THE EARTH'S PLASMASPHERE A CLUSTER, IMAGE, AND MODELLING PERSPECTIVE

J. De Keyser - taking notes

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Foreword by Michel: What is a physical process? Usually not to explain a single observation, but a whole set of them, in this case by Cluster and Image. Removal of spatio-temporal ambiguities leads to better modeling.

1 Introduction (history, physical processes)

1.1 History - Storey (whistler), Carpenter (whistler), Gringauz (satellites)

1. DON: History, involving Storey, Gringauz, Carpenter, in regard to early discoveries.

   Owen Storey 47 : PhD at Cambridge : discovery of the plasmasphere, years before the space age. Radio noise involving whistlers. Frequency-time diagrams. Propagation paths? Propagation in a plasma, long distance, could not be within ionosphere, but must be along the Earth's magnetic field. Signal would depend on plasma density. Is remote sensing. Jack Ratcliffe, supervisor, was skeptical (URSI meeting in 1952). 1953: density estimate 400 cc, much higher than believed at that time from barometric distribution. In 1972 Ratcliffe publishes a book, has accepted. Gringauz: pioneering discovery of the density gradient at the outer limit of the plasmasphere with the Lunik 2 probe. Quadrispherical ion traps to measure densities. 1962. between 100 and 1000 cc up to 4 RE. In the Lemaire and Gringauz book. In 1963 average profiles from whistlers compared with the Gringauz stuff. In 1959 discovery of density depressions in the magnetosphere after magnetic storms. Calm high density case versus magnetic disturbance low density case. Depletion outside the knee. Later in the 60ies mapping of the plasmapause using whistlers became possible. In the 70ies with Antarctic data one could get a global picture from ground-based data. In 60ies argument over the knee as being real. Did not show up in retarding potential analyszer data, Serbu and Maier. Problems with spacecraft potential were identified to explain this. Realization that temperature <10 eV. Later one learned more of whistlers to understand L-shells, density irregularities, ... Digital processing, more detailed analysis of existing data. Some of the richest data not looked at. Some huge whistler receiving stations are being established. Active experiments. On conjugate points. On the south pole. Optimal spacing: direction-finding. 500 km in IGY. Depends on collecting area. Closer spacing for phase analysis. Ray-tracing to find origin of emissions, e.g. hiss.

1.2 First missions - DE, ISEE, PROGNOZ, OGO, GEOS, AKEBONO, ...

1. DON: Ogo 2 and 4 on the light ion trough; Alouette 1 and 2 on the lower hybrid resonance noise breakup at the plasmapause and first echoes at 2000 km from a steep plasmapause.

   ISIS and Alouette at 1000-2000 km altitude in polar orbit. Whistlers recorded, lower hybrid resonance = measure of field strength + mean ion mass at this location. Transition from proton-dominated to O^+ dominated. The light ion trough. Highly variable density (outer, beyound $L = 3$, recorded poleward.

   SAR arc observations by Alouette and OGO 2 at 1150 km altitude near edge of plasmasphere. Establish relationships between space and ground concerning relative positions of SAR arcs and plasmapause.

   OGO 5 data from Chappell instrument. Set of density profiles across L. Shows erosion effects, density depletions and peaks. Systematic difference between nighttime and afternoon types of profiles, now related to plumes. Plotting per local time the PP position as function of Ae.

   Taylor using OGO 2 understanding increase in mean mass, evidence of light ion trough as you move across the plasmapause. Mapping out of plumes.

   Ray propagation analysis to detect the density wall at the plasmapause.

   Some of this work before its time: Not immediately evident of how to absorb this into an overall picture.

   Whistler interpretation relies on diffusive equilibrium density distribution of the density. Model might have to be revisited now that we know more about it?

   Spacecraft before 1970: Lunik 1 and 2, Electron 2 and 4, OGO 1, 1, 5, IMP 2

2. FABIEN: Plasmasphere measurements from spacecraft (19701980 and after 1980).

   Satellite insruments during 70 - 80

   Prognoz, Geos 1 and 2, ISEE 1

Decreau et al 1982: Geos density and temperature profiles. Carpenter and anderson 10992: electron density profiles across L.

After 1980: DE 1 and 2, CRRES, Interball, ..., Image and Cluster.

DE 1 shos examples of various categories of density profiles: smooth, steep, multiple plateau, separated peaks (plumes?).

CRESS: waves

Polar: Laakso et al 1982 : statistical distribution of average eletron density in te msph for different Kp.

1.3 Physical processes - plasmapause formation and position, refilling, density structures formation, corotation or subcorotation, SAPS, SAID, ...

1. DON: Physical processes: Park's demonstration that dayside coupling fluxes are large enough to make the plasmasphere a reservoir for the nighttime ionosphere. The dynamic duskside bulge (now the base of the plume).

   Park: Is the upward flux of dayside ionosphere sufficient to populate the upper regions so to give you a reservoir to fill the nighttime ionosphere. Idea: diffusive barrier above the O+ maximum for the H+ to cross to reach the higher regions. The upward flux is larger than the downward flux needed to fill the nighttime ionosphere - found from whistlers in 1965.

   Observations of increasing density on particular flux tubes where you had whistlers: refilling. Even for days-long intervals you can see the nighttime decreases. Also shows how the density in the ionosphere decreases in the ionosphere and the plasmasphere during storms, and recover afterwards, with possibly different time scales. Problem with interpretation? From GEOS 2 and DE 1 one could track the increase in PP position. Understood the effect in terms of how fast the PP position changes, and how you can track that with a fixed position ground station.

2. JERRY: Observational paradigm: Standard scenario as response to a disturbance. Image EUV data, showing a plume, later quiet. Semi-automated extraction of PP position. Relation with IMF from ACE as measure of SW input, driver of convection, ie energy input. Canonical progression:

   - initial state,
   - erosion plus plume formation
   - rotation with narrower plume
   - wrapping with even narrower plume and differential rotation
   - refilling to get a big oval PP when quiet again. Sometimes with notches.

