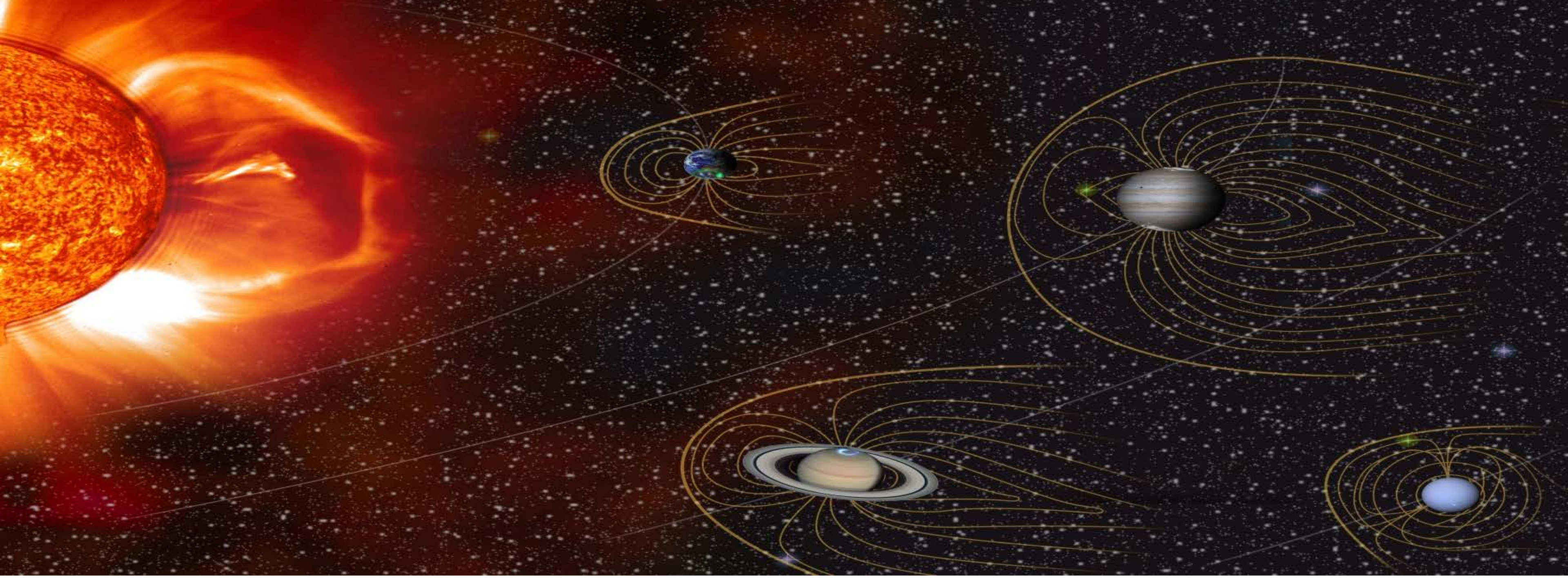

Modeling of plasma dynamics in the inner geospace during enhanced magnetospheric activity

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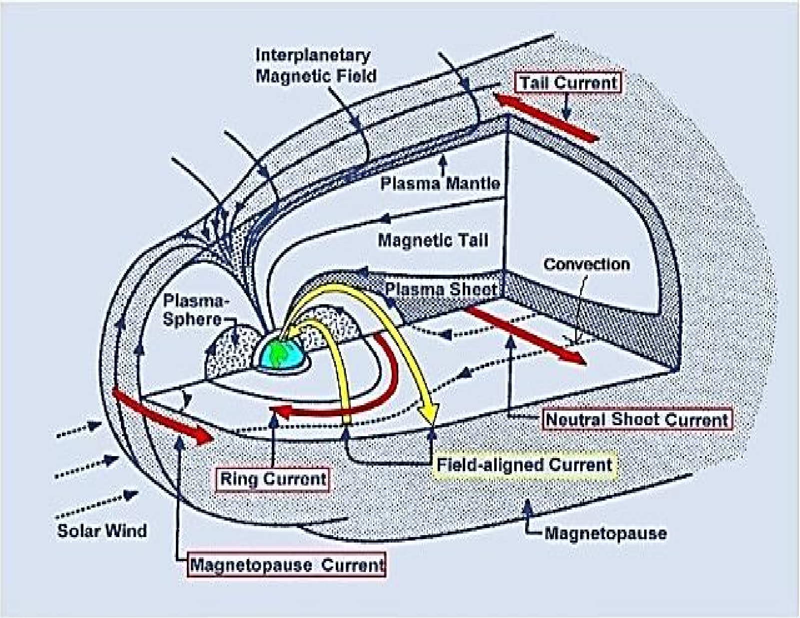
Objectives of our research

