MULTI-SATELLITE OBSERVATIONS OF THE NEAR EARTH PLASMA SHEET AND FLANK MAGNETOPAUSE: RESPONSE TO THE 5TH DECEMBER 2004 CME

M.G.G.T. Taylor(1), B. Lavraud(2), M.F. Thomsen(2), A.N. Fazakerley(3), M.W. Dunlop(4), J.A. Davies(4), C.P. Escoubet(1), H. Laakso(1), H. Khan(1), A. Masson(1), H.J. Opgenoorth(1), R.H. Friedel(2), H. Rème(5), C.M. Carr(6), T.L. Zhang(7) and E.A. Lucek(6)

(1)ESA/ESTEC, SCI-SH, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands
(2)Los Alamos National Laboratory, Los Alamos, New Mexico, USA
(3)Mullard Space Science Laboratory, University College London, Surrey, UK
(4) Space Science and Technology Department, RAL, Oxfordshire, UK
(5)Centre d'Etude Spatiale des Rayonnements, Toulouse, France
(6)Imperial College, London
(7)IWF, Space Research Institute, Austrian Academy of Sciences, Graz, Austria

ABSTRACT

On 5th December 2004 after an extended period of weakly northward/dawnward directed interplanetary magnetic field (IMF), a coronal mass ejection (CME) impacted the Earth's magnetosphere. The interplanetary magnetic cloud was characterised by an extended (> 12 hours) period of northward IMF (although initially with a clock angle ~ 45 degrees) and a rapid solar wind dynamic pressure increase from 1 – 9 nPa. During this time numerous magnetospheric spacecraft were operational: The ESA Cluster spacecraft were inbound from the southern hemisphere, dusk-flank magnetosheath; on the same flank, the CNSA/ESA TC-1 spacecraft was skimming the magnetopause; closer to the Earth, the CNSA/ESA TC-2 spacecraft was in the northern hemisphere lobe/mantle/plasma sheet boundary region at an altitude of about 5 Earth Radii and we also made use of multipoint measurements from the LANL geosynchronous spacecraft. From previous studies, the impinging Solar wind/IMF conditions characterising this event (northward IMF and compressed magnetosphere) are conducive to the delivery of cold dense plasma sheet (CDPS) material into the near-Earth region. In this case study we investigate the possible source and means of formation of this material and put it in context with other recent CDPS studies.

1. INTRODUCTION

The plasma sheet is a source for numerous dynamic magnetospheric processes (e.g. substorm plasmoids, aurora and the ring current). The formation and persistence of the plasma sheet is therefore of great scientific interest. The dominant supplier of plasma to the plasma sheet is the solar wind. Under southward directed interplanetary magnetic field (IMF) conditions the magnetosphere can be very active. Solar wind gains ready access to the magnetosphere via reconnection at the dayside magnetopause, supplying the mantle/lobe region, which in turn supplies the plasma sheet in the tail via reconnection in the distant magnetotail [1]. With enhanced activity, the density and temperature of the plasma sheet increase [2]. Under northward IMF conditions, little or no reconnection occurs on the dayside, providing much quieter geomagnetic conditions. During prolonged periods of northward IMF, the characteristics of the plasma sheet are markedly different to the same region under a southward IMF. In particular the plasma is much cooler and more dense [3] and is termed the cold dense plasma sheet (CDPS). Previous studies (e.g. [3], [4] and [5]), have suggested several transfer mechanisms to supply the plasma sheet with solar wind plasma, with the prime candidates being: slow diffusive access across the flank low-latitude boundary layer (LLBL), transfer across the flank boundary via the Kelvin-Helmholtz instability (KHI) [6] and finally reconnection in both hemispheres, poleward of the cusp. More recent studies have been able to identify transport processes related to CDPS formation: Utilising Cluster observations [7] have provided evidence of KHI like transport along with flank magnetopause boundary; [8] and [9] used a multi-spacecraft and MHD simulation to identify lobe reconnection leading to CDPS formation. We note that these studies could not exclude the other transfer processes mentioned previously in forming the CDPS in each case.

In this paper we present multi-point, multi-spacecraft observations of the formation of the CDPS. In Section 2 we present an overview of the event, reviewing the IMF/Solar wind and magnetospheric conditions during this period. In Section 3 we present a discussion of the observations and relate our observations to recent studies on the formation of this region i.e. [7], [8] and [9].

