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Nonlinear solar wind - magnetosphere coupling using MHD models

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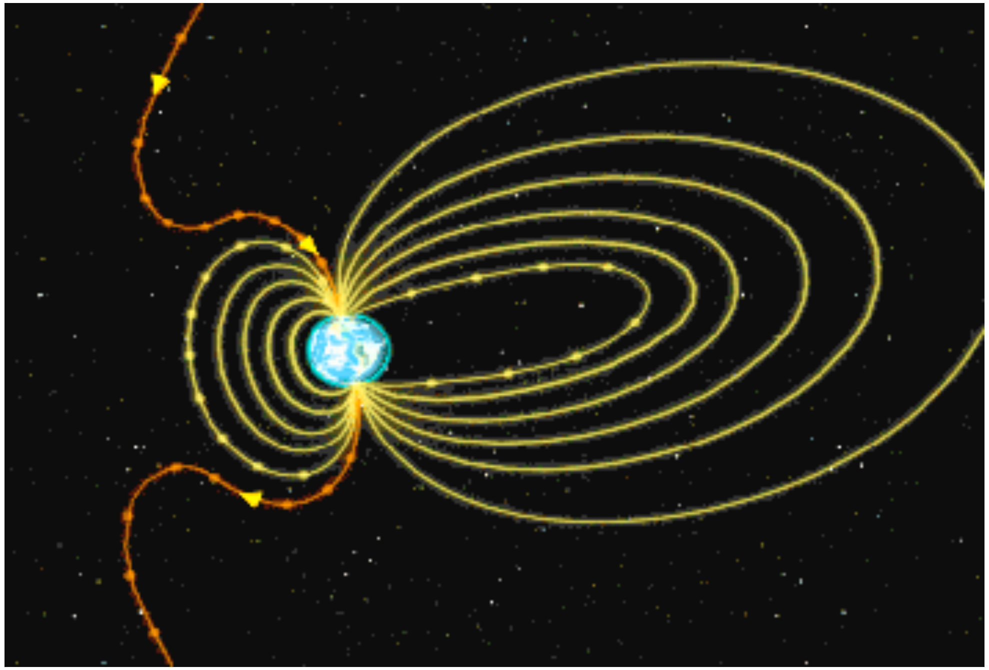
Solar wind parameter controlling energy input into magnetosphere

Role of magnetotail in the energy circulation process

Coupling of energy transfer through magnetopause with magnetotail state and dynamics

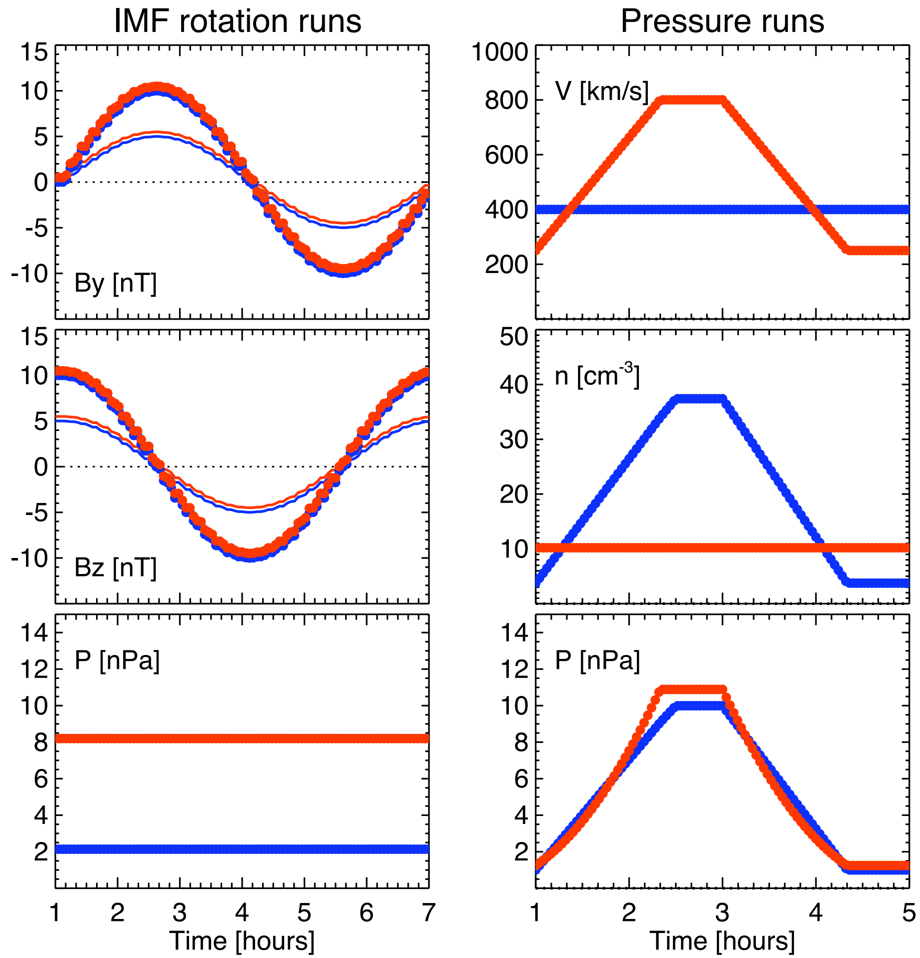
Convecting-reconnecting magnetosphere

- **Dungey, 1962**
  - **convection cycle driven by reconnection**
- **McPherron, 1970**
  - **loading-unloading cycle of substorms**