- **Motivation and milestones**
  - *Model for the near-Earth plasma response to geoeffective events*
    - *Goal:* Space weather prediction
    - Final link in the Sun-to-Earth analysis of solar eruptions *(Patsourakos et al 2015)*
  - *Focus on ring current dynamics*
    - Origin and transport of RC ions during storms and substorms
    - Interaction with other sources
    - Correlation with event's phases



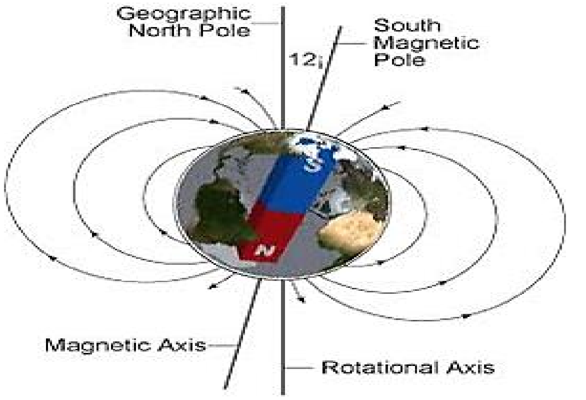
- **Requirements for building a physics-based model**
  - *Description of the electric and the magnetic field in geospace*
  - *Computation of the plasma dynamics in the inner magnetosphere*
  - *Utilization of the data from the numerical computations*
    - Estimation of the associated geomagnetic indices (*Kp, Dst/Sym-H...)*
    - Comparison with ground-based and satellite/spacecraft measurements

Model for the geomagnetic field

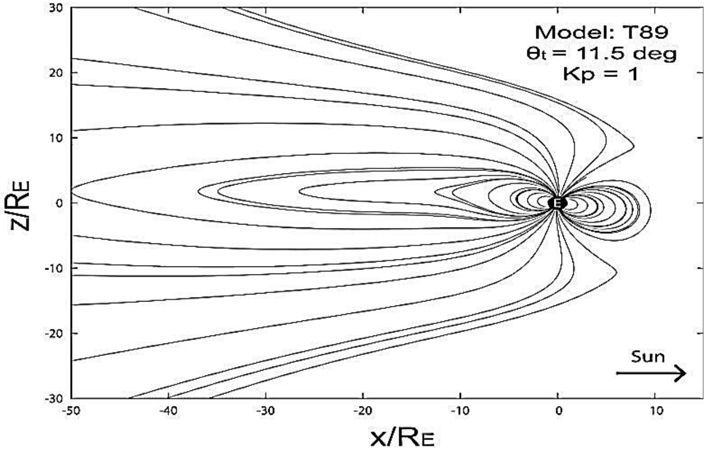
- **<u>B-field in the inner magnetosphere:</u>**
  - *Tilted dipole* (Earth's physical magnet)

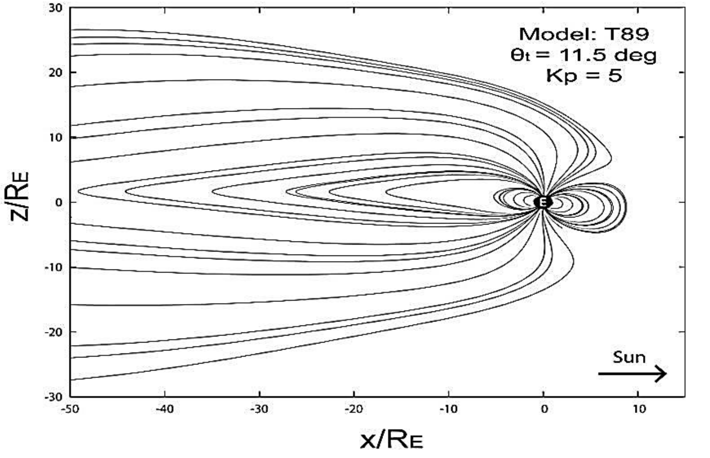
$$\mathrm{B_{dip}} = \frac{\mu_0 M_{dip}}{4\pi r^3}\left[3\left(\hat{\mathrm{m}}_{\mathrm{dip}}\cdot\hat{\mathrm{r}}\right)\hat{\mathrm{r}} - \hat{\mathrm{m}}_{\mathrm{dip}}\right]$$