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2. OBSERVATIONS

2.1 Interplanetary conditions

On 3rd December 2004, the Large Angle Spectroscopic Coronograph (LASCO) [10] instrument on Solar and Heliospheric Observatory (SOHO) [11] observed a Halo coronal mass ejection (CME). On the 5th December 2005, the Advanced Composition Explorer (ACE) [12] observed the resultant magnetic cloud and plasma signatures. Figure 1 shows the solar wind and IMF conditions around this period, surrounding the event in this study.

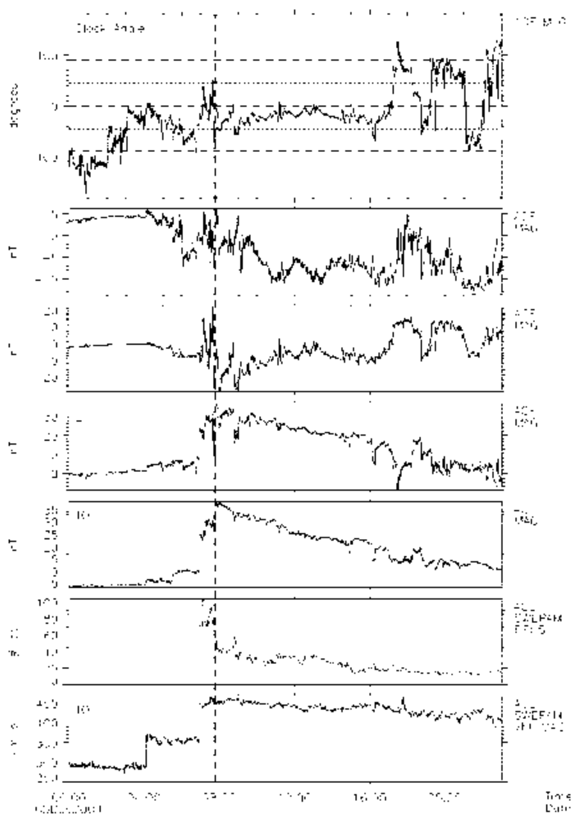

Figure 1. IMF conditions from the ACE spacecraft, showing IMF clock angle, B GSM x,y,z coordinates and magnitude and solar wind density and speed. The horizontal lines in the top panel show the -90, -45, 0, 45 and 90° clock angles, with the dashed vertical line at ~ 8 UT showing the approximate impact time of the shock at the Earth, as determined from LANL GEO observations of the magnetosheath (see Figure 2).

Data from the ACE Magnetic Field Experiment (MFE) [13] and the Solar Wind Electron Proton Monitor (SWEPAM) [14] show an initially dawnward IMF, with a Solar wind speed of ~300 km/s. We note that density measurements are not available up to ~07:00 UT. After around 04:00 UT ACE observes an increase in solar wind speed and the magnetic field becomes more variable, until just before 07:00 UT when ACE observes the passage of the CME magnetic cloud, with a jump in density, velocity and magnetic field magnitude. The cloud is also associated with a large positive B_Z component, where the clock angle stays between -45 and 0 degrees for an extended period from around 09:00 to 17:00 UT.

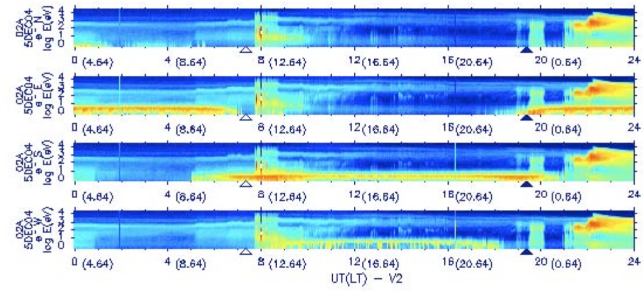

Figure 2. LANL-02A electron data, showing the impact of the CME related shock at ~07:46 UT and the subsequent magnetosheath entries. Panels show (from top to bottom) North, East, South and West look directions, with the solid (open) triangle on the time axes denoting midnight (noon) Local Time.

Figure 2 shows electron data from the Magnetospheric Plasma Analyser (MPA) [15] instrument onboard the Los Alamos Geosynchronous spacecraft LANL-02A. At ~07:46 UT up to 5 LANL GEO spacecraft (orbiting at L~6.6 R_E) observed the impact of the CME related shock.