GUMICS-4 global MHD: test runs

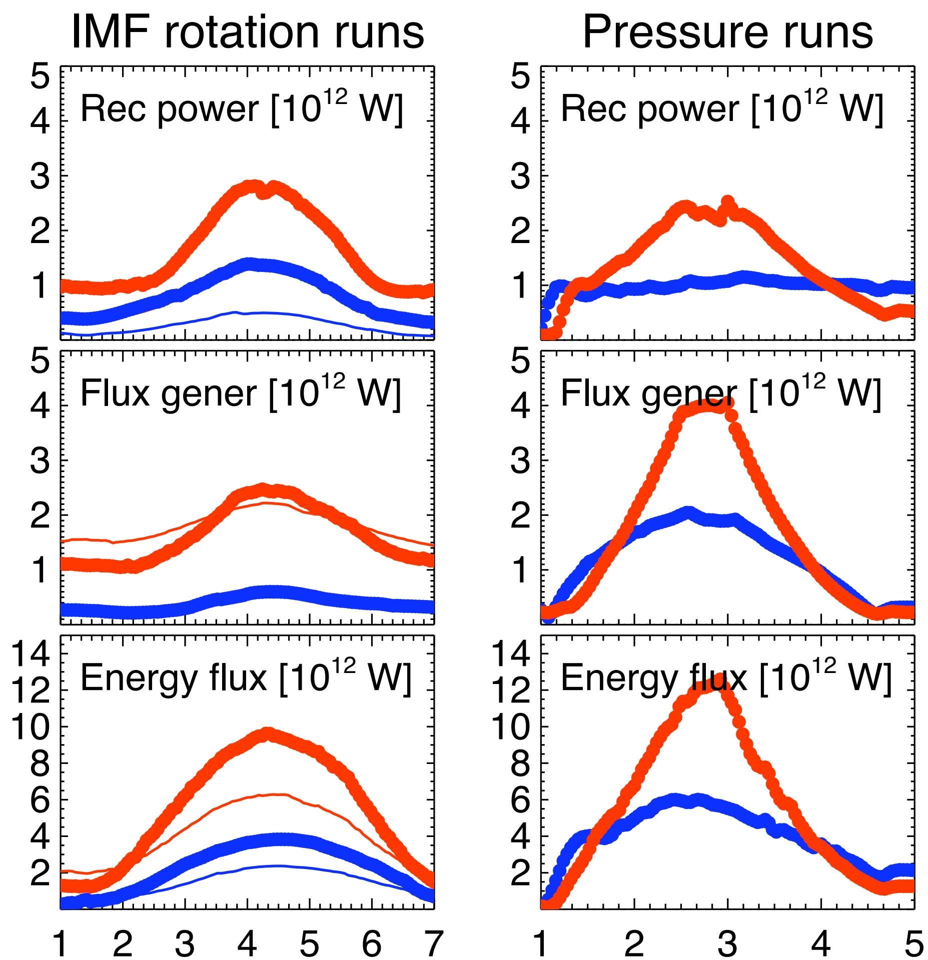
- **Test runs with artificial input**
- **Four IMF rotation runs:**
  - **slowly rotating IMF**
  - **constant speed and density**
- **Two changing pressure runs:**
  - **changing speed**
  - **changing density**



Magnetopause energy conversion

- **Reconnection power**
  - **flux annihilation at magnetopause from Poynting flux divergence**
- **Flux generation power**
  - **at magnetopause from Poynting flux divergence**
- **Energy input through boundary**
  - **trace total energy vector**

(see Palmroth et al., 2003, 2006; Laitinen et al., 2007)

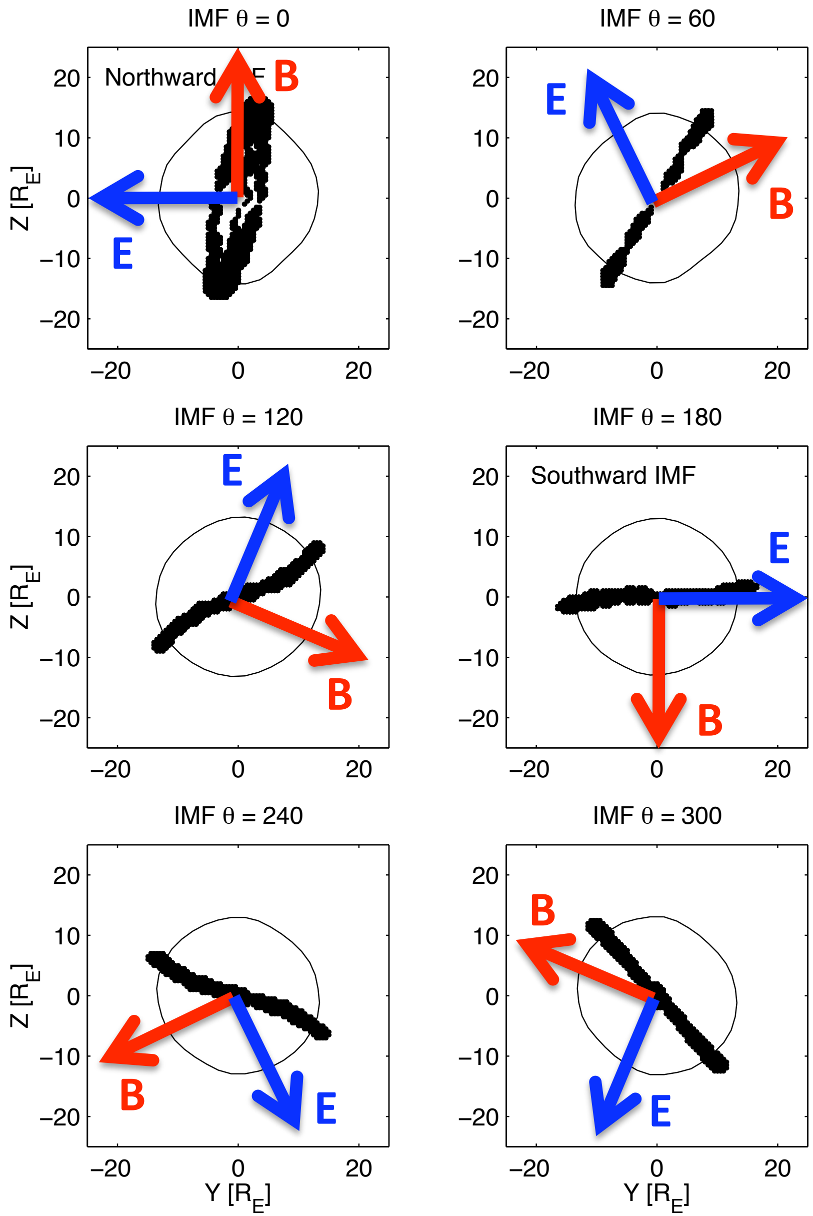


X-line orientation

- **Reconnection line in GUMICS-4 global MHD simulation**
  - **black: X-line**
  - **red: B-direction**
  - **blue: E-direction (E = −V×B)**

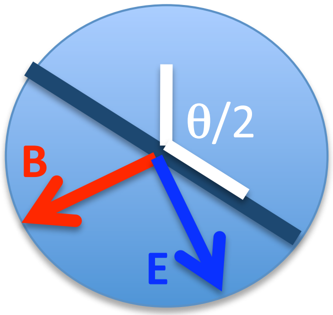
- **Reconnection line orientation**
  - **angle roughly half of the IMF clock angle ($\tan\theta = B_Y/B_Z$)**

(*Pulkkinen et al., 2009*)