  - *External field* (RC, magnetopause & tail)
    - *Tsyganenko model of 1989 (T89)*
    - *<u>Input:</u> Tilt angle, Kp index*



- **Visualization of B → Field-line tracing**
  - *<u>Benchmark with T96-TS05:</u> Minor deviations in the simulated region*



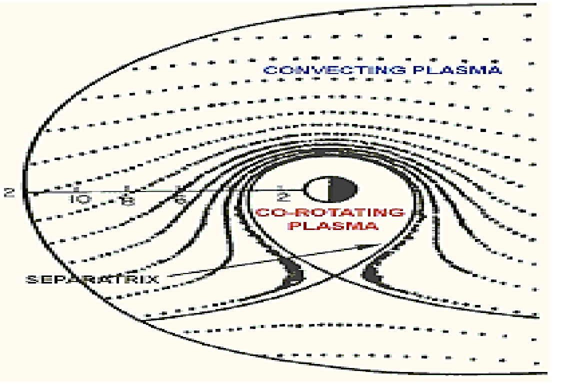


Model for the electric field

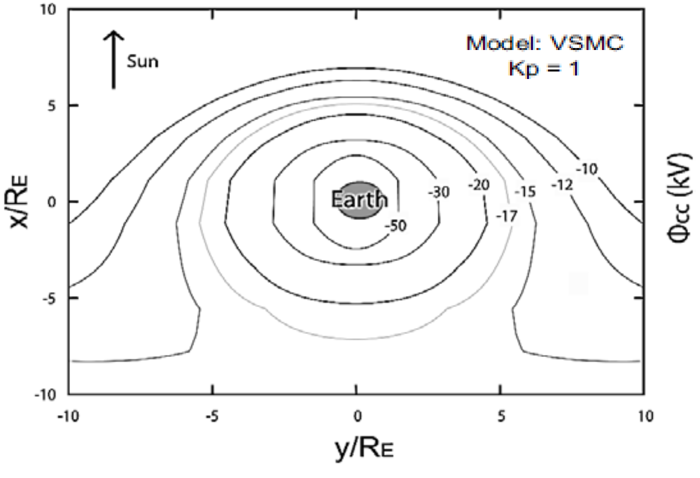
- **E-field in the inner magnetosphere:**
  - *Plasma convection and corotation*
    - *Volland-Stern-Maynard-Chen model (VSMC)*

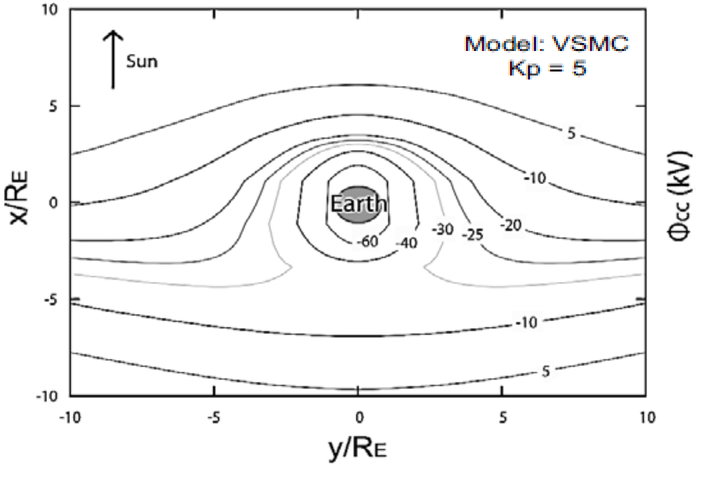
$$\Phi_{cc} = \frac{v_1}{(v_2 Kp^2 + v_3 Kp + 1)^3} \cdot \frac{y r^{\gamma-1}}{R_E^{\gamma}} - \frac{\omega_E B_E R_E^3}{r}$$

  - *Magnetic induction (Faraday's law)*
    - Generated by the Sun-driven variation of **B**



- **Visualization of E cc → Equipotential contours**
  - *Benchmark with BRH97/WM05:* Deviation only in the pause and far tail



