Nonlinear solar wind - magnetosphere coupling using MHD models

Tuija I. Pulkkinen

Finnish Meteorological Institute, Helsinki, Finland
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
Convec2ng‐reconnec2ng 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 ($E = -V \times B$)

- 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 $E_{\text{PAR}}$**

- Electric field along X-line

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

- For $\theta > 60^\circ$:
  - response only dependent on $E_{\text{PAR}}$ for all clock angles
  - energy flux and reconnection power almost independent of pressure

**Efficiency: power / $E_{\text{parallel}}$**

- IMF rotation runs
- Pressure runs

- Solar wind $P$ [nPa]
- Clock angle [Deg]
• 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

- **Joule heat**
- **Field-aligned current**
- **Polar cap potential**

**Ionospheric response**

- **Efficiency as function of clock angle**
  - $JH/E_{\text{PAR}}$
  - $FAC/E_{\text{PAR}}$
  - $PCPot/E_{\text{PAR}}$

**B, V increase enhance response**

Efficiency only dependent on $E_{\text{PAR}}$
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 $E_{\text{PAR}}$ 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
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
Poynting flux focussing

- Papadopoulos 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
- Steady convection event as response
- Examine changes in response, if
  - IMF Bz increased
  - solar wind speed increased
  - solar wind density increased
Mass and Poynting flux averages in tail

Tail cross-section at $X = -15$ Re

Mass flux

$\langle nV_x \rangle [10^9 \text{ m}^2/\text{s}]$

Poynting flux

$\langle S_x \rangle [10^6 \text{ J/m}^2/\text{s}]$

Steady

Dynamic

Original run

Increased B

Increased V

Increased N

Plasma sheet average

Plasma sheet variance

Tuija Pulkkinen, June 2009
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)
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*
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
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
Conclusions

- Reconnection rate $E_{\text{PAR}} = E \sin(\theta/2)$ 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 $\Rightarrow$ steady convection (SMC)
  - intermediate speed $\Rightarrow$ periodic activity (sawtooth)
  - high speed $\Rightarrow$ 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