Global Particle Simulation for Plasma Sail Concept Study

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Various methods

- **MHD simulations (since 1981) provide a quantitative picture**
  without kinetic effects
- **Tailored simulations with modules**
  work well with local simulations, can be combined with MHD simulations
- **Hybrid simulations [*Quest and Karimabadi*, ISSS-6, 2001]**
  electrons fluids (ions: kinetic)
- **Global particle simulation**
  difficult to establish good spatial and temporal resolutions with a reasonable mass ratio at the present time, but it will become a vital model
- **MHD simulations with localized particle simulations**
  very difficult to transfer physical values at boundaries

Present global particle simulations can do

Reproduce the gross features of Magnetosphere including

a reasonable (qualitative) representation of

- *** the bow shock**
- *** the magnetopause with magnetopause (Chapman-Ferraro) current**
- *** the cusps**
- *** the magnetotail**
- *** the effects of the IMFs (reconnections, particle injections)**
- *** fields and currents (field-aligned, partial ring current, etc)**

Reproduce the fundamental features of the dynamic Magnetosphere:

- *** substorms**
- *** transient events due to variations of solar wind conditions**
- *** convections**
- *** particle acceleration**

Why do we need to use particle simulations?

*** In MHD simulations some of kinetic effects are not included**

⇒ dynamics of boundaries are not properly simulated

⇒ particle injections are not included in MHD simulations,

in particular accelerated high energy particles

⇒ ring current is not included in MHD models at the present time

*** Computer power (memory and speed) will be available in**

ten years or so in order to perform global particle simulations for

quantitative comparisons with observations including velocity distributions

*** Prepare for future possible plasma sail concept in order to provide useful**

information for planning

*** Predictions of kinetic instabilities for improvements for plasma sail concept**

Basic equations

Maxwell equations

$$\partial \boldsymbol{B}/\partial t = -\nabla \times \boldsymbol{E} \quad \text{and} \quad \partial \boldsymbol{D}/\partial t = \nabla \times \boldsymbol{H} - \boldsymbol{J}$$

As well as Newton-Lorentz (relativistic)

$$d m \boldsymbol{v}/dt = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

$$\varepsilon_0 = 1 \quad \text{and hence} \quad \mu_0 = 1/c^2$$

$$\boldsymbol{D} = \boldsymbol{E} \quad \text{and} \quad \boldsymbol{B} \hookrightarrow c\boldsymbol{B}$$

$$\boldsymbol{E} \Leftrightarrow \boldsymbol{B} \quad \text{(symmetric)}$$

Plasma parameters

$\omega_e = (nq_e^2/m_e)^{1/2}$: electron plasma frequency

$\omega_i = (nq_i^2/m_i)^{1/2}$: ion plasma frequency

$\Omega_e = q_eB/m_e$: electron gyrofrequency

$\Omega_i = q_iB/m_i$: ion gyrofrequency

$\lambda_e = v_e/\omega_e$: electron Debye length (***ignored in Hybrid simulations***)

$\lambda_i = v_i/\omega_i$: ion Debye length

$\lambda_{ce} = c/\omega_e$: electron inertial length

$\lambda_{ci} = c/\omega_i$: ion inertial length

$\Delta x \geq 3\lambda_e$: (to avoid numerical instability)

$\Delta t \leq \Delta x/c$: Courant (CFL) condition ($c = 0.5$)

if $c = 10v_e$, $T_i = T_e$, and m_i/m_e=**16**	if $c = 20v_e$, $T_i = T_e$, and m_i/m_e=**100**
$\lambda_e << \lambda_i << \lambda_{ce} << \lambda_{ci}$	$\lambda_e << \lambda_i << \lambda_{ce} << \lambda_{ci}$
1 4 10 40	1 10 20 200

Numerical considerations for solar wind-magnetosphere

- **Scale Size**

  * **the scale of the system ranges from 10s of Kms in the ionosphere to 100s of Earth radii in the far tail. $\Rightarrow$ unstructured grids**