X-line reconnection rate E_{PAR}

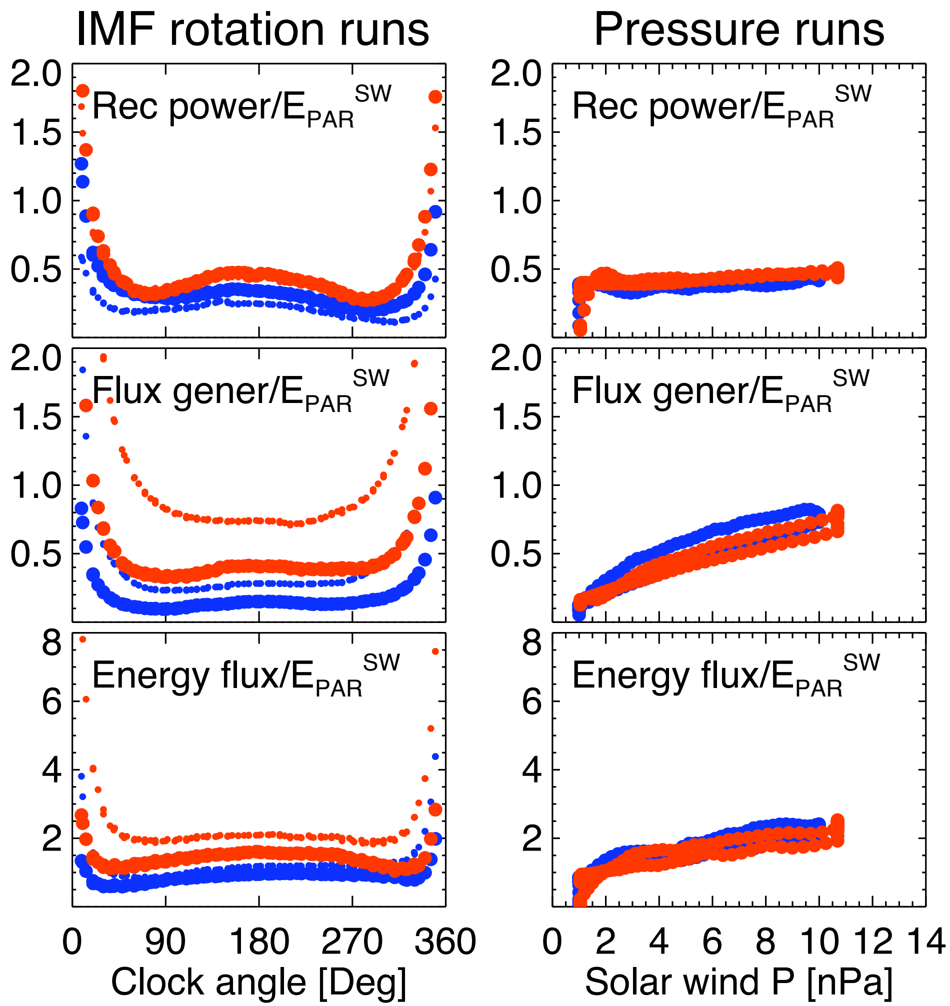
- **Electric field along X-line**



$E_{PAR} = E\sin(\theta/2)$

- **For θ > 60°:**
  - **response only dependent on E_{PAR} for all clock angles**
  - **energy flux and reconnection power almost independent of pressure**