May depend on when multiple disturbances occur when equilibrium has not yet been reestablished. When erosion is weaker, a plume + channel are not formed, but a notch is created (Dennis).

SAPS

- extra erosion on the dusk side,
- during recovery: even after the main disturbance is done, the ionospheric current system is maintained, so that it can keep the plume
- can drag plasma out to create a narrow plume. much more filamentary.

Are there interior cavities from EUV data? Line-of-sight measurements are not completely conclusive. Channel overdraped with a very narrow plume is close to it ...

3. JOHN: Subauroral electric fields (SAPS/SAID) and plasmasphere erosion plumes.

   SAPS: ring current overlap with plasmasphere is limited to the outer edge. Initial state: ragged bondary. During storms: very sharp transition. SAPS immediately outside the transition.

   SAPS forms the PP gradient, but does not drive the plumes.

4. JOHN: TEC from GPS. Looking through the bulk of the plasmasphere. Projection of plumes at ionospheric heights. You can use Tsyganenko mapping to give an equatorial map, showing the boundary of the erosion plume. Storm enhanced densities SEDs is the ionospheric picture of the plume.

   SAPS is not the plume. It is the electric field. DMSP observations of the equatorward edge of precipitation. 5-10 deg wide enhancement of E field across low conductivity subauroral ionosphere, SAPS peak at the equatorward edge. Field-aligned and Pedersen currents. Low conductivity. The SAPS electric field erodes the outer plasmaspheric region. In the ionosphere: formation of a trough. Statistics 90% of the cases show SAPS. SAPS = Recurrent prominant feature of the plasmasphere boundary layer. Most of it is dusk to midnight.

   The SAPS channel = plasmasphere interaction with the ring current. Provides closure of the current system. Lasts as long as the disturbed ring current is recovering. SAPS all map to SED. SAPS all map to sharp PP. SAPS continue up to the dawn side, but are weaker there.

   Discussion: this is in the wrapping stage? Fossil SAID low altitude, reforming of a previously existing structure.

   Mechanisms for SAPS? Induced fields, polarization fields, electrostatic fields.

5. MARK: Stormtime dynamics of plasmasphere

Only 10% of CRESS orbits show classic plasmapause profile with a knee. The rest shows multiple density structures, plumes, ... PP position afo Kp: clear average trend, but there is a huge spread. Depends on MLT, phase of the storm, ...

Plumes form in the aftermath of enhanced convection. Looking at profiles: complicated by plasmasphere corotation. PP typically moving in after a storm, in the midnight to dawn sector. Different in noon and dusk sector. Clearer picture in Image EUV.

Differences between CIR and ICME types of storms?

6. DENNIS: Abridged history of plasmasphere refilling.

   Time line. In situ detection of Gringauz: shows erosion, so there must also be refilling. Diffusive euilirium models. Parks 1970 diurnal breathing with ionosphere - plasmasphere exchange. Hydrodynamic top-down refilling. T anisotropy. Experimental work triggering new things. Two stream refilling with interhemispheric shocks. Sem-kinetic models Wilson 1992. Gallagher 2000 to approximate the field-aligned density profile. The Image era: RPI refilling, ...

7. BILL: Subcorotation of the plasmasphere.

   Sub-coratation discovered. Sandel SSR 2003. Notches persist for up to 60 hours. Rotating features are actually subcorotating. Sometimes motion is linear, sometimes stepwise. As you track longitude afo time. 85 to 90 % of corotation speed.

   Burch et al. GRL 2004. Motion of the plasmasphere reflects ionospheric motion. Comparing with ion velocities from DMSP - matches EUV results.

   Gallagher et al JGR 2005: Motion *often* reflects motion of the underlying ionosphere. These were all fairly deep notches. Nothing special about L-shells. Differences from corotation sometimes larger.

   Mechanism: heating, but should only apply close to the auroral zones? Why do notches are rigid with L? Seems to imply strong magnetospheric shielding. Differences in terms of lifetime afo subcorotation? Hypothesis: smaller events, shorter-lived, larger corotation differences: local time effects? Sometimes even super-corotation.

8. VIVIANE: Formation of the plasmapause (different mechanisms: last closed streamline/ quasiinterchange instability, dynamical simulations, development of plumes and other structures, influence of the geomagnetic activity level storms and substorms, different models of electric fields and magnetic fields).

   Formation of PP. Simulation by lauching plasma elements and finding out where they move to using a KP dependent electric field model. Last closed streamline - can produce plumes. Quasi-interchange ZPFS. Stronger geomagnetic activity: instability point closer to earth, erosion = spilled off material. Differences: Interchange gives smaller plasmasphere. Compares well with Image EUV. After substorm quasi-interchange gives a clear plume and shoulder and other details. Study the effect of the convection electric field model that is used.

1.4 Methodology

1. JOHAN: Computation of gradients in the plasmasphere from multipoint measurements.

2. FABIEN: New techniques to analyse data from multipoint missions.

3. IMAGE a pioneer of global imaging techniques

4. DENNIS: Derive from IMAGE EUV images quantitative plasmaspheric flow fields (plasmaspheric flows are the result of a variety of forces, which of course include the influence of electric and magnetic fields).

   Computing drifts from EUV images. This was an original goal of Image. Trying to correlate line-of-sight integrated images, ie correlate similar density structures. Raster across a whole image. Works only if you have structure. Deal with noise by Poisson noise filtering. Produces flow field, erosion flow with inward motion of the boundary plus azimuthal motion. You can clearly see systematic differences that are significant. Some problems with the detection of significance of results.

2 Fields (electric and magnetic)

2.1 Magnetic field global orientation (gradient), models

1. JOHAN: Physical implications of overall plasmaspheric gradient computations

   Cluster meant to compute gradients. What you can use a magnetic field gradient for?