  * **physical values vary up to 7 orders of magnitude, e.g.,**

    $B \approx (10^{-2} - 10^{4})nT,\ \beta \approx (10^{-5} - 10^{2}),\ n \approx (10^{-2} - 10)/cm^{3}$

- **Time step**

  * **the smallest time step is considered by the fastest wave speed in the system, which is of order of the fast mode speed – this can be very high near the Earth.**

- **Verification**

  * **one of the best tests of a numerical method is to compare its results with observations – however, since the observations are usually single or dual, the comparisons are not easy or comprehensive. (Establish a scaling law)**

Numerical considerations for M2P2 concept study

- **Scale Size (needs to be modified)**
  - * the scale of the system ranges from 10s of Kms in the ionosphere to 100s of Earth radii in the far tail. $\Rightarrow$ unstructured grids
  - * physical values vary up to 7 orders of magnitude, e.g., $B \approx (10^{-2} - 10^{4})$nT, $\beta \approx (10^{-5} - 10^{2})$, $n \approx (10^{-2} - 10)/cm^3$
- **Time step**
  - * the smallest time step is considered by the fastest wave speed in the system, which is of order of the fast mode speed – this can be very high near the Earth.
- **Verification**
  - * one of the best tests of a numerical method is to compare its results with observations – however, since the observations are usually single or dual, the comparisons are not easy or comprehensive. (Establish a scaling law)

Motivations for global particle simulations

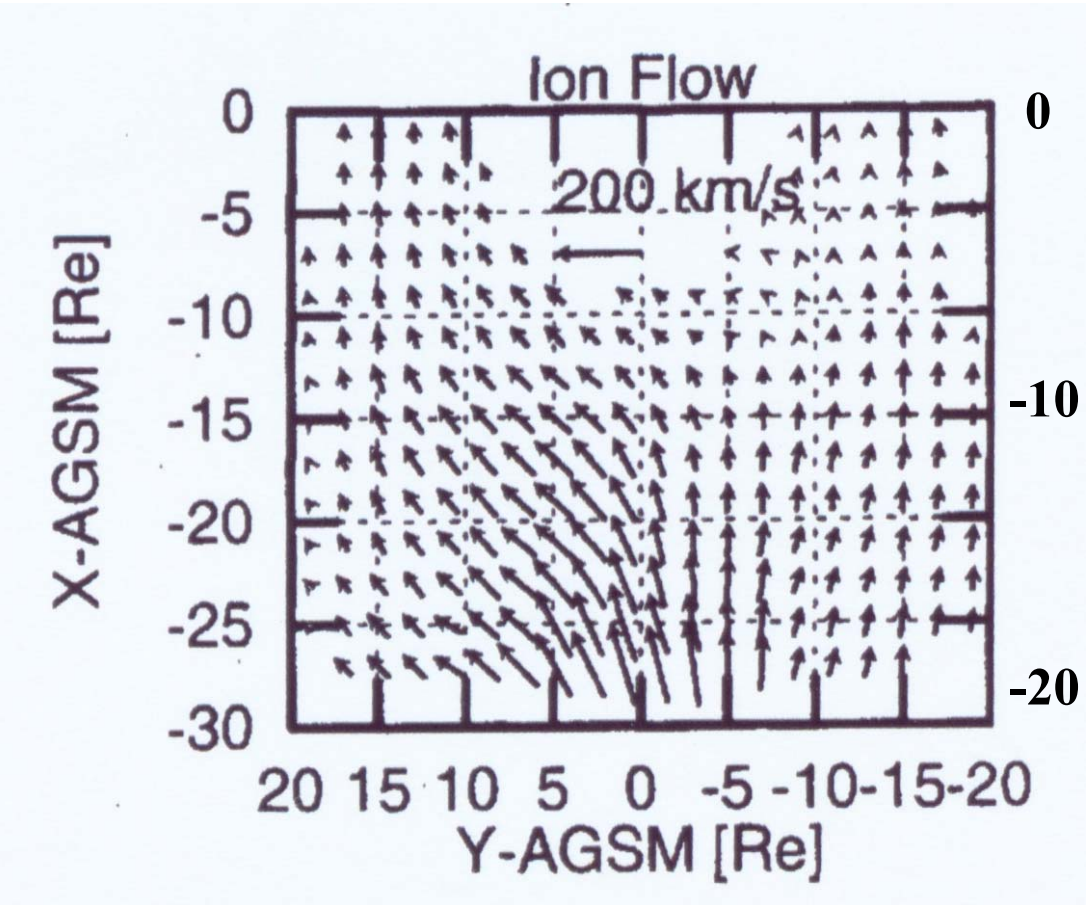
- **Kinetic processes reveal essential physics involved in plasma sail concept which is not investigated by MHD simulations**
- **3-D Electromagnetic Particle Model (EMPM) for plasma sail concept study is a challenging project, however it is necessary for predicting more realistic interaction of solar wind-plasma bubble interaction for propulsion**
- **Take advantage of modern supercomputers using parallel processing (MPI) on IBM p690**