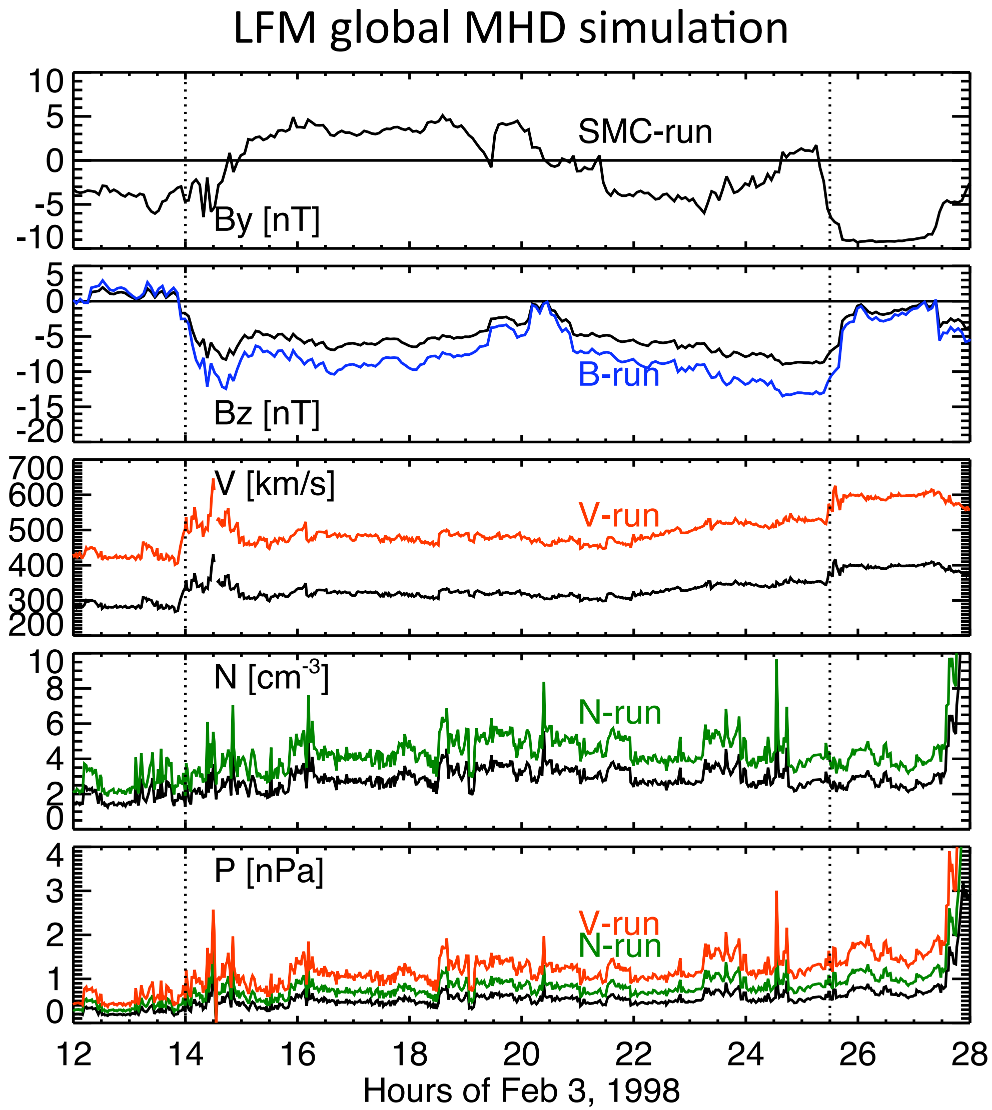
Efficiency: power / Eparallel



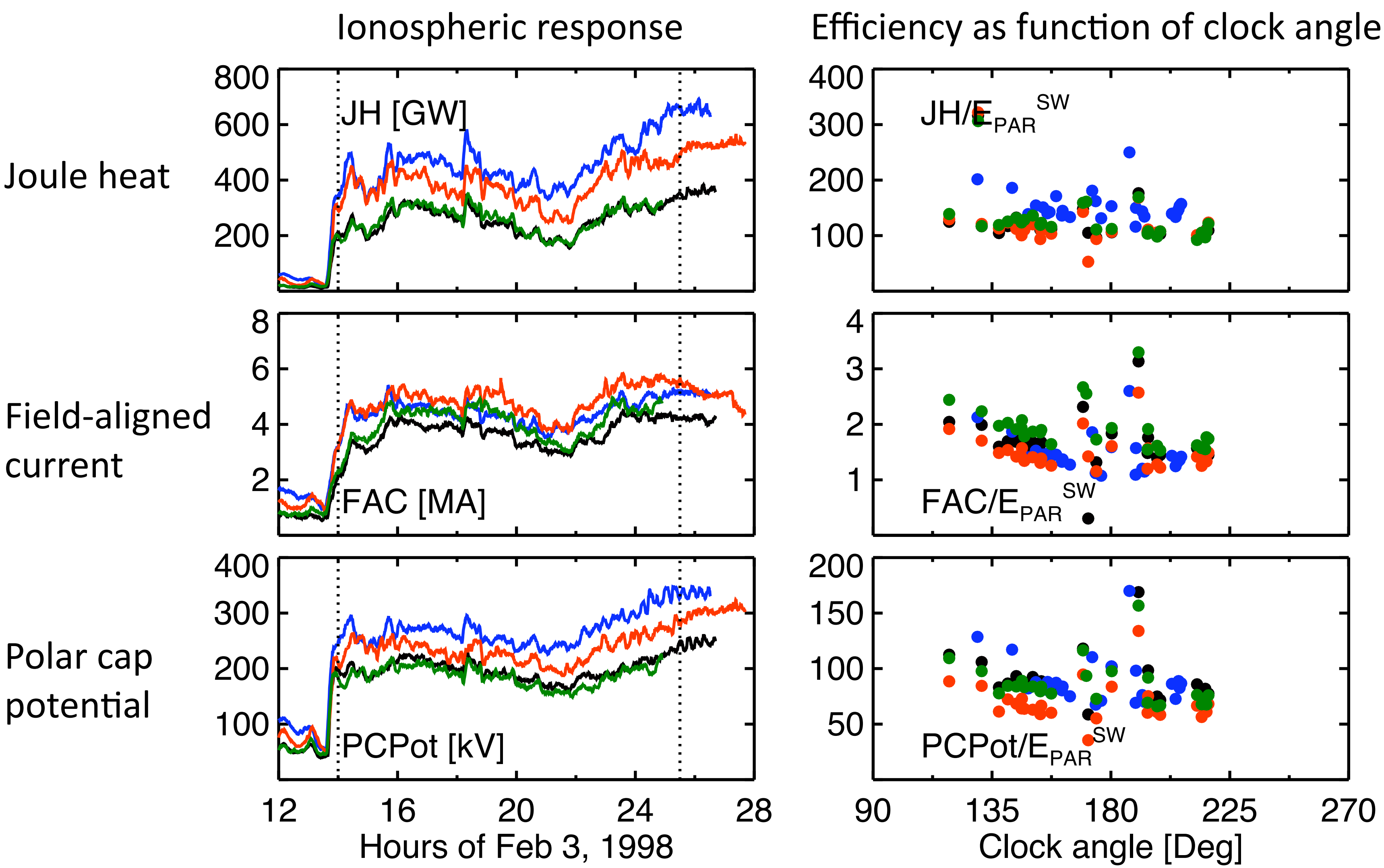
LFM global simulation test runs

- **Magnetic cloud as a driver**
- **Steady convection event as response**
- **Examine changes in response, if**
  - **IMF Bz increased**
  - **solar wind speed increased**
  - **solar wind density increased**

(*Goodrich et al., 2007; Pulkkinen et al., 2007, 2009*)



Efficiency in ionosphere: LFM simulation



B, V increase enhance response

Efficiency only dependent on E_{PAR}

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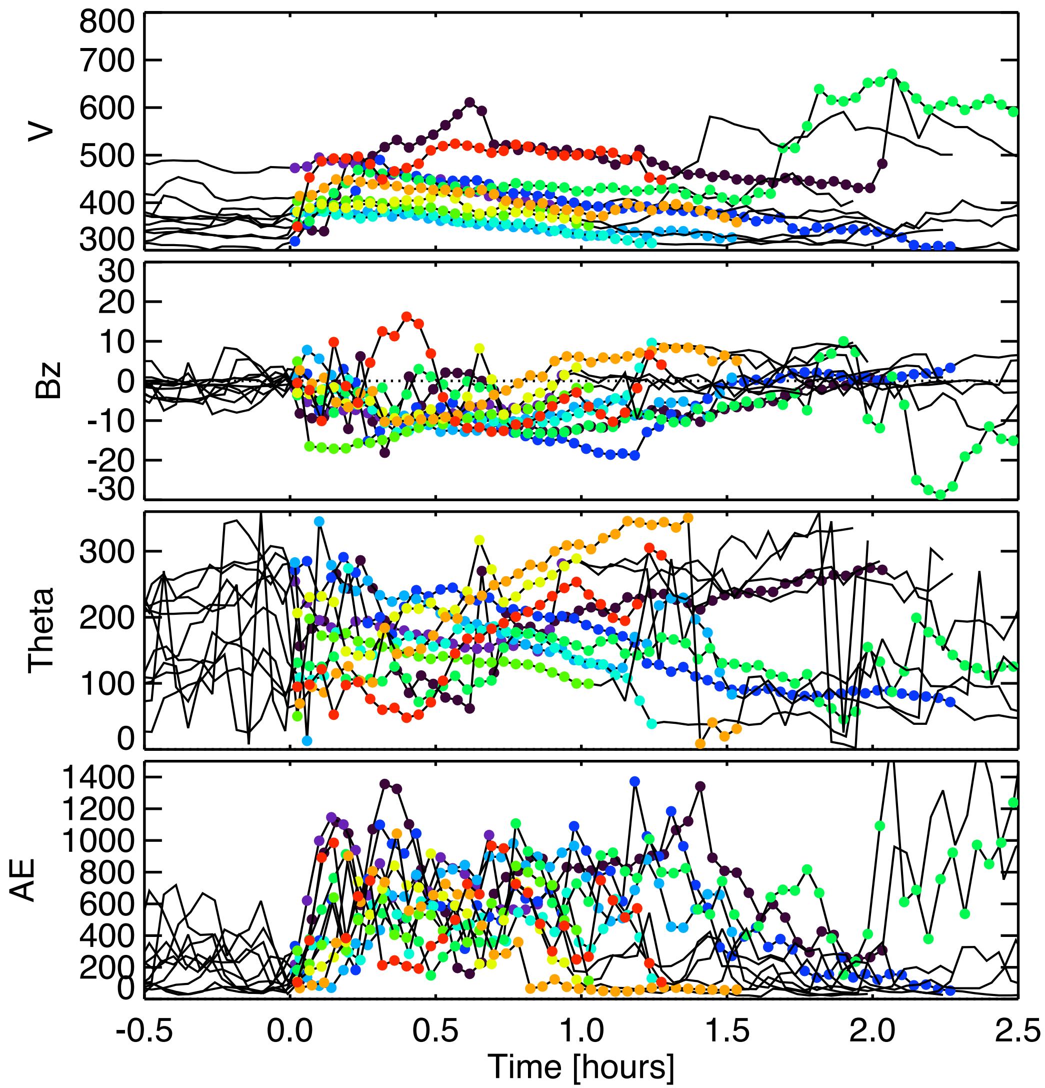
Efficiency in ionosphere: magnetic clouds