2. FABIEN: Magnetic field a (spatial gradient) from Cluster data and models

   Emphasizes the classical gradient method and its limitations. Time delay analysis as a method for planar surfaces.

   Difference of magnetic field from model gradient, e.g. looking at orientation: not dipolar! Cluster allows us to study the overall gradient in the plasmasphere. Main conclusion is that the parallel gradient and the perpendicular gradients are of the same order, the parallel one dominating at higher magnetic latitudes.

2.2 Electric field - statistic, drift velocity, plasmaspheric flows, SAID, models

1. DON: Nightside cross-L substorm-associated plasma drifts. Dayside cross L SQ system drifts. Strong duskside flow drifts.

   Well-defined bulk motion derived from whistlers. Gradual evolution of dispersion properties of a whistler to determine displacement of the structure over a couple of hours during a substorm. Determination of westward electric field associated with that. In/out motion of the PP in an old picture of the 60ies. Interpretation that these were the SQ dynamo profiles. Showed the bulge in the afternoon-dusk sector.

   Looking at geosynchronous data: one to one correlation with substorm growth phase and geosynchronous particle depletion - induction effect? Has been seen in relation with the ring current variability (Jerry).

2. HIROSHI: Electric fields in the inner magnetosphere measured by CLUSTER Electric field measurement by EDI instrument; merging EDI and EFW data; various types of electric fields measured: solar wind origin, SAPS or SAID, ionospheric dynamo, ULF wave components (as large as DC components).

   Electric field measurments from EDI. EDI measures the two perp components. (EFW measures the spin-plane components.) EDI uses an electron beam. Works well in the inner magnetosphere. EDI works better with big magnetic field. Electric field is fraquently measured inside the electron nner edge and in the polar cap. Detects strong outward fields, 1.5 mV/m in corotating frame, as a SAPS structure. Note also ULF fluctuations.

   Statistics of data give electric potential patterns sorted by IMF Bz using 5 years of Cluster data. Some shielding is visible.

   Various origins of electric fields: solar wind-msph interaction, ionospheric dynamo, SAPS and ULF waves.

3. JOHAN: Modelling of SAID and their relation with the plasmasphere.

   Evolution. Observation of equatorward motion is confirmed.

4. HIROSHI: Plasmaspheric structure around the SAID region (Magnetospheric and ionospheric conjunction events measured by CLUSTER and DMSP; ionospheric density trough observed at SAID location at DMSP altitude, while plasmasphere observed at CLUSTER altitude).

   Puhl-Quinn et al JGR 2007. Mapping of cluster to DMSP altitude works well. There is a B variation caused by the field-aligned currents. Number density variation not consistent between the two. Estimate current density on Cluster from 1D assumption. Compare with DMSP. Both match. Only the density measurements do not appear to be consistent. DMSP observes a peak just in front of the SAID, lower density after.

Cluster observes the SAID Vpeak exactly on the plasmapause. At ionospheric heights there is a trough, would be locally produced density decrease due to high velocity and ion-neutral collisions. Ionospheric density would be a bite-out caused by the SAID in the normal ionospheric profile. Question about the time-scales at which the system evolves. Response of the ionosphere. Magnetosphere modifications as it tries to become compatible with the new SAPS field.

5. JERRY: Inner magnetospheric electric fields and the plasmasphere.

   Infer E field from plasmapause motion. Tracking boundary motions. Goldstein 2007c. Gives detailed ideas about the E field and how it maps out. Demonstrates that there is indeed enough information in EUV images.

   Goldstein and Sandel 2005 and Goldstein 2005d. Indentation starts at a particular point first, then widens up, producing a V-shaped pattern as the structure becomes wider in MLT. Always an MLT-UT effect. Can we check whether models and observations match and can explain this?

   SAPS may hit just in front of the foot of a plume: will affect plume, but also an eastward moving ripple. There is a finite propagation effect. From E field, you can derive the rate of expansion is 1 km/s in the ionosphere. Multiple injections with same rate (parallel lines). Propagation is about 45 min to broaden it up. So this is something that should be part of the standard scenario. Goldstein 2006.

6. HIROSHI: Effort for modelling electric fields; future possibility to put electric field model developed from Cluster data set into simulations.

   Trying to arrive at an electric field model for the inner msph. Merge various types of electric field data measured by Cluster. Use of EDI, EFW, and CIS data. CIS gives velocity moments and thus drift electric field. Should arrive at merged Eperp data. Statistics organized by ACE interplanetary data for its predictive capability. UNH-IMEF. Use of a ring current atmospheric interaction model to infer ring current distribution and Dst index to validate the electric field.

   Electric field: problem since both EDI and EFW measure only two components of the Efield. Both instruments complement each other. Sometimes spurious field in EFW data due to photoelectrons or spacecraft wakes. Use of EDI to remove average offsets from EFW. In this way one can obtain a suitable merged E field measurement set.

   In principle Eparallel could be obtained as well.

7. JOHN: SAPS and plasma transport in the SED/erosion plumes.

   Ground based GPS maps TEC plumes. Foster et al GRL 2002. Millstone Hill radar gives speeds from Doppler shift. Combining both gives the actual fluxes. Flux is oriented at 800 m/s out along the plume (corresponding to SED).

Radar scan across latitude shows ionospheric density with a SED. Using data from DMSP from another but similar event: matches SED, shows limit of electron precipitation. The SAPS channel goes from PP to electron precipittion boundary. The actual SAID is narrower in the lower conductance region just outside the SED, embedded within the SAPS channel. From radar scanning over time, you can obtain an equivalent picture of the ionospheric plume.

Foster et al JASTP 2006. From DMSP you see corotation, then deviation, then SAPS region. Location of SED and sunward ion flux.

