 for electrons and 1 for ions.
- ♦ Analysis of electron omni-directional differential fluxes by the 6th energy channel with **energies 244.1-406.5 keV** (fluxes averaged from all detector directions and all spin sectors).

♣ Statistical analysis of RAPID data on C3, April 2007 - March 2009 (**259 radiation belt crossings**) **[REF. 4]**:
- ♦ **All MLT sectors covered**, except around midnight, for the same reasons as for CIS (not possible to determine the boundaries with the RAPID instrument).
- ♦ Outer boundary of outer belt : L = 4-9 R_E, **mainly L=6-8 R_E [FIG. 5]**.
- ♦ Inner boundary of outer belt : L ~ 4.5 R_E.
- ♦ Outer boundary of inner belt : L ~ 3.5 R_E.
- ♦ Positions at **slightly larger L values than deduced from CIS**, due to different energy than CIS observations.

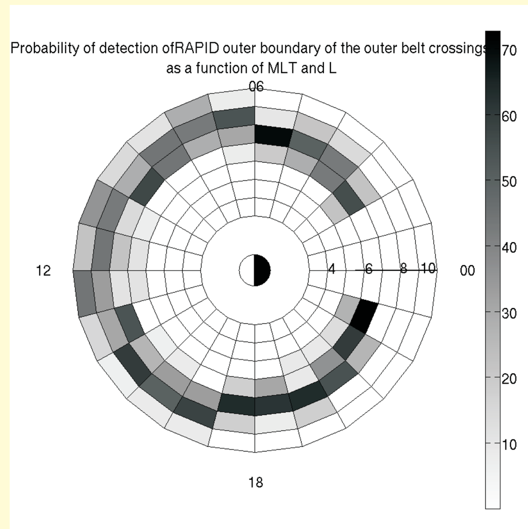

FIG. 5*: L–MLT probability of occurrence of the outer boundary of the outer radiation belt as inferred from inbound crossings and determined by CIS onboard C3 from 1 April 2007 to 31 March 2009.*

4. COMPARISON.

♣ Boundaries selected during **entrance into the plasmasphere and into the radiation belts**, and not during exit because:
- ♦ **Inbound plasmapause usually more clearly seen** on the WHISPER spectrograms due to the orbit of the spacecraft more perpendicular to this boundary, and then easier to detect.
- ♦ Radiation belts boundaries usually more clearly defined during the inbound pass than during the outbound one.

♣ From January 2009, the **background counts measured by CIS were very weak**
⇒ Determination of radiation belt boundaries quite difficult (due to low geomagnetic activity as well as new orbit of the Cluster satellites crossing the belts at higher magnetic latitudes).

♣ Main results **[FIG. 6] - [REF. 4]**:
- ♦ **Inner boundaries of outer belt less variable than outer boundaries.**
- ♦ **Plasmapause very dynamic, even during this quiet period.**
- ♦ **Plasmapause corresponds rather to outer boundary of outer belt of 2 MeV electrons**. It occasionally matches with inner edge of outer belt of the 244.1-406.5 keV electrons (especially when the plasmapause is closer to the Earth, which corresponds to high geomagnetic activity periods).
- ♦ **Shift in positions of inner and outer belt boundaries for the 2 electron populations considered**. The inner and outer edges of the belts depend on the considered energy. The higher is the electron energy, the less extended is the radiation belt. This is also reproduced by radiation belts model like AE8.
- ♦ **Energy range of the considered particles is fundamental when considering correlations between radiation belts and plasmapause.**

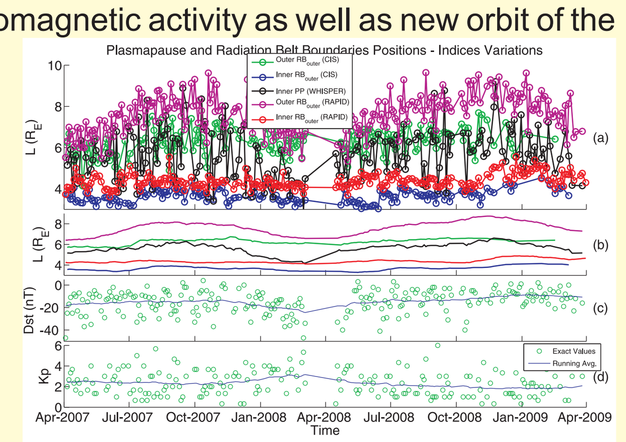

FIG. 6*: Positions of plasmapause and outer belt boundaries by C3 during April 2007 - March 2009 during inbound crossings: (a) Plasmapause (black) from WHISPER; inner (blue) and outer (green) edges of outer belt from CIS; inner (red) and outer (magenta) edges of outer belt from RAPID; (b) running averages of the data on panel (a); (c-d) min-max values of the Dst-Kp index in the 24 hours preceding an event (green circles) and running averages (blue line).*