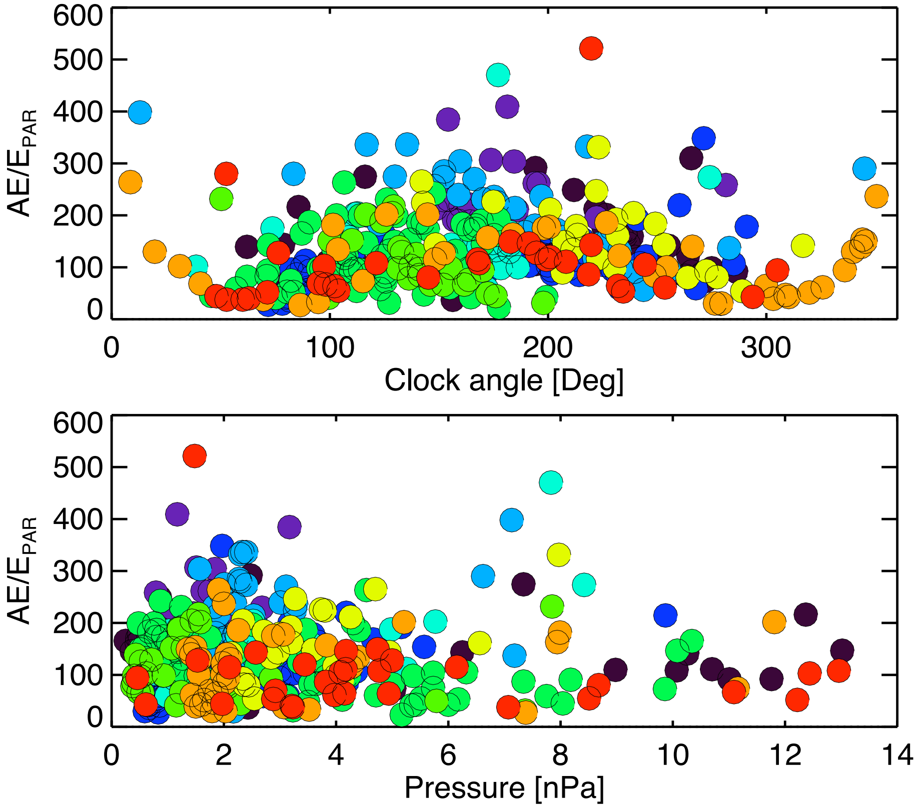
- **10 magnetic cloud events with slowly rotating IMF**
  - **no prior sheath driving: clean response to cloud**



Efficiency in ionosphere: magnetic clouds

- **10 magnetic cloud events with slowly rotating IMF**
  - **no prior sheath driving: clean response to cloud**

- **Ionospheric response by AE**
  - **efficiency AE/E_{PAR}**
  - **only dependent on E_{PAR}**
  - **independent of pressure**



Results

- In 3D situation, reconnection rate E_{PAR} along the tilted X-line at the magnetopause determines how much energy enters the magnetosphere
  - pressure/speed has a minor role in controlling flux generation tailward of the cusps

- Explains empirical results of dependence on $\sin(\theta/2)$ in e.g. epsilon
  - IMF clock angle controls X-line orientation

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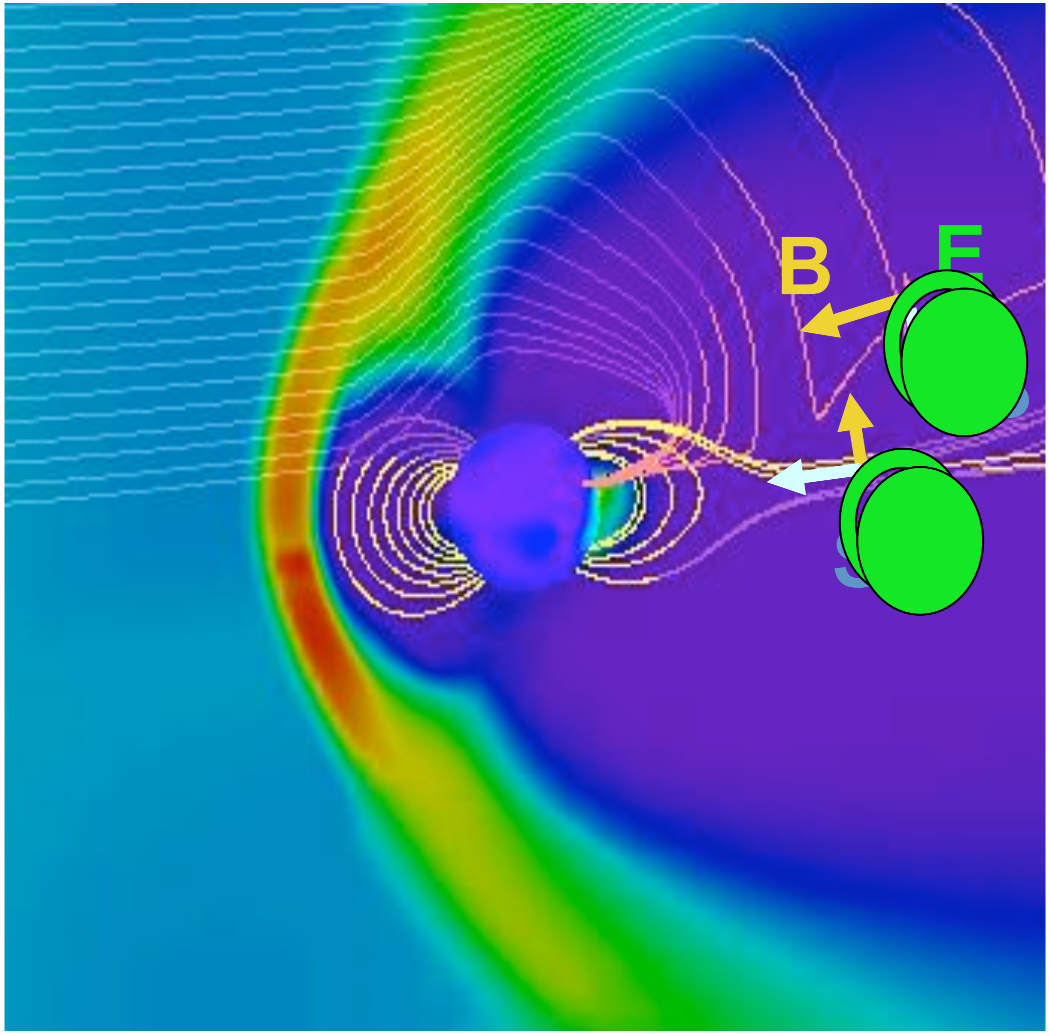
Poynting flux focussing