SED plumes as a source plasma. SED plumes carry dense low latitude plasma into the cusp, to the dayside over the polar cap and then goes into the auroral region. Recirculation of plasma. The field lines of ionisation can put the material to the tail and come back in. This is inferred from the ionospheric perspective. You can also look at it from the magnetospheric perspective. Can lead to superdense plasmasheet.

Question related to the density profile along the flux tube. Evidence that not only the ionospheric footpoint, but the whole flux tube remains filled. Mass loading of reconnection both at the dayside and in the tail. Could be a trigger for substorms. Eroding the plasmasphere slows down reconnection in the tail. Stuff might also coming out into the magnetosheath.

Discussion about possibilities to verify this magnetospheric transport from existing satellite data, even close to the magnetopause.

8. VIVIANE: Electric field models used in simulations.

   Overall electric field models used in simulations.

   - Volland-Stern 1973 has a uniform dawn-dusk E field determined empirically.
   - E5D MacIlwain
   - Differences are large especially for larger Kp. Volland-Stern usually leads to a more compressed plasmasphere. E5D has dawn-dusk asymmetry.
   - Weimer model driven by solar wind parameters. Derived from low altitude, high latitude convection velocity measurements.
   - other models ... should also take into account induced electric field, which are not included in a potential field.

   Discussion: compare with UNH model? need to update the E5D model, which has a good parameterization but still with limited data, in fact never claimed to be ok for storms. Urge to include induced fields. Possible to do it from new Tsyganenko models.

3 Waves (electrostatic and electromagnetic)

3.1 Electrostatic waves - equatorial at (n+)Fce, echoes (diffuse echoes, fieldaligned echoes, resonance echoes, Fcp echoes)

1. FARIDA : (n+.)Fce, statistical results, n(1.1)Fce

   Whisper observations in plasmasphere. Emissions: chorus near equator, NTC, fce, fLH, ...

   Fine emissions above the plasma frequency, first detected on Cluster. Linear polarization in the spin plane. Occur at 4, 4, 5, 6 fce, in both hemispheres. High occurrence in the pre-midnight sector. Statistical analysis. Predicted by relativistic theory.

   Equatorial emissions at (n+0.5)fce near the equator. Frequency structure. This fine structure forms sub peaks in the harmonic bands. Higher intensity gives rise to more substructure. Nonlinear decay? Statistical study shows that these emissions occur most in the postmidnight/dawn sector. Strongly confined to the equator, but this is probably simply due to the fact that Cluster is closest toward Earth when crossing the equator. Equatorial plasma frequency is a proxy of plasmapause position. Statistical analysis of intensity as function of local time for the different bands, again highlighting the dawn sector. Idea that these waves could be related to precipitation for diffuse aurora.

2. DON: IMAGE: Z mode and whistler mode probing (new tools for diagnostics in the transition region from the ionosphere to the plasmasphere).

   Image observing at low altitudes. Wave observations that were not really planned for.

   Plasma dispersion diagram to show the Z mode. Z-mode more prominent as $f_{pe} < f_{ce}$. Between $L = 2$ and 4 there is a Z-mode propagation cavity-like region. RPI can do Z-mode sounding to get echoes from different directions, both above and below. Produce complex but discrete echoes. Multiples of the bounce paths. Cavity effects can be analyzed. Altitude of the cavity mimimum frequency can be found from RPI data. Can be checked with predicted density-altitude profiles, e.g. diffusive equilibrium. This relates to ion composition in topside ionosphere, how to distribute H+ and He+ and O+ profiles.

   Whistler observations. Frequencies depend on the effective ion mass. From the lower hybrid resonance one can get an estimate of the distribution of effective ion mass along the field line. Magnetospherically reflected whistler: minimum and maximum flh can be determined, also diagnostic for the ionosphere-plasmasphere transition.

3. JIM: RPI observational aspects of the plasmasphere from the IMAGE perspective . . . (passive and radio sounding).

IMAGE orbit precessed over time.

Discussion of what sort of modes you can stimulate from Image. Whistler, Z-mode, RX, LO mode. You may have ducted waves that return, or directly or diffusely reflected waves, all producing echoes. Conversion of echo delay time into virtual range.

Observation of ducted echoes from N- side, S-side, and sum of both as manifestation of the sum of the paths. You also see their lower frequency limit, which reveals something about the ability of the duct to prevent leakage of the waves.

Ray tracing calculations show propagation of waves at a given frequency in all directions. For the right frequency you observe the ducting. Cold plasma ray tracing assumption. Ducted whistler modes. Just a few degrees off-pointing from B field, even if you only have only a few percent density depletion. Duct size of the order of 100 km.

Plasma density depletions observed from RPI. Most plasmagrams do not show ducts. Occurrence is highest postmidnight. Might indicate filling and draining, both diurnal cycle and storm time. Fung et al GRL 2003.

Refilling theories:

- top-down: plasma accumulates at equator and fills up the tube: timescale of minutes to hours
- bottom-up refilling, timescale of hours to days

Both would lead to different duct echo patterns. Very sensitively depending on the density distribution along the whole field line. Issues: how long does it last, and can you see it with the instrument. Question concerning scattering of the waves. Effect of interhemispheric differences.

Observations with ducted echoes never have shown the C-signature of the top-down scenario. Bottom-down refilling favored. From this you can get empirical field-aligned density models and radial as well: you get 2D slices. Observations of interhemispheric differences with season.

Note: ducts with a few percent contrast were known to exist before from scintillations in radio astronomy quasar observations. The ducts were known to exist, but not really emphasized in the Image science proposal. There were some earlier observations, but Image shows this in more detail with multiple echoes, ...

Discussion about possible direct in situ measurements of the density depletions.