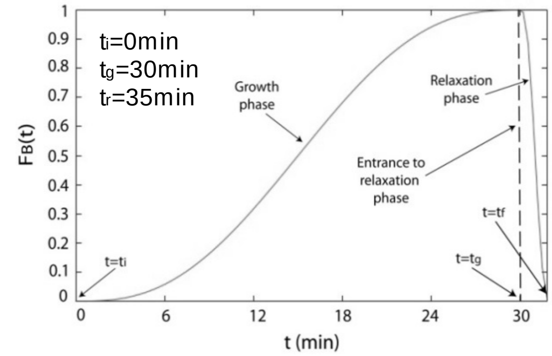


Dynamic variation of the fields

- **Event-based description of B(t), E(t)**
  - *Disturbances in the ion motion time-scale*

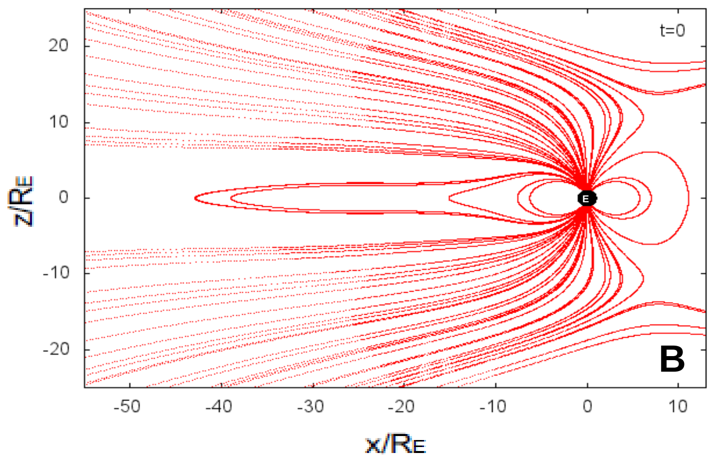
$$\frac{\partial \mathbf{B}_{\mathrm{ext}}}{\partial t} = \sum_j \left(\frac{\partial \mathbf{B}_{\mathrm{ext}}}{\partial G_j}\cdot\frac{dG_j}{dt}\right) \longrightarrow \mathbf{B}(\mathbf{r},t) = \mathbf{B}_{\mathrm{dip}}(\mathbf{r}) + \mathbf{B}_{\mathrm{ext}}[\mathbf{r},G_j(t_i)] + F_B(t)\cdot \{\mathbf{B}_{\mathrm{ext}}[\mathbf{r},G_j(t_f)] - \mathbf{B}_{\mathrm{ext}}[\mathbf{r},G_j(t_i)]\}$$

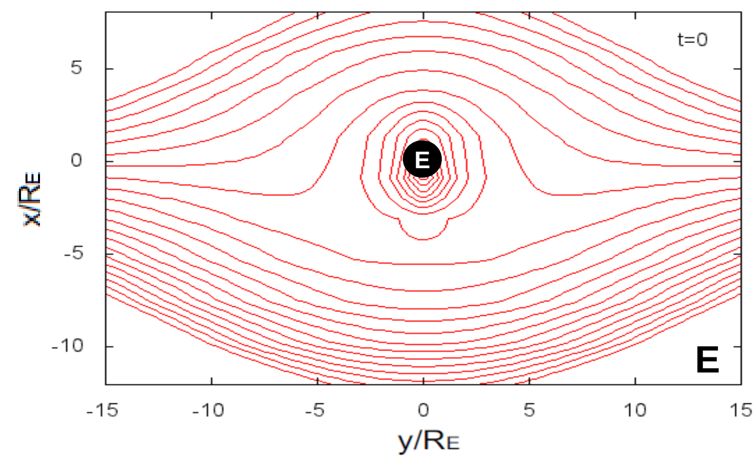
    - F_B defined according to observed event scales: *Set-off at $t=t_i$,peak at $t=t_g$ and restoration at $t=t_r$*
    - **G** depends on the **B**-field model ([θ_t,Kp] for T89)



  - *The electric field is defined accordingly* $\longrightarrow$ $\mathbf{E}(\mathbf{r},t) = -\nabla\Phi_{cc}(\mathbf{r},t) - \dfrac{\partial \mathbf{A}_{\mathrm{ext}}(\mathbf{r},t)}{\partial t}$