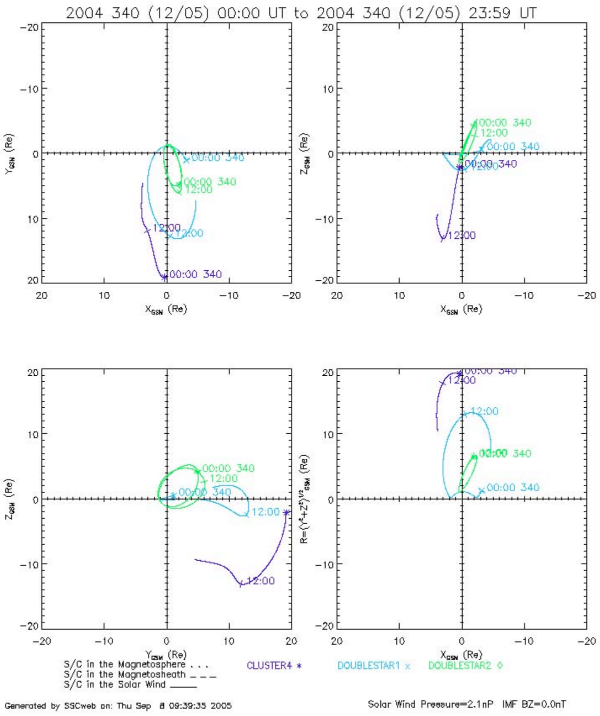

Figure 3. Overview of Cluster 4, TC-1 and TC-2 orbit data in GSM for 00:00 – 23:59 UT on 5th December 2004.

Figure 2 shows only data from LANL-02A, which made 3 brief excursions into the magnetosheath, indicating the impact of the CME (and subsequent magnetospheric compression) and was back in the magnetosphere by 08:05 UT (although some observations of boundary layer like plasma occurred at ~08:47 UT). After about 21:00 UT the spacecraft observes a cool, dense plasma sheet population.