4. MARK: Using ULF resonance data to study plasmaspheric mass density

   Plasmasphere is rich in waves. Analogy with a harp. One possibility is using longitudinal arrays of magnetometers, listening to field line resonance waves excited by the solar wind. The frequency is a measure of the string length and of the associated inertia. With a good magnetic field model you can recover the density distribution. Cross-phase method for determining FLR frequencies. A single longitudinal array shows an L-UT map as the Earth rotates. With multiple arrays you can address azimuthal variations.

There are more heavy ions at higher L shell. Certainly at disturbed times. Berube and Moldwin JGR 2005.

Chi and Russell 2006 determine the plasmapause position with this technique. You can model the propagation of fast modes in the magnetosphere by looking at arrival times on the ground.: travel-time method. You are then able to get a nice radial density profile.

Definitely better when using Tsyganenko magnetic field model rather than dipole, even at lower L.

3.2 Electromagnetic waves - non thermal continuum, kilometric continuum, whistler, hiss, chorus

1. PIERRETTE: Continuum, waves close to plasmasphere, role of irregularities of density, statistical analysis, new event (2007)

   Previously: Generation: not much known. Beaming properties near source: role of B and gradient of density. Propagation and reflection, hope to do remote sensing.

   NTC source localization. Test of Jones' generation mechanism. Cluster observes NTC above fpe, during an extended interval, double beam relative to the equator. Cluster allows direciton-finding, showing converging ray paths, suggests a punctual source. Large direction anle range of the k-vectors can only be understood if there is transverse local time structure, and it has to be very localized. Ray tracing has been done, but it is hard to pinpoint the source precisely.

   Spectrograms afo L-shell: show the continuum.

2. ARNAUD: Hiss near the plasmapause.

   Seen in WHISPER and WBD instruments. 2-10 kHz emissions. Statistical study to identify the type of emission. No MLT dependence. There is a strong Kp dependance of the central frequency of the hiss. First-time observation of mid-latitude hiss at magnetospheric altitude. Association with a notch is quite clear: Cluster is going through the notch seen in Image.

3. FRANTISEK: Magnetosonic Equatorial Noise (the most intense among all the natural emissions below lower hybrid frequency; occurrence rate of about 60%; observed both inside and outside of the plasmapause; possible role in acceleration of radiation belt electrons, transferring energy from the ring current ion population to hot electrons).

   Construction of an average distribution of emissions. between -60 an +60 degrees.

Magnetosonic equatorial noise occures in 60% of the perigee passes. Most intensity peaks within 2 deg or the equator, FWHM about 3 deg. Generated by energetic protons with ring-like ditribution fuctions at a pitch angle of 90 deg. These waves are not important for loss into the atmosphere? Amplitude increases with time diffs between the spacecraft, not xy differences.

4. FRANTISEK: Whistlermode Chorus (among the most intense naturally occurring emission in the inner magnetosphere; nonlinear generation process (theory and simulations); can play a significant role in the process of local acceleration of electrons in the outer radiation belt, transferring energy from the denser low energy populations).

   Whistler-mode chorus. Among the most intense emissions. Nonlinear generation process. Role in local acceleration process of electrons Horene et al Nature 2005. Chorus source region also close to magnetic equator, propagating away from the equatorial plane into both hemispheres. Cross-correlation of wave power indicates that the perpendicular scale is 10s of kilometers. Substructure of wave packets. Reverse ray tracing (Freja, Demeter).

5. FRANTISEK: Observations of cutoff below the local hydrogen cyclotron frequency (observed by low orbiting spacecraft; reflects the local ion composition; could be used to localize the light ion through connected to the plasmapause).

   Observation of cut-off below local hydrogen cyclotron frequency. Observed by low orbiting spcecraft. Reflects local ion composition, could be used to localize the light ion trough. Observations of cutoff by Demeter. You see incident and reflected waves.

6. JIM: RPI observational aspects of the plasmasphere from the IMAGE perspective.... (passive and radio sounding).

   Mode coupling between Zmode into continuum LO mode. Examples that show that this indeed can happen near a fce decrease: the Zmode is converted and escapes as kilometric continuum. Kilometric continuum observations with significant substructure. With Image trying to find the source of the continuum. Appears to be in notches. The kilometric continuum is beamed along the magnetic equaltor from a small source region, not generated from inside the plasmasphere over a broad region. From ray tracing, narrow beam pattern formed by a notch structure can explain earlier observations. Observed only within a few degrees of the magnetic equator. Source location. CRRES observatiosn of kilometric continuum trapped in plasmaspheric cavities are consistent with plasmaspheric notch structures. Type III radio burst in notches confirm that the apparent cavity is open. Beam pattern: observations from Image and Geotail simultaneously. Allows you to map out the source region. Confirms narrow beaming near the equator. Increasing frequency at the begin of kilometric continuum seems to indicate the source to be moving inward.

IMAGE sees trapped continuum and escaping continuum from low to very high frequencies (christmas tree, specific frequency structure can be explained: emission cone dependence with frequency plus emission across the magnetopause). Rather than a notch, the radiation appears to be generatef from a larger source region. Two- and one-beam structure. Spatial distribution of NTC. Most seen in the morning side, some at the evening sector (associated with plumes?) least in the afternoon. Emission at PP, also seen between plume and main plasmasphere.

Whistler-mode emissions. Plasmaspheric hiss carves out the slot region between the inner and outer radiation belts. Statistical spatial plots of EM equatorial oise, and plasmaspheric hiss. Sorted by IMF direction. EM equatorial noise only at dayside, changes with Bz. Hiss always preseent, most intense in the late afternoon throughout the entire frequency range. Mapping those data to the Earth's surface. More intense on day than night, seasonal changes. Natural pattern of lightning. Initial lightning whistlers might evolve with time into hiss. Coordinates studies while flying over observed thunderstorms.