- ***A substorm's tale:*** **t_i=0, t_g=35m, t_r=40m - θ_t=0, Kp=1↔5**



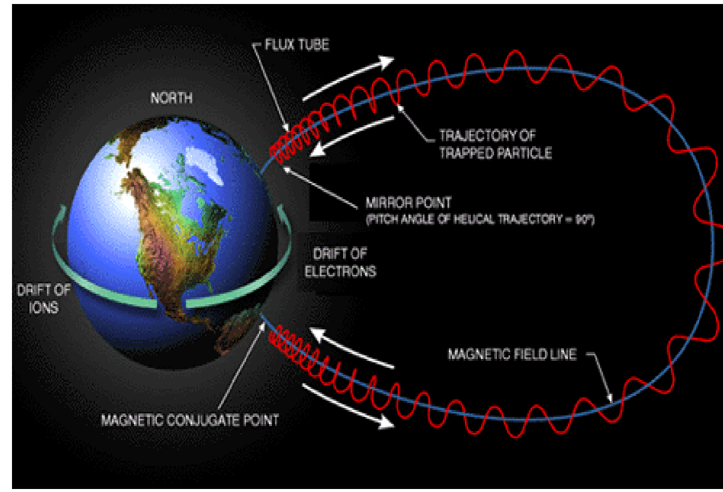


Model for the ion trajectories

- **Overview of test-particle code**
  - *Geomagnetic field:* *T89 model*
  - *C&C electric field:* *VSMC model*
    - + Induced field = Total electric field
  - *Motion equations:* *Lorentz forcing*

$$m\frac{d^2\mathbf{r}}{dt^2} = q\left(\mathbf{E} + \frac{d\mathbf{r}}{dt}\times\mathbf{B}\right) + m\mathbf{g}$$

    - *GC approximation (cutoff criterion):* Deviations when AIs are broken



- **Setup of the test-particle computations**
  - *Initial conditions:* Ions launched at t_0=-8min and move until t_f-t_i≈3h
    - *Ion species:* (I)+(II) O^+ (amu=16), H^+ (amu=1)
    - *Kinetic energy $E_K(t_0)$:* (I) 4KeV, 7KeV, 0.5KeV, (II) [0.5-20] KeV
    - *Coordinates $r(t_0),\varphi(t_0),\theta(t_0)$:* (I) 20$R_E$, (II) [2,30]$R_E$, (I)+(II) 24h, 25°
    - *Velocity pitch angle $\alpha(t_0)$:* (I)+(II) 90°
  - Numerical computations are performed for two purposes
    - *[Part I] Exploration of different orbit types (trapped, escape, precipitating)*
    - *[Part II] Dependence of the ion dynamics on the initial conditions*

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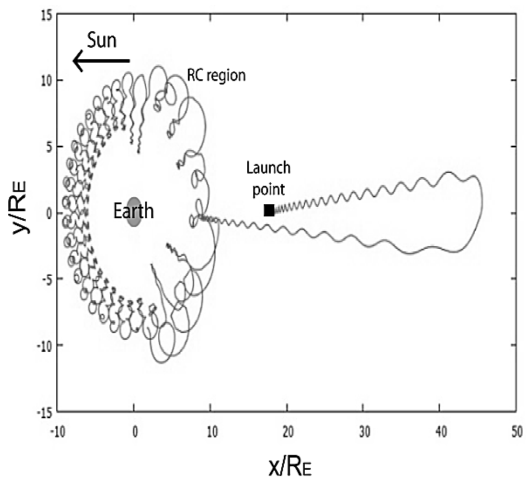
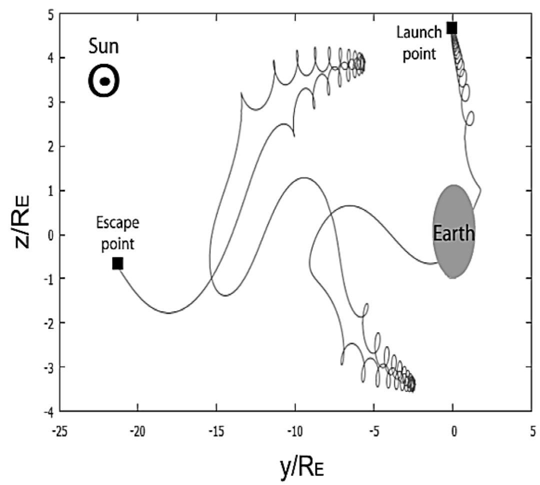
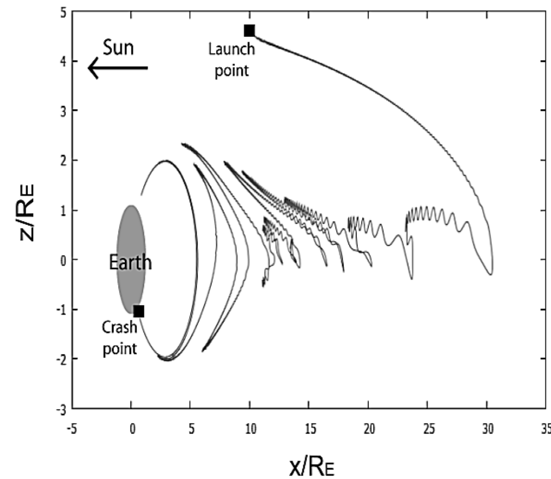
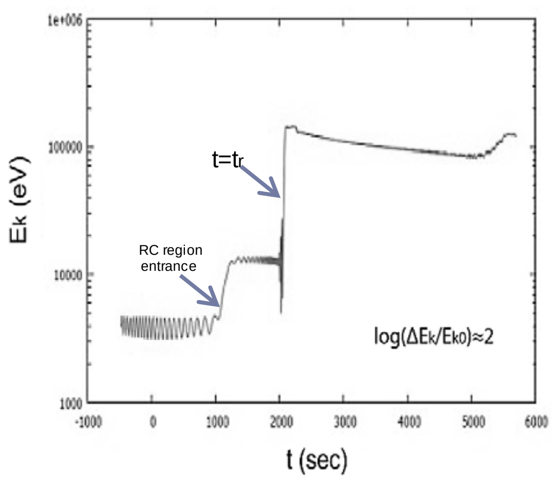
Results from Part I (all species)