- **Papapdopoulos et al., 1993**
  - **magnetosphere as a lens for MHD waves**

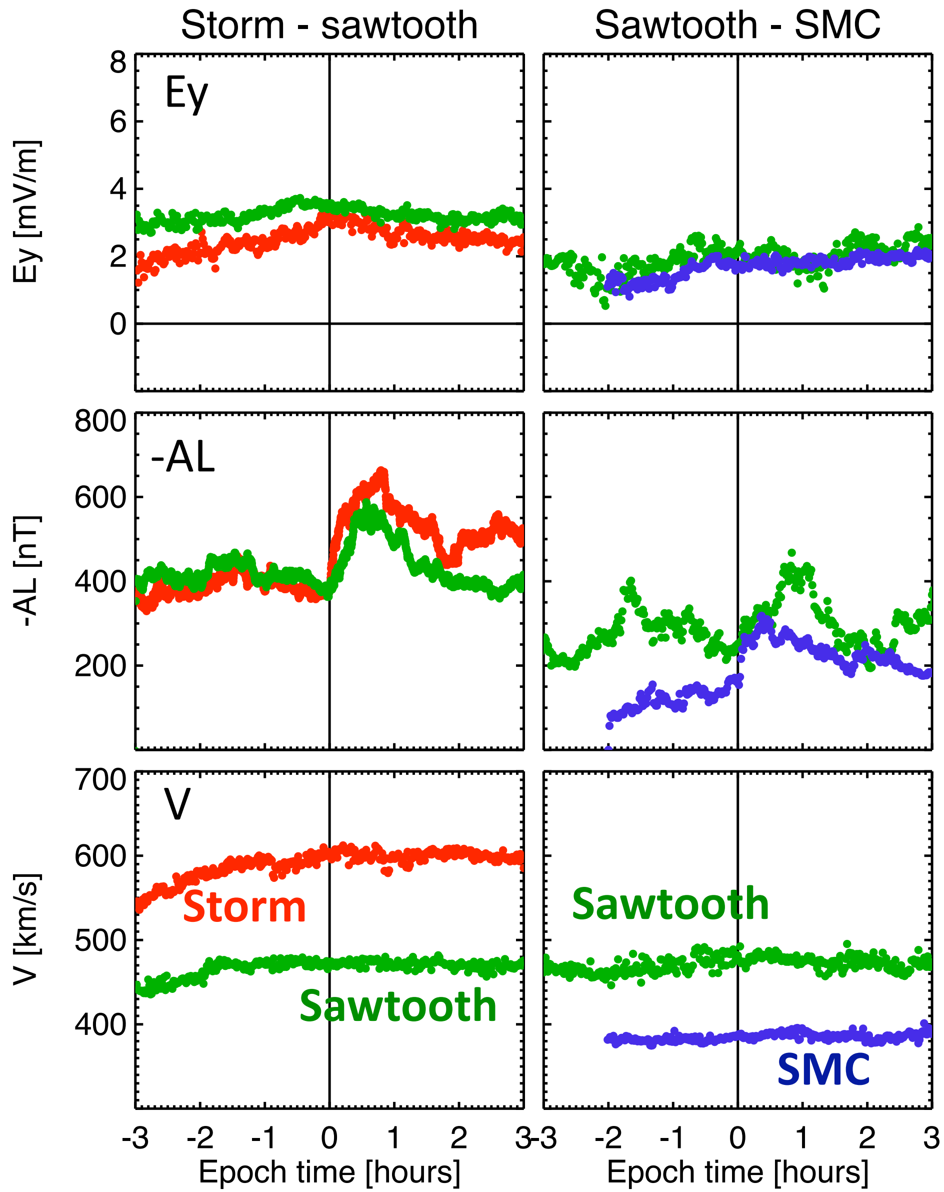
- **Papadopoulos et al., 1999**
  - **Poynting flux focussing to the inner magnetosphere as driver of substorms**
  - **natural explanation for NENL formation**



Role of solar wind speed in creating activity

- **Large-scale solar wind structures**
  - **e.g. magnetic clouds**
- **Magnetospheric responses**
  - **steady convection periods**
  - **sawtooth oscillations**
  - **magnetic storms**
- **Key distinguishing parameter**
  - **solar wind speed**

(*Pulkkinen et al., 2007*)



LFM global simulation test runs

- **Magnetic cloud as a driver**
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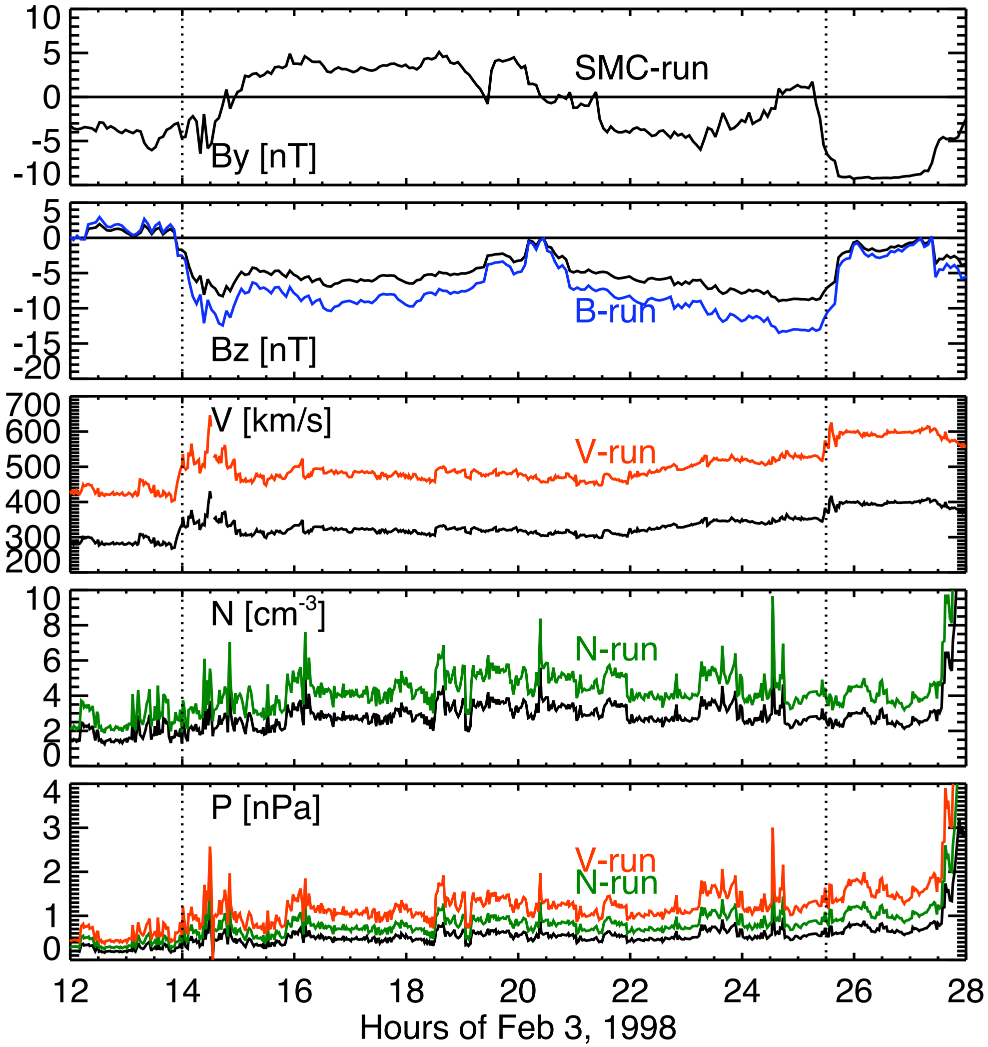
LFM global MHD simulation