Global spatial distribution:

- EM equatorial hiss/magnetosonic : late afternoon
- psph hiss similar
- ground transmitters in postmidnight
- chorus, far out, morning side

4 Plasma (density structures, electron and ion composition)

4.1 Density structures - duskside bulge, plume, notch, shoulder, ...

1. PIERRETTE : Density structures seen by WHISPER.

   4sc distribution of densities. Gradients, blobs, appear generally field-aligned. The PP boundary nicely fits the field lines, also plume boundaries do so. Irregularities near the Roche limit. Density irregularities too small for Cluster typical spacecraft separation distances - impossible to correlate observed structures on different spacecraft.

   Smaller scale structures inward of the PP sometimes really seen together on several sc as they follow each other and pass almost the same field line. You can then see some evolution. Are small-scale structures at the PP moving? shaped along MLT with azimuthal structure?

2. DENNIS+BILL: Plasmaspheric morphology: a new look and language for plasmaspheric structures.

   Standard definition of nomenclature for density structures: fingers, crenulations, channel, notch, shoulder, plume, plasmapause. Assume rigidity of these structures.

3. MARK: Using GPSTEC tomography to study plasmaspheric plumes and plasmapause.

   GPS TEC: dual frequencies give phase information. With millions of ray paths from the ground, and with some LEO spacecraft, you can do plasmaspheric tomography. Altitudinal density profiles. You can see the plasmapause position, agrees with the equatorward edge of the trough.

   Tomography using LEO GPS Yizengaw et al 2005 JGR. A lot of topside ionosphere structure is established, plus time evolution.

   Discussion: notches as a result of ionospheric storm negative effect

4. FABIEN: Density irregularities (CLUSTER) and plasmaspheric plumes (CLUSTER, IMAGE).

   Density irregularities. Applying gradient. Gradient perpendicular to B. Characteristic size is about 400 km, 20% density contrast. Seen at all MLT, all Kp (even small, no data for large Kp).

   Plumes. 3 years of Cluster data. Plumes on about 15% of the crossings. Most plumes for Kp = 4 to 6. Typical characteristics: all possible density variations, thickness scale is 1.5 RE. Most plumes in afternoon and premidnight, none in the early morning sector. Widths largest in the afternoon sector. Broadest plumes only have small density variations. Outbound usually at slightly higher L, and at slightly lower density as you pass the plume closer to its tip.

   How close are afternoon plumes to the magnetopause?

5. JERRY: "Residual Plumes", i.e., plumes left over from prior epochs of erosion, and how they might contribute to density structure inside new plumes.

   Fine structure inside plasmasphere. The remains of plumes? Plumes can be wrapped around the plasmasphere multiple times. This might give some explanation. Question: role of filling? This would destroy the strong contrast in the example given.

6. JOHN+JERRY: Plasmaspheric plume and enhanced ionospheric/polar cap tongue of ionization.

   Density contour in EUV maps on the ionosphere TEC maps.

   Longitude effects. Observations of plumes involve a higher TEC. Plumes are observed at other longitudes as well, but apparently there is a UT effect, implying higher TEC values above America.

At dusk terminator: conductivity gradient. Because of the particular field orientation around the SAA, and with the offset of the magnetic poles, the polarization terminator electric field happens to have a significant poleward component. This leads to an asymmetry in the equatorial ionization anomalies. The anomaly crests are surf-riding the polarization terminator, leading to a more pronounced structure: the EIA crest is just moving with the earth rotation. The wave breaks once outside the SAA and then the conductivity gradient points differently, no longer a significant N-S gradient. This mechanism explains why you have more material pumped in N-hemisphere plumes. This explains the specific situation for America. There is also the seasonal effect, leading to different illumination conditions. SAA reduction of 30% leads to smaller upward lifting of plasma. Effect would be strongest for N hemisphere summer.

7. ARNAUD + DENNIS: Plasmaspheric notches.

   Notches come in various shapes and sizes. Origin. Some behind a plume, sometimes notch, sometimes a channel. Difference is the strength of erosion. Notches can be used to look at subcorotation, to see how refilling proceeds. Notches seem to keep their shape until filled (effects of change of perspective?). The notch depression is also seen in the ionosphere.

   EUV and IDM/DMSP ion drift differ sometimes. Differences only for long time tracked. Question whether this refers to longevity of the notches, rather than the observational coverage.

8. DENNIS: Plasmaspheric fingers; visual evidence of globally driven ULF oscillation?

Fingers: easier visible in difference images. Only visible at rather quiet times. Sometimes fingers seem to be bifurcating. Model: standing wave inside flux tube. Could perhaps come from interchange?

4.2 Plasma composition - hydrogen, oxygen, helium

1. DON: Loss of plasma during disturbed periods from within the eroded plasmasphere. Helium abundance at topside altitudes. Plasmasphere as a target for radio sounding (IMAGE); rough outer surface and internal field aligned irregularities causing scattering of sounder pulses.

   Lightning is exciting a certain number of whistler ducts, so sometimes you observe various whistler simultaneously at a single receiving station.

   Park: Observation of partially evacuated whistler duct: localized density depletion, but still within the plasmasphere. Inward motion of flux tube together with downward draining of tube into the ionosphere. Input from Mark Moldwin on this subject: both inward motion of PP and depletion. Don: Measure of the inward penetration of the overlapping hot ions during disturbance?

Ion composition: refine our abilities through radio techniques to get a better handle on H+ and He+ ions. Topside ionosphere composition and higher could be better diagnosed, eg from Z mode cutoffs.

RPI: rough surface echoes upon approach of the PP. Inside Psph you have ducted echoes. Whistlers with multihop paths. PP seems to be rough, often has small-scale structure imposed. Ray tracing sometimes showing multiple propagation paths.

2. IANNIS: Analysis of ion distribution function measured in situ by the CLUSTER spacecraft, and ion composition results.