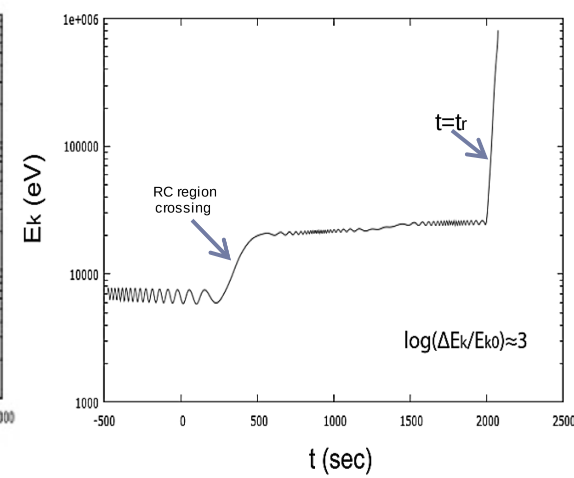


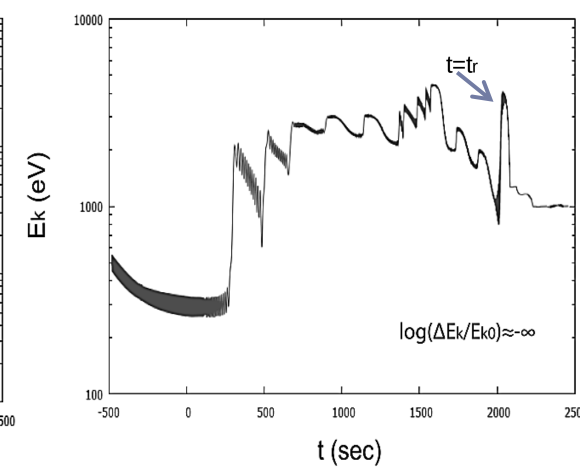




Trapped orbit **(O^+)** | **Escape orbit** **(H^+)** | **Precipitating orbit** **(H^+)**