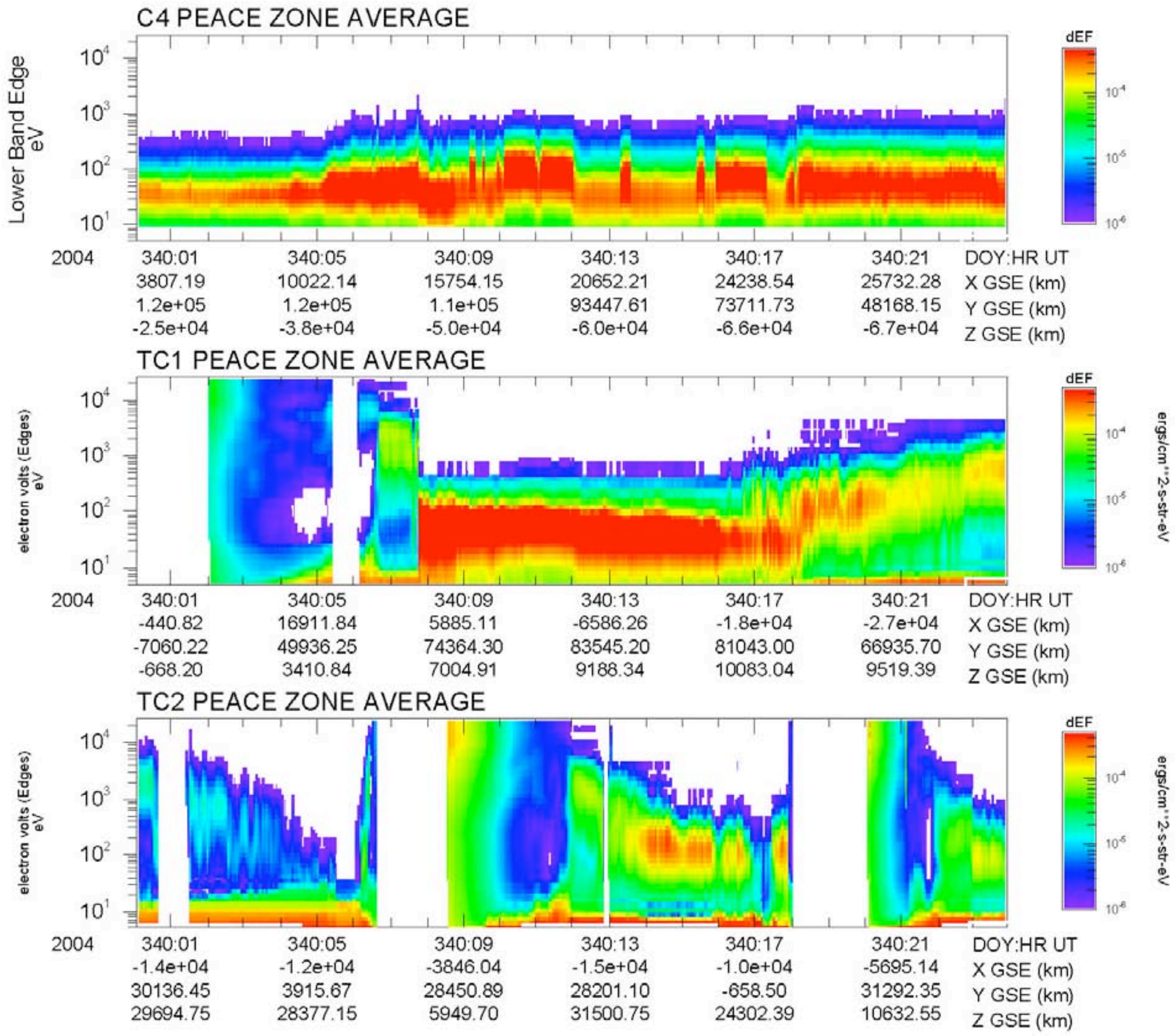

Figure 4. Overview plot of PEACE electron data from Cluster 4 (upper panel), TC-1 (middle panel) and TC-2 (lower panel)

2.2 Cluster and Double Star

For this event we treat Cluster [16] as a single spacecraft, using Cluster 4 as the reference spacecraft. Figure 3 shows an overview of the spacecraft orbits for the time period 00:00 – 23:59 UT, 5th December 2004. We note that this projection shows the TC-2 orbit design that has it locked at very similar Magnetic Local Time (MLT) to Cluster. We also note the overlap in MLT with TC-1. Such synergy provided an excellent opportunity to investigate large-scale magnetospheric processes. During the time period shown, Cluster (orbit period ~ 57 hours) is inbound from the Solar wind and magnetosheath, while TC-1 progresses through a significant portion of its total orbit (orbit period ~27 hours), moving though perigee, the dayside magnetosphere and out towards the evening flank. The same amount of time for TC-2 sees portions of 3 separate orbits, due to the comparably smaller orbital period ~11 hours. The actual regions visited by the spacecraft are perhaps better described by the data themselves.

In Figure 4 we show PEACE [17], [18] electron data from Cluster, TC-1 and TC-2 for the same period as plotted in Figure 3. The upper panel shows Cluster data, which begins in a rather rarefied magnetosheath that gradually becomes denser until just before 8:00 UT, when the bow shock crosses the spacecraft and signals the arrival of the CME observed ~ 50 minutes previously at ACE (we note solar wind electrons have a rather broad spectral density after this initial bow shock crossing). There then follows a series of bow shock crossings, moving Cluster from magnetosheath to solar wind and back again, until after 18:00 UT, when the spacecraft persistently observe the magnetosheath until the end of the period in question. In the second panel we present TC-1 PEACE data, where at the beginning of the period the instrument is off, due to the proximity of the radiation belts. Just after 02:00 UT, the instrument is turned on and observes the outer radiation belts, identified by electron flux at all energies. Just after 06:00 UT TC-1 observes the dayside plasma sheet, with characteristic energies of >1-5 keV. As with Cluster, just before 08:00 UT, the spacecraft observes the effect of the CME impact, in this case entering the magnetosheath. TC-1 remains in the magnetosheath until around 17:00 UT when it begins to observe magnetopause boundary layer plasma, characterised by quasi-periodic bursts of higher energy, CDPS-like plasma interspersed with the magnetosheath plasma. After ~ 18:30 UT TC-1 enters a more persistent, CDPS-like population at an energy of ~100s eV, which gradually rises to around 1 keV up to the end of the period. Finally in the lowest panel we show TC-2 data. As described previously, during the selected overview time that spacecraft completes just over 2 whole orbits, which is reflected in the data where we can see sections of 3 orbits. At the beginning of the time period TC-2 observes the tail plasma sheet (energies > keVs) followed by the plasma mantle region/lobe. The instrument is then powered down as it approaches the radiation belts. The beginning of the next orbit is characterised by a broad spectrum of electrons, signifying the proximity of the radiation belts and hence penetrating radiation. At around 12:00 UT the spacecraft enters the tail plasma sheet (energies > keV) with a gradual decrease in the peak energy of the population until ~13:30 UT when the spacecraft observes a much lower energy, denser CDPS population with a peak energy of ~100s eV, similar to the plasma observed at TC-1 between 18 and 21:00 UT.