   Discussion of CIS composition stuff. RPA mode absolutely necessary. CODIF sees 2-30 eV: H+, He+, O+. Normal mode does not see this plasma at all.

   TOF distribution close to magnetic equator showing H+ and He+, effect of sampling technique so as not to be overwhelmed by H+.

   H+ partial density and bulk velocity. Integration over only part of the phase space. Velocities to be understood as showing corotation. He+ also gives partial density, 1/15th of H+, also velocity.

   Distribution function cuts close to the magnetic equator for H+ and He+. Search for a plasmaspheric wind. Comparing incoming versus outside detector channels. Systematically more going out than in. Both for H+ and He+. Outward wind radially estimated 4.5 km/s; have to take into account the RPA mode of operation. Similarly we can check corotation by looking at other detector orientations. Happens for a series events, always checked at the magnetic equator. But not during eclipse.

   Multi-nose structures: plasmasphere - ring current interaction.

   Outside rad belts no background, then O+ becomes visible.

   Event during an eclipse: no photoelectron emission: visible in the spectra: 1 to 2 eV difference (spacecraft potential effect).

   Estimate of plasmaspheric wind escaping: 1.6e27 ions/s continuously escaping. Matches input from SW under quiet conditions more or less.

3. RICHARD: Comparison of mass density from Alfven waves to electron density yielding the average ion mass.

   Given the frequency, find the mass density. Then use those mass measurements and number density (electron density) from plasma frequency to get average ion mass. (With CRRES you find Alfven waves plus harmonics.) Higher average ion mass peak around 2 at L=2 and then up to 4 around L= 5 and then down to 2 at L=6 again; so-called He+-O+ torus. Dependence of the average ion mass: going up with Kp.

   Different O+ populations. Ring current: extra population, source for O+, injected from the plasmasheet back to earth, while they were originally coming from the ionosphere. Injections of a few to 10 oxygen particles per cc. Question about the role of charge exchange and the geocorona.

4. BODO: 2D electron density images obtained from inward sounding along the IMAGE orbit can be used to differentiate different plasma regions that have distinct density distribution characteristics: the solar wind/IMF effects should be included in any statistical study of the electron density distributions in those regions. Distinct regions include inner psph, outer psph, plasmatrough, cusp, polar cap. Evolution can be followed upon repeated passes. Images can be improved by normalizing away the electron densities by the radial $1/r^5$ dependence in the polar cap. Normalizing also the field-aligned velocity derived from flux conservation. This shows refilling in the outer plasmasphere, and acceleration in the depletion region and cusp. No acceleration inside the plasmasphere. Strong acceleration in the trough around 3 RE; acceleration likely due to pressure gradient. Tu et al, JGR, 2005.

   Effort to derive field-aligned density profile through multi-variant least-squares fit. Tu et al 2006. Each pass you have part of the profile along the field line. The fits in inner and outer plasmasphere are similar, other and/or variable constants in plasmathrough and polar cap.

4.3 Global orientation and velocity of structures

1. NICOLAS :

   Bringing ideas from Jupiter and Saturn to the plasmasphere since those magnetospheres are also rotation-dominated. At L=2, 10-15 % corotation lag observed - Implication on plasmasphere dynamics. Jupiter and Saturn: Mass-loading in the outer magnetosphere, conservation of angular momentum. Deviation from pure corotation can also be due to deviation from the electric field model. Use in situ plasma velocity measurements - CIS. Look at RPA data to quantify the lage with the help of Cluster perigee data.

2. JOHAN: physical implications of overall plasmaspheric gradient computations and FABIEN: Electron density (spatial gradient) from CLUSTER data and models.

   Density gradients mostly perpendicular between +/-30 degrees. Sometimes strong azimuthal density structure.

3. BILL: Longitudinal and seasonal variations in plasmaspheric density, and another studied plasmaspheric densities during a prolonged disturbed interval by combining field line resonance, whistler, and EUV measurements.

   Seasonal and longitudinal variations in plasmaspheric electron density related to time when footpoints are in sunlight. He+ follow those seasonal trends.

   Composition: equatorial mass density from FLR, ne from VLF, equatorial He+ from EUV. Grew et al., GRL 2007. From various measurements, you can solve for H+, He+, and O+ abundances.

- H+: 50-90 %
- He+: 7-20 %
- O+: O-10 % but up to 40-80 in the outer plasmapause

4. RICHARD: Field line dependence of electron density and mass density in the plasmasphere and plasmatrough (for electron density, power law dependence assumed; mass density very flat within about 20 degrees from the magnetic equator).

   Power-law used: $n = n_0 cos^{-2\alpha}\lambda$. Denton et al JGR 2004, 2006. Obtained from Polar which crosses the same L value twice, so you can compare two latitudes. $\alpha = 1$ in the plasmasphere, equivalent to diffusive equilibrium. $\alpha = 2 - 3$ in plasmatrough, in between the collisionless solution and diffusive equilibrium. Power-law model does not rise that steeply at high latitude.

   Infer field line dependence of ρ. Based on the ratio of first and second harmonic frequencies. At L=7-8 the mass density might be peaked at the equator.

   Example using Cluster from waves at L=4.8, $\alpha = 6$ for a case with 8 harmonics. Compares reasonably to the IRI model.

5. BODO: Smooth transitions of the electron density from the plasmasphere to the auroral region can occur at various magnetic local times: plasmaspheric wind??

   Cases without pronounced PP, 3-10%. Mostly quiet time periods. Both RPI and EUV on Image agree on this. This finding is also compatible with cold plasma that is seen at geosynchronous orbit.

4.4 Refilling

1. BILL: Global view of refilling of the plasmasphere (EUV, RPI, radial variations in [He+]/[electrons], interspecies differences in refilling rates).