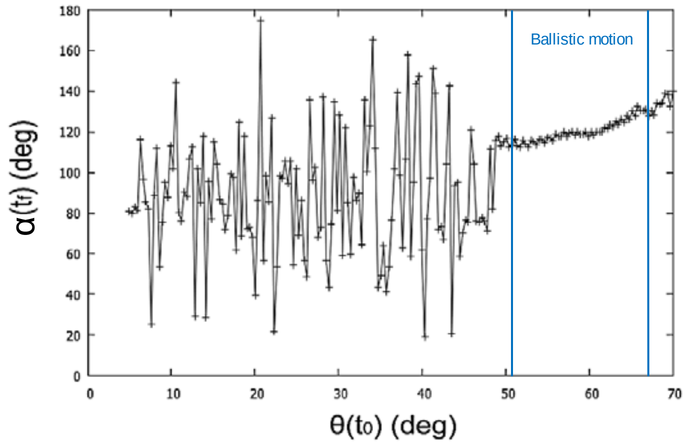




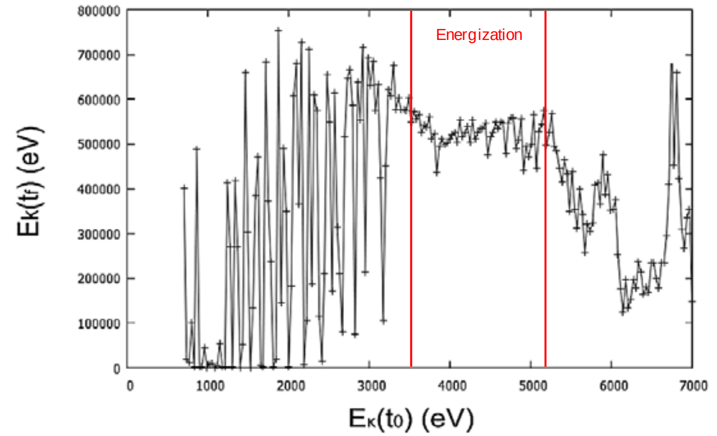


Results from Part II (only O^+)

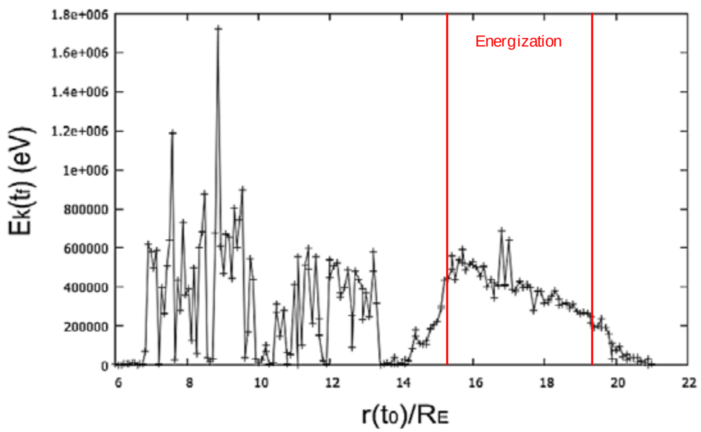
Pitch angle dependence on latitude



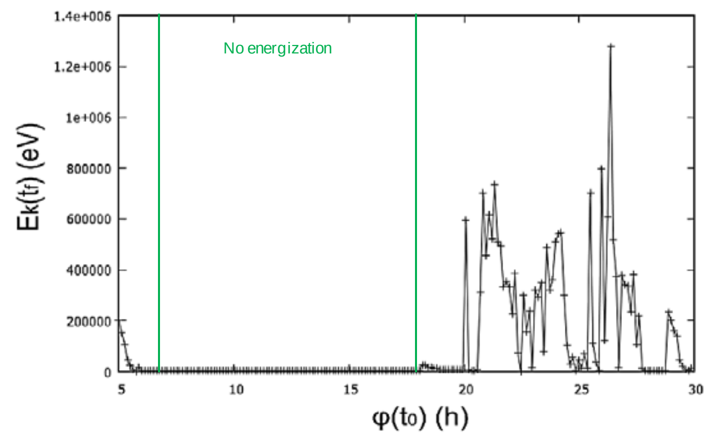
Acceleration dependence on energy



Acceleration dependence on location



Acceleration dependence on MLT



Overview of results on dynamics

- **Test-particle orbits reveal fragments of the RC dynamics**
  - *O^+ ions launched from the plasma sheet are driven towards Earth during the disturbance and get trapped in the ring current*
    - Acceleration is stronger during the substorm relaxation phase *($t_g<t<t_r$)*
    - Similar behavior in latitudes from ±5º to ±25º → See poster *S1.24*
  - *High latitude H^+ ions launched from the PS are not trapped in the RC*
    - Different picture for low latitude particles → See poster *S1.24*
- **Analysis using ensembles of test particles**
  - *Sensitive dependence of ion dynamics on the initial conditions*
    - *Counteract:* IC regions exhibiting specific trend(s) in phase-space kinetics
  - *PS = Reservoir of O^+ which enhance the RC energy in storm-time*
    - In quiet-time, H^+ is the majority ion species in the ring current
- ***Validation* of the above results**
  - *Estimate the statistical weight of each ion population (RC, near-Earth tail, precipitating and escape) per species*
    - 10^4 high-latitude ions launched from PS

Ion type	N_{ens}	N_{rc}	N_{ntl}	N_{ter}	N_{esc}
O^+	10000	4596	2271	673	2460
H^+	10000	378	2414	3365	3843