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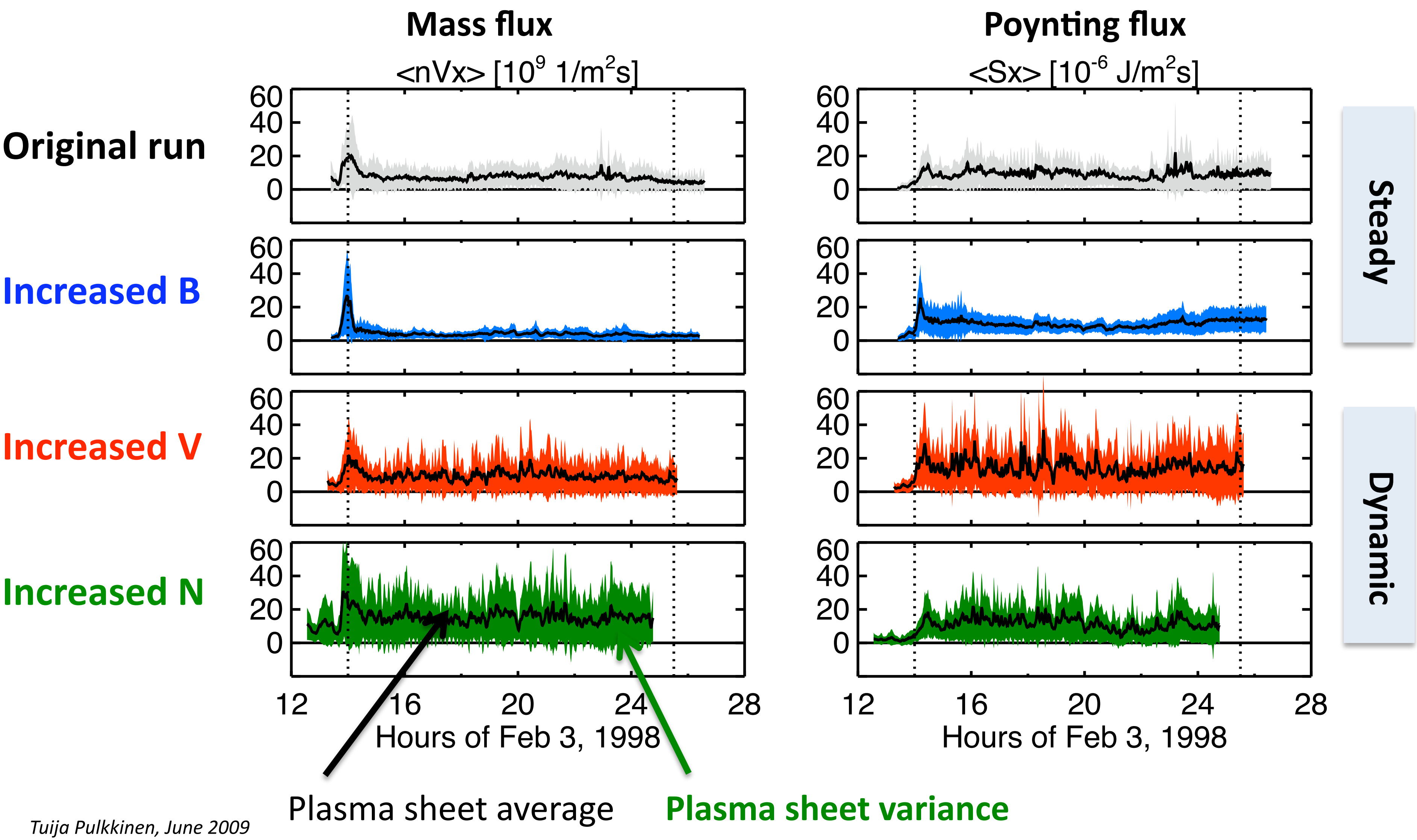
Mass and Poynting flux averages in tail

Tail cross-section at X = -15 Re



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Results

- **Effect of solar wind speed**
  - **changes tail response; higher speed induces more dynamic tail**

  - **low speed** → **steady convection (SMC)**
  - **intermediate speed** → **periodic activity (sawtooth)**
  - **high speed** → **strong irregular activity (storm)**

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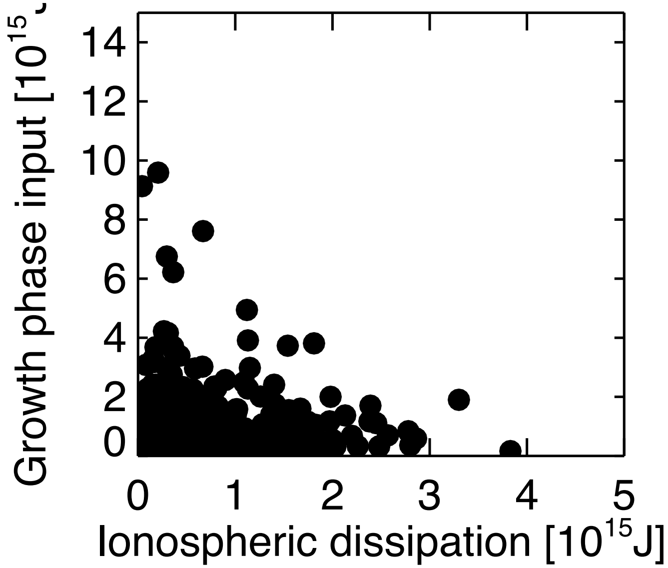
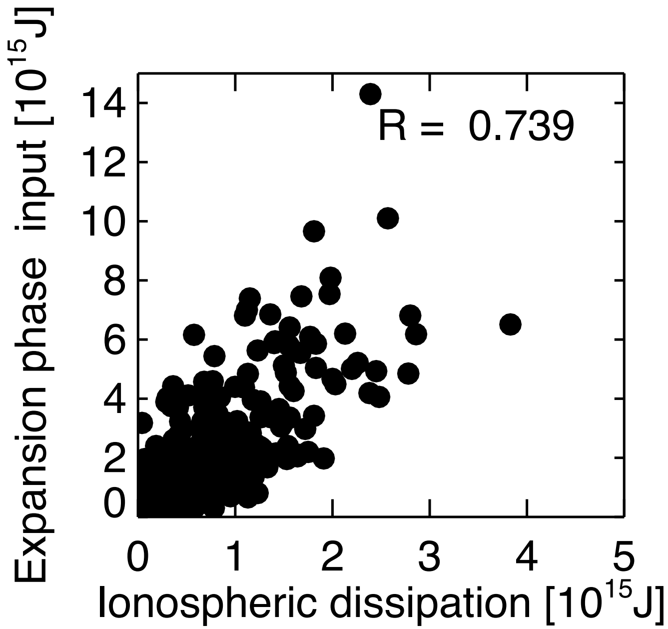
Observations: Size of substorms