   Ideal study case: a moderate erosion event, followed by a quiet time. You then can follow the refilling history quite well. After erosion: distinct PP, plume. Afterwards smoother PP moving out. Orderly progression from RPI observations. Integrated He+ column abundance (azimuthal averaging smoothes away the sharp PP at the start). One can then compute the refilling rate; going down with increasing L. Matches with previously published data. (Two different refilling rates have been advocated in the past?)

2. DENNIS: Study the plasmaspheric refilling physics using IMAGE RPI data.

   True field-aligned densities. Inversion of RPI plasmagrams for ducted emissions. This is the first and only situation where you are sure that you are measuring along the same field line. Comparing measurements as eroded and as refilled. Solar, season and activity dependent refilling rates. Starting a statistical study of such field-aligned density profiles.

3. BODO: Plasmasphere depletion/refilling processes investigated by analyzing the density variations through the life cycle of a storm as observed by the Radio Plasma Imager (RPI) on the IMAGE satellite; comparison of simulation results with IMAGE RPI observations. Plot with refilling percentages. Refilling after two-three days seems to be complete, but PP continues to move out. Below a certain L-value there was basically no change, so psph is stripped. Question: what is the minimum L of not being disturbed: Lmin = 2 ¡= 2.3, except perhaps for very strong storms. Very strong storms can go below L = 2.

5 Simulations, modelling

5.1 MHD simulations

1. JERRY: (skipped to save time)

5.2 Simulations based on interchange instability

1. NICOLAS : Interchange instabilities in the plasmasphere - Necessity of a plasmaspheric wind. The plasmasphere during prolonged periods of quiet geomagnetic activity (Kp ¡ 3) : Evidence for a plasmaspheric wind ?

   Prolonged quiet geomagnetic activity, after refilling (no other confounding effects): the psph can arrive at a saturated configuration with PP beyond $L = 7$. Even at this stage there is a density deficit at large L, so that refilling keeps going on; there must be an additional plasma loss. Evidence for a plasmaspheric wind.

   Such a wind could result from plasma interchange motion. Quasi-interchange: stratification-driven instabilities. Modeling the description: examine the effect of the field-line curvature. With an exospheric density model, the equatorial plasmasphere appears to be unstable. This model is only 1D, using cold plasma only, static. Stability while the flux tube is filling?

2. JOSEPH : Study the oscillations/instability of interchange and quasiinterchange in the magnetosphere, and Plasmaspheric wind

   In MHD, all ExB drift. No field-aligned potential differences, field-aligned currents, ... All the plasma would move like a whole flux tube. This is not needed if there are inductive electric fields. Grad B and curvature drift. In addition to pure interchange, there is quasi-interchange: wavelength along the field line is not infinite. Transverse and field-aligned modes.

   Cross-L motion: Expansion toward the equator and outward: could be the plasmaspheric wind. Plasma could be moving to form a specially dense trapped cold plasma layer at the equator. Related to special wave emissions?

3. VIVIANE : Model of plasmasphere and plasmatrough (exospheric model, number of trapped particles, temperature, comparison with other models)

   Kinetic exospheric model describing number density, flux, bulk velocity, temperature, ... Based on analysis of types of particle orbits. This model can be used for polar wind, in auroral regions, and to describe the plasmasphere. Some arbitrariness as to what are the trapped particles, depends on Coulomb collisions.

5.3 Density models (equatorial, 3D, ...)

1. VIVIANE : Model of plasmasphere and plasmatrough (three dimension model, comparison with CLUSTER and IMAGE observations)

   3D kinetic model. Number density given by kinetic exospheric model and Cluster and Anderson equtorial density model. PP position is given by the dynamic quasi-interchange model.

   Comparison of equatorial density profiles with different density models and with Cluster and Image/RPI profiles. Also comparison of field-aligned distribution.

2. HIROSHI: Evolution of plasmaspheric electron density simulated by the ring current atmosphere interactions (RAM) model: location of the plasmapause depends on choice of electric field models.

   Storm-driven plasmaspheric density. ICME storm considered. Goal is to follow ionospheric supply and loss and flux volume changes. The cold plasma distribution affects the ring current particle pitch angle distributions. Role of the electric field models. At the same time trying to compute Dst.

3. MARK: Development of plasmasphere density and plasmapause location models; using ULF resonance data to study plasmaspheric mass density

   Using the ULF resonance technique to estimate average mass afo R.

4. JERRY: Whatever mechanism, dynamical transitions have to be considered.

5. JOHN: stresses the difficulty of predicting SAPS or incorporating it into a model

6. BODO: Field-aligned density profiles along the filled and depleted flux tubes can be well fitted by the a simple functional form, but with two different groups of fitting parameter values: potential to construct realistic global empirical plasmasphere/plasma trough models; potential to determe the density profiles along the depleted flux tubes for plasmasphere refilling studies.

From RPI plasmagrams, you can do sounding and establish density profiles if you invert the measured echoes. You have to use a certain type of modeling assumptions to determine ducted mode propagation characteristics along its path. One measured profile every minute or so. In 20 minutes you cross the plasmasphere, 20 profiles. You can fit that as a whole to get a 2D meridional cut. You can repeat that over time. Profile variation with latitude: empirical form of which you fit the parameters. Reinisch et al GRL 2001. Having the model from ducted mode echoes, you can compute the Z-mode echoes that you should get, and can be verified that these echoes are indeed observed. This is a confirmation of the correctness of the approach. Question concerning the uncertainties. Range uncertainty is about 500 km: a few percent at most. Practical difficulty lies mostly in determining the cutoff frequency precisely. You can convert this to TEC.

Similarly you can look at the polar cap. Latitudinal, Kp and solar zenith angle, F10.7 flux dependence. A general fit is possible, leading to an empirical model.

FLIP simulations

6 Conclusions

6.1 Perspectives

1. VIVIANE : Missions ChangE2 and KuaFu: Chinese with ESA participation
2. JOHAN : Mission WARP
3. Others: Future Missions ???