10^4 test ions, injected from the high-latitude PS, distributed to ring current (N_{rc}), near-Earth tail (N_{ntl}), precipitating (N_{ter}) and escaping (N_{esc})

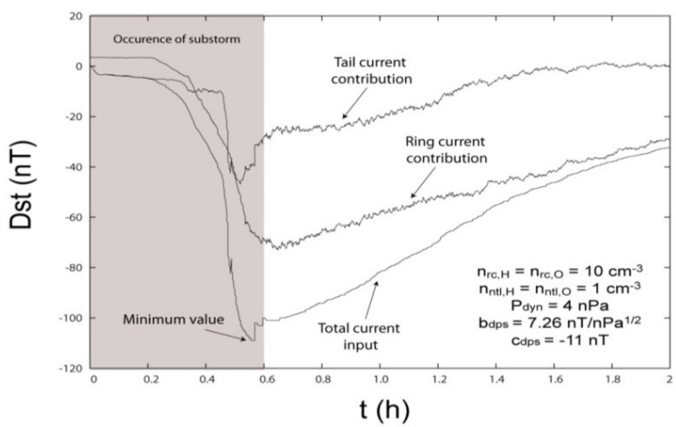
Estimation of geomagnetic indices

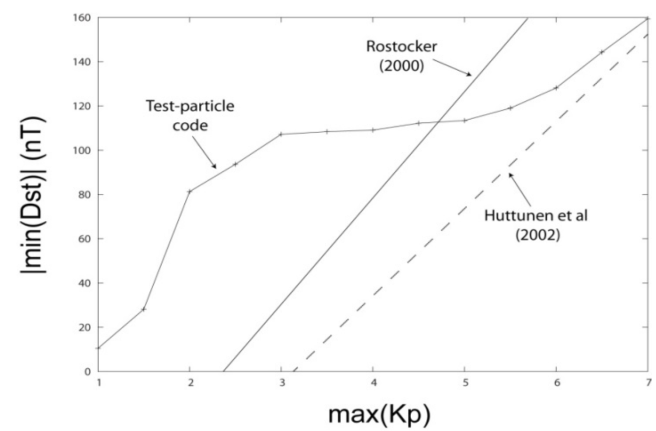
- **Computation of the Dst index from ion kinematic data**
  - Dessler-Parker-Sckopke (DPS) relation in test-particle simulations

$$Dst = -\frac{\mu_0}{2\pi B_E R_E^3}\sum_{pp} E_{pp} + b_{dps}\sqrt{P_{dyn}} + c_{dps} \qquad E_{pp} = V_{pp}\sum_i n_{pp,i}\left\langle E_k \right\rangle_{pp,i} \quad V_{rc} = 2\pi^2 R_{rc} r_{rc}^2 \text{ and } V_{ntl} = R_{ntl}^3 - V_{rc}$$

    - *<u>RC region:</u>* Torus (R_{RC},r_{RC}) containing equal portions (densities) of H^+ & O^+
    - E_{pp} computed for ions travelling from the PS to the RC & near-Earth tail

- **Numerical results for Dst (+ comparisons)**
  - *<u>Contribution of tail current to Dst:</u> ~30% (25% reported in literature)*
  - *Benchmark with observations (Rostocker 2000; Huttunen et al. 2004)*
    - Max(Kp) is modified from 1 to 7 → Minimum value of Dst is recorded





Concluding remarks

- **Analysis of substorm events using test particles**
  - *"Open-loop" study of ring & near-Earth tail current dynamics*
    - Model for the Sun-driven electric & magnetic field in the inner geospace
    - Computation of the ion motions in the disturbed magnetosphere
  - *Estimation of associated geomagnetic indices and their interrelations*
- **Workaround of approximations in our model**
  - *Kp-based description of the geomagnetic field during substorms may be partially in contrast to its global and averaged character*
    - Computed correlation of Kp & Dst connects to previous studies
  - *Use of the (older) T89 model for the disturbed magnetic field*
    - Benchmarks have shown only few differences in the region of interest
    - Use later Tij models → Numerical computation of **A** from **B** is required
- **Work currently under development**
  - *Benchmarking and verification against RBSP data (→ poster S1.24)*
    - Study injections during substorms with reverse-time test-particle simulations
  - *Inclusion of other "drivers" (forces) for the test particle dynamics*
    - Various types of electromagnetic waves (ULF, whistler, chorus, …)