We note that this population is persistent, with some brief plasma mantle/lobe encounters, up to ~18:00 UT when the instrument is powered down. Just after 20:00 UT the instrument is powered on for the next orbit, and again sees remnants of penetrating radiation, followed by a rather rarefied mantle/lobe like encounter. Unlike the previous orbit there is no evidence of > keV plasmas sheet populations, but instead remnants of the sub-keV CDPS population observed in the previous orbit, albeit at a lower flux level.

3. DISCUSSION

As was alluded to in the introduction above, the source of the CDPS is of great interest: is it formed via plasma transport at the flank boundary (e.g. [19] and [7]) or via the tailward convection of closed flux tubes by double poleward-of-cusp reconnection (e.g. [8] and [9])? The multipoint observations presented in this paper provide an interesting perspective for the investigation of CDPS formation. [8] reported a 3 hours time scale for the plasma sheet to complete its transition from hot and rarefied to cold and dense. In this current study, we cannot compare with this result, as we have no monitor continually in the tail plasma sheet. However, we can give timescales for the introduction of the CDPS to the near Earth region. Los Alamos geosynchronous spacecraft observe CDPS some 4 hours after the CME impact, while TC-2 observes the hot tenuous plasma sheet (HTPS) until ~13:00 UT, when it is replaced by the much cooler CDPS population some 5 hours after the CME impact.

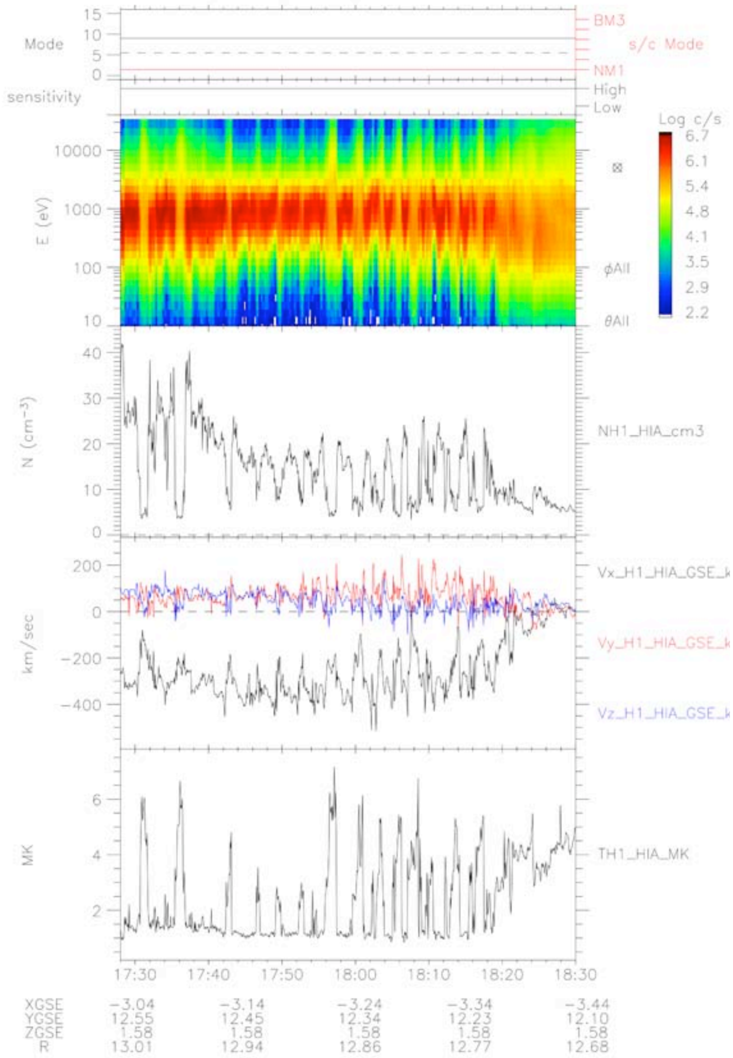

Figure 5 TC-1 HIA ion data. Upper panel shows an energy-time spectrogram, second panel shows density, third panel velocity and bottom panel temperature.