5. HIGHER GEOMAGNETIC ACTIVITY

♣ Determination of the electron fluxes (244.1-406.5 keV) from **RAPID (C1, C2, C3, C4)** during higher geomagnetic activity time period (June-October 2010) **[REF. 5]**, and comparison with plasmapause position from **WHISPER (C1, C2, C3, C4) [FIG. 7]**:
- ♦ **Inner belt quite stable** (in position and intensity).
- ♦ **Outer belt moving** and more intense after increase of geomagnetic activity.
- ♦ Possible 3rd belt (at L~3 R_E), but need further verifications...
- ♦ **Plasmapause position very variable** (but just a few points during this time period), but good agreement when several spacecraft available.
- ♦ **No clear conclusion about links between plasmapause and outer belts.**

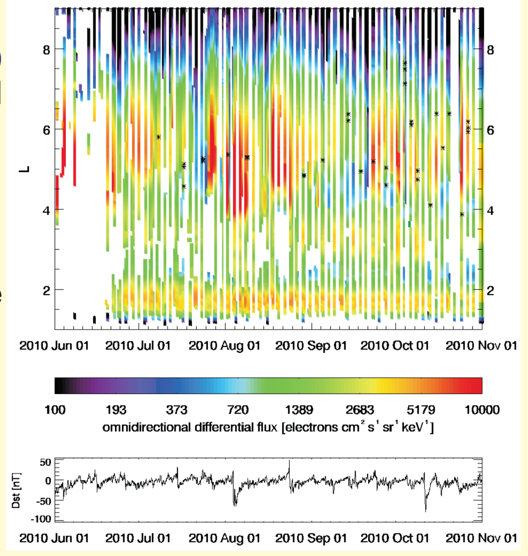

FIG. 7*: L-variations of the radiation belt fluxes from RAPID during June-October 2010, and plasmapause position derived from WHISPER (black stars).*

♣ **Comparison with plasmasphere kinetic model** (Kp dependent) **[REF. 6]**: Plasmaspheric density and plasmapause location (pink) in the equatorial plane on 24 October 2010 at 19:00 UT **[FIG. 8]**:
- ♦ **Plasmasphere contracted** (geomagnetic storm 2 days before), with 2 shoulders in afternoon and night sectors.
- ♦ **Plasmapause at L~3.5-4 R_E** (close to WHISPER position around 3.9 R_E at 16 MLT).

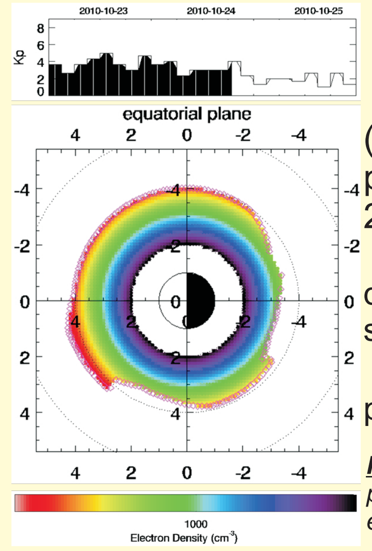

FIG. 8*: Plasmasphere density and plasmapause position (pink) in the equatorial plane on 24 October 2010.*

5. CONCLUSIONS.

♣ During April 2007 – March 2009, the **Cluster spacecraft penetrated deep in the plasmasphere and the radiation belts** since its perigee became as low as L=2. We analyzed during this period of time the electron populations of different energies observed by **3 different instruments onboard Cluster**:
- ♦ The plasmasphere with WHISPER (cold 1 eV electrons);
- ♦ The radiation belts with CIS (electrons with E > 2MeV) and RAPID (electrons with E = 244.1-406.5 keV).

♣ The **plasmapause coincides more to the outer boundary of the very energetic electrons (>2 MeV) than to the inner boundary of the radiation belts [REF. 5]**. The radiation belt population coexists with the plasmasphere up to large radial distances. Many daily variations are recovered, but some differences appear in the different electron populations.

♣ Due to low geomagnetic activity, **the radiation belts are very week and the plasmasphere is very extended at L>5**. The plasmapause position is very variable due to different conditions and has strong interactions with geomagnetic activity.

♣ Radiation belt positions are related to energy bands. We use 2 instruments based on different measurement methods with 2 different energy bands. **Links with plasmapause need specification of considered radiation belt population.**