- **Tanskanen et al., 2002**
  - **substorm size not proportional to energy input during growth phase**
  - **substorm size depends on energy input during expansion phase**

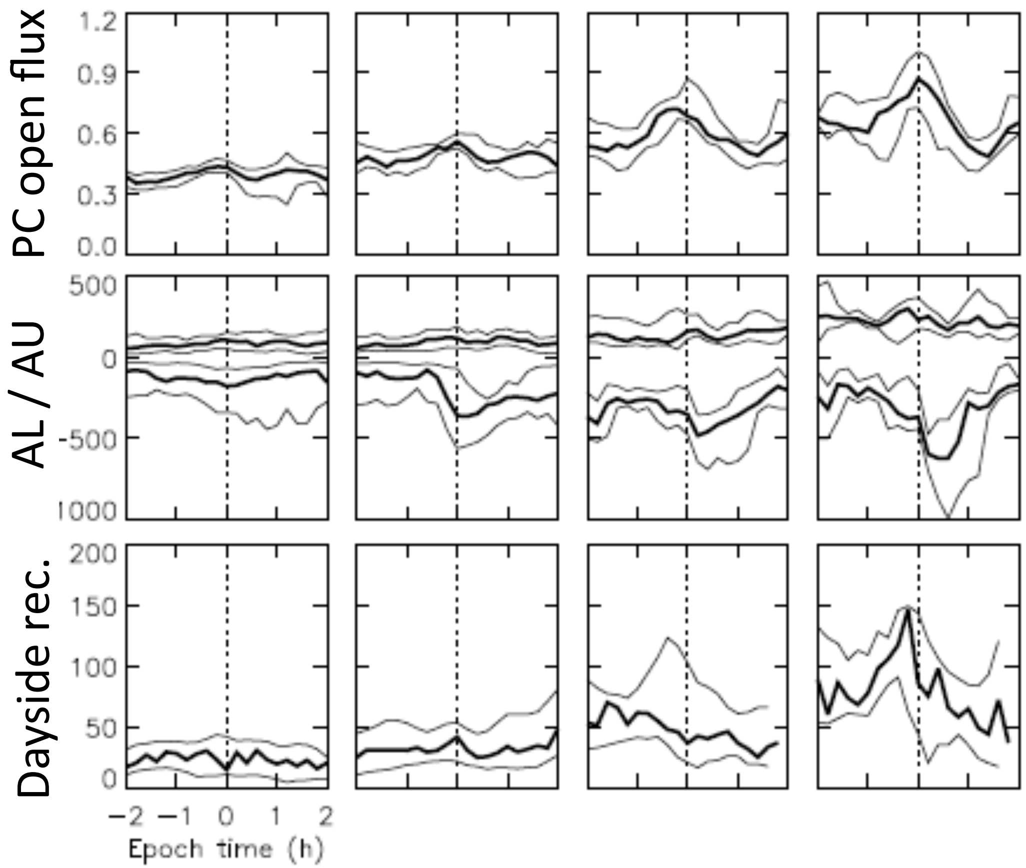




Observations: Driver of substorms

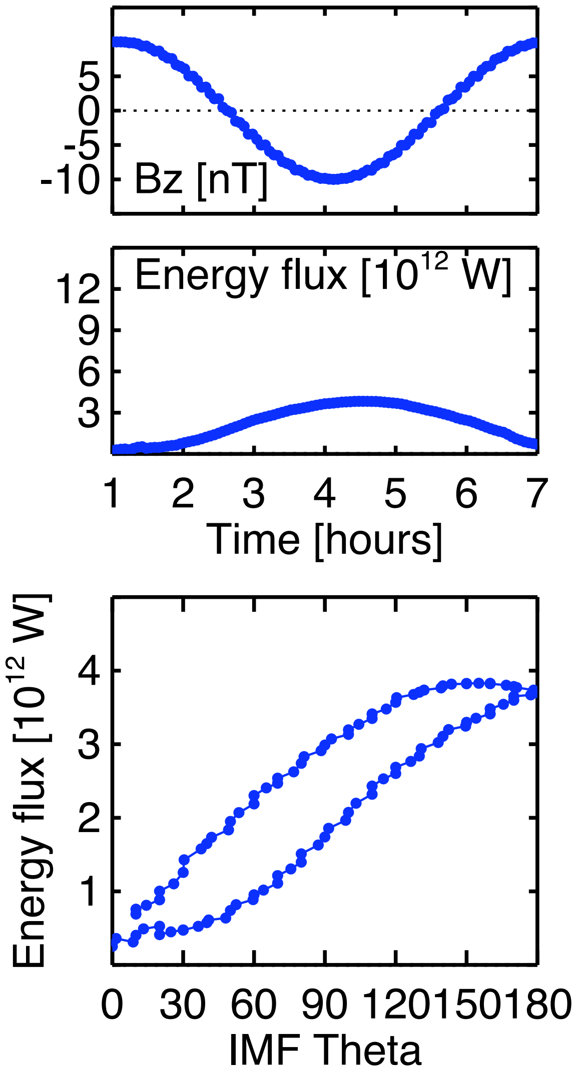
- **Milan et al., 2008: substorm size determined by**
    - **polar cap open magnetic flux**
    - **dayside reconnection rate**

Four categories according to PC flux level



GUMICS: Non-linear magnetopause response

- **Pulkkinen et al. 2006, Palmroth et al. 2006**
  - **no immediate response of energy input to IMF rotation changes**
  - **energy input through magnetopause directly affects energy dissipation in magnetosphere and ionosphere**
  - **delay generated already at the magnetopause**



Results

- Energy entry through magnetopause controlled by solar wind and IMF parameters AND magnetospheric state
  - magnetosphere only takes in what it can dissipate
    - explains substorm size correlation with integrated energy input
    - explains substorm timing dependence on dayside reconnection rate
  - possibly arises from dayside reconnection process dependence on magnetospheric convection

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Conclusions

- Reconnection rate $E_{PAR} = E\sin(\theta/2)$ along tilted X-line determines energy entry to magnetosphere
  - explains epsilon dependence on $\sin(\theta/2)$
  - IMF clock angle controls X-line orientation

- Solar wind speed determines magnetotail response mode
  - low speed → steady convection (SMC)
  - intermediate speed → periodic activity (sawtooth)
  - high speed → strong irregular activity (storm)

- Solar wind energy entry controlled also by magnetospheric state
  - substorm size correlation with energy input
  - substorm timing dependence on dayside reconnection rate