As was shown in Figure 4, TC-1 observes the flank magnetopause boundary layer from ~17:30 to 18:30 UT. In Figure 5 we concentrate on this period at TC-1, where we show (in Figure 5) TC-1 ion data from the HIA instrument [20]. The most striking features in these data are the quasi-periodic (~2 minutes) bursts of a magnetospheric flank population, with higher temperature, lower density and reduced magnetic field magnitude than the adjacent magnetosheath. We note that the FGM instrument [21] data (not shown) also shows significant oscillations/perturbations in the magnetic field. During the period that TC-1 observed this boundary, Cluster does not observe any similar fluctuations or perturbations in the magnetosheath, suggesting the TC-1 observations are locally driven and not by the magnetosheath/solar wind. These periodic signatures are similar to previous flank study reports of Kelvin-Helmholtz instability (KHI) like surface waves (i.e. [22] and [7]). However, unlike [7] the ions have a distinct bi-directional pitch angle in the boundary layer (not shown) as do the electrons, which we show in Figure 6 for the same time period as Figure 5.

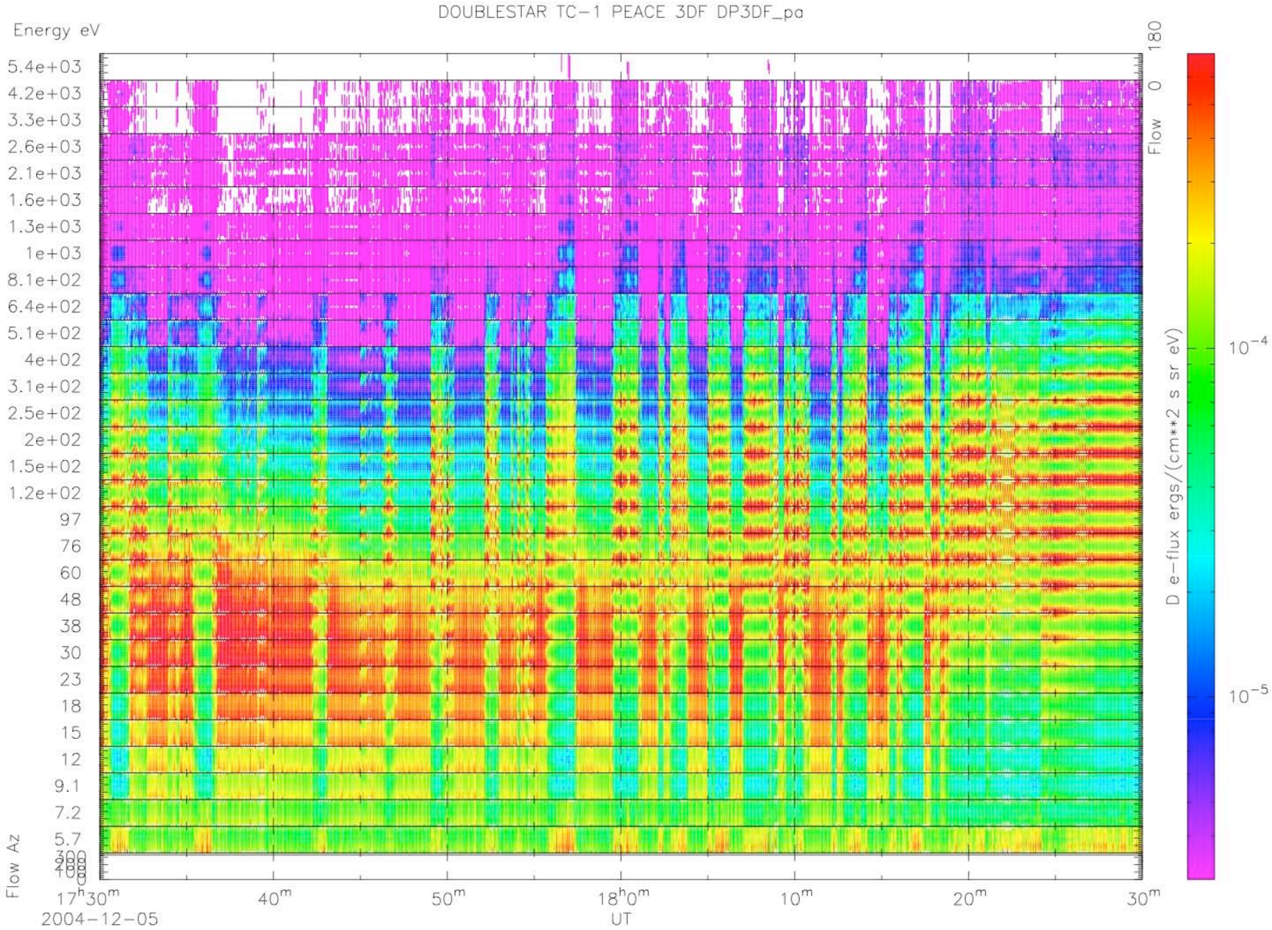

Figure 6 TC-1 PEACE data for same time period as Figure 5. Data is present as a Sauvaud plot, with each energy channel presented as a pitch angle versus time plot with 0 (180) degree pitch angle at bottom (top) of each panel.

This Sauvaud plot of the PEACE data shows each energy band as a pitch angle versus time plot, where we can see the obvious bi-directionality of the electrons in the boundary. We also note the distinct differences in energy of the 2 populations, with the boundary at energies between ~ 48-600 eV and the more isotropic magnetosheath population ~15-200 eV. This type of bi-directional electron distribution has been associated with closed magnetic flux tubes, in particular those formed by double (northern and southern hemisphere) poleward-of-cusp reconnection. In recent studies, ([8] and [9]), the role of poleward-of-cusp reconnection has been highlighted in the formation of the CDPS. During the current event, as shown