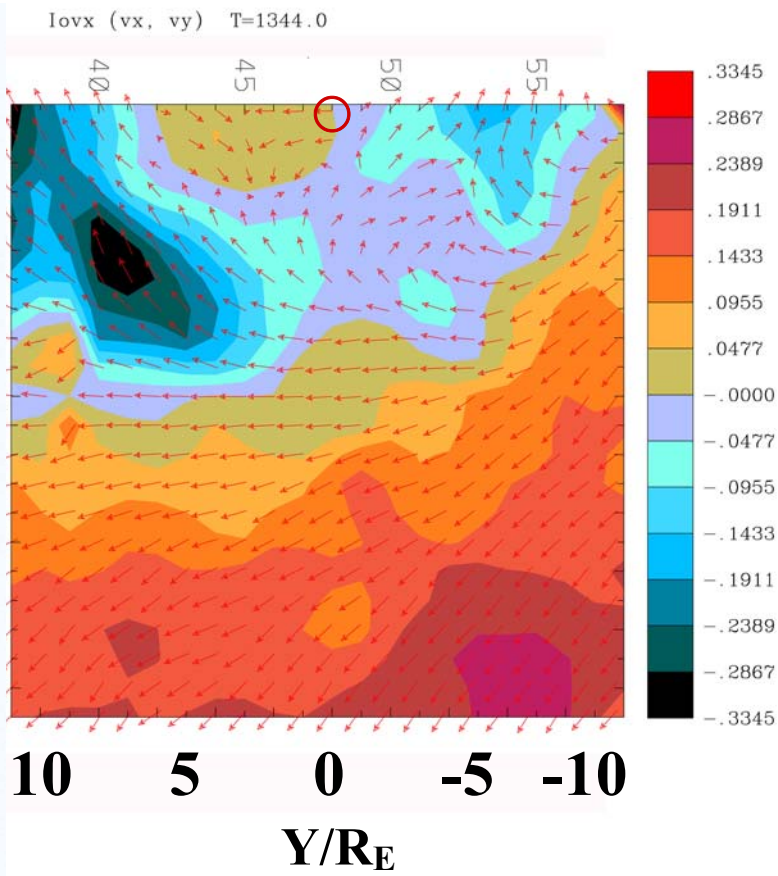
Objectives

- What is the time sequence of bubble dynamics with southward turning or northward IMF?
- Does the reconnection take place with the magnetic fields created the vehicle?
- Do reconnection, BBFs, flow braking, and CD take place with M2P2 system?
- What is the main mechanism of creating momentum transfer?
- How does the IMF B_y component affect these processes?
- How is the ring current generated in the bubble?
- How is the ring current generation affected with heavy ion injection?
- How are energetic particles generated and how are they injected into the bubble?

Comparison with observations

0.30 UT





Averaged ion flow pattern in the plasma sheet (Geotail observations)