in Figure 7, the Far Ultraviolet Instrument (FUV) on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) spacecraft [24] observed a persistent auroral spot, poleward of the sub-solar oval, consistent with a lobe reconnection site [25] which was evident from ~12:00 – 17:00 UT. This evidence of lobe reconnection in addition to 'closed' magnetic flux tubes strongly suggests that lobe reconnection is ongoing, possibly pertaining to convected double poleward-of-cusp reconnected flux tubes (c.f. [8] and [23]).

The trajectory of TC-1 is such that is tracks the proposed path (i.e. flanks to central tail) of the CDPS, and, as was noted in the observation section, reveals a gradual increase in the peak CDPS energy as it moves

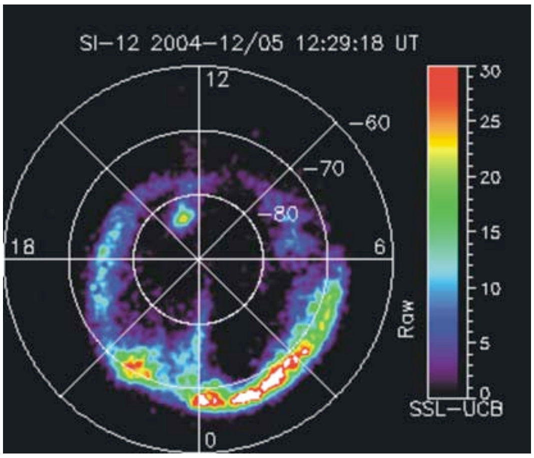

Figure 7 IMAGE FUV data. We note the bright high latitude spot in the post noon sector, indicative of lobe reconnection.

closer to the central tail, reflecting results from previous studies [19]. The ions from 20:00 – 22:00 UT show a much more 'mixed' appearance, as was reported by [26]. We note the similarities in peak energies observed by TC-2 (between 13:00 and 16:00 UT) and the CDPS population observed at TC-1 (from 22 UT onwards), suggesting possible mapping of TC2 field lines to close to the magnetopause boundary layer.

4. CONCLUSIONS

The 5th December 2004 event was observed by a constellation of spacecraft providing a large-scale snapshot of the formation of the CDPS, with evidence of CDPS material observed at LANL GEO, TC-1 and TC-2. We highlight the following:

- Timescale of CDPS formation of approximately 3-4 hours, although this figure is based on geosynchronous and high latitude measurements so may provide an upper limit.
- Evidence of both flank boundary activity (waves?) AND poleward-of-cusp reconnection, as shown in Figure 8.
- Evidence of flank boundary waves, possibly driven by Kelvin-Helmholtz waves, were observed by TC-1.
- The lack of mixing at the flank boundary suggests it is stable to KHI at that position, such that wave growth has not been significant to drive instability to create vortices and generate transport (c.f. [7]).

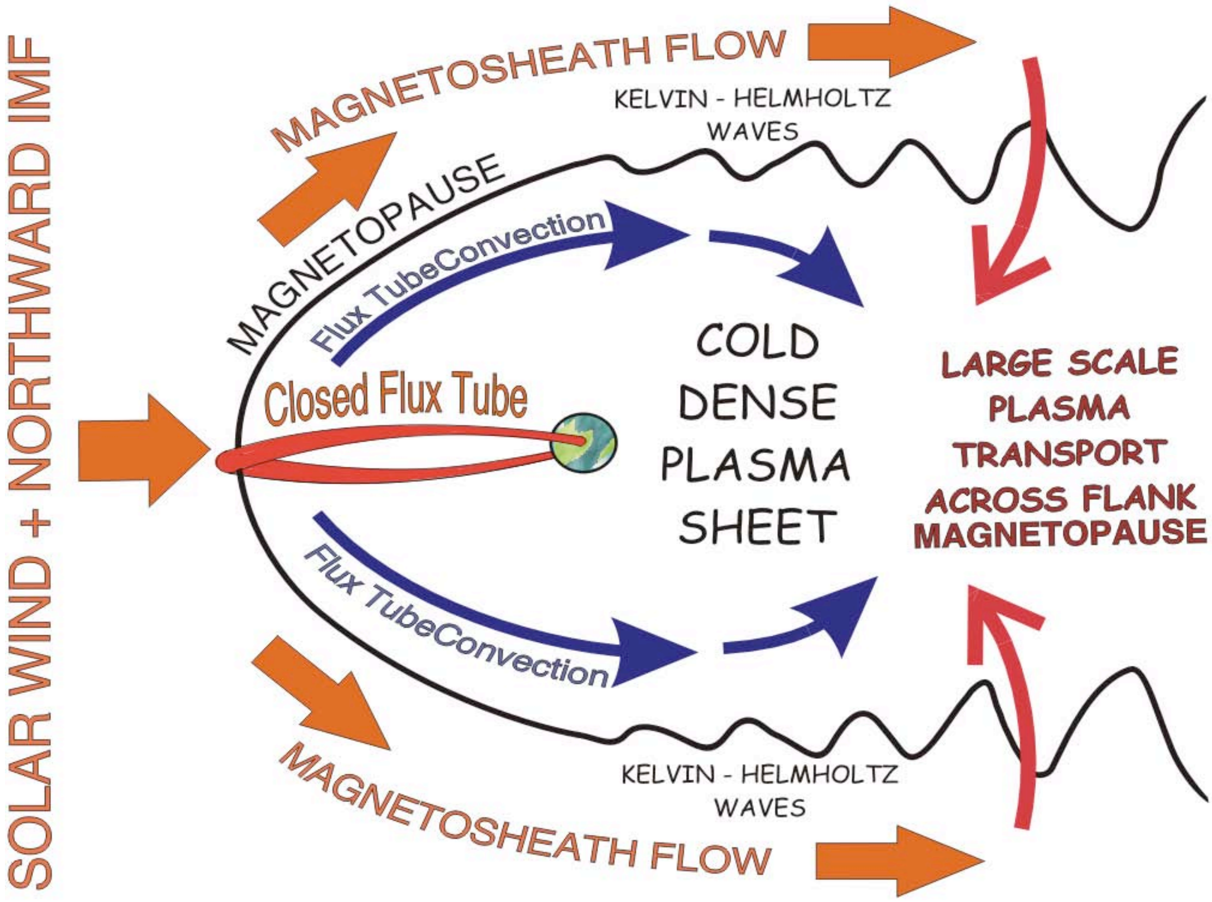

Figure 8 Cartoon of magnetosphere related to multipoint observations in this case study.

- Bi-directional electrons (and ions) in the CDPS at the boundary suggest a more closed configuration.
- IMAGE observations suggest lobe reconnection is ongoing, although observations are not as definite at time TC-1 crossed boundary.
- It is not clear what effect boundary fluctuations have on CDPS i.e. could this cause observed pitch angle?
- Observational confirmation (Figure 7) of ongoing lobe reconnection, in addition to 'closed' electron/ion boundary layer existence at flank boundary suggests poleward-of-cusp reconnection may be dominant source of CDPS.
- Transport via KHI (c.f [7]) may be possible further downtail, where the waves would have become unstable.

This event is currently under further study to link an additional conjunction with the Polar spacecraft along with ground based measurements and simulations of the boundary interaction, to try and single out which process is dominant from Figure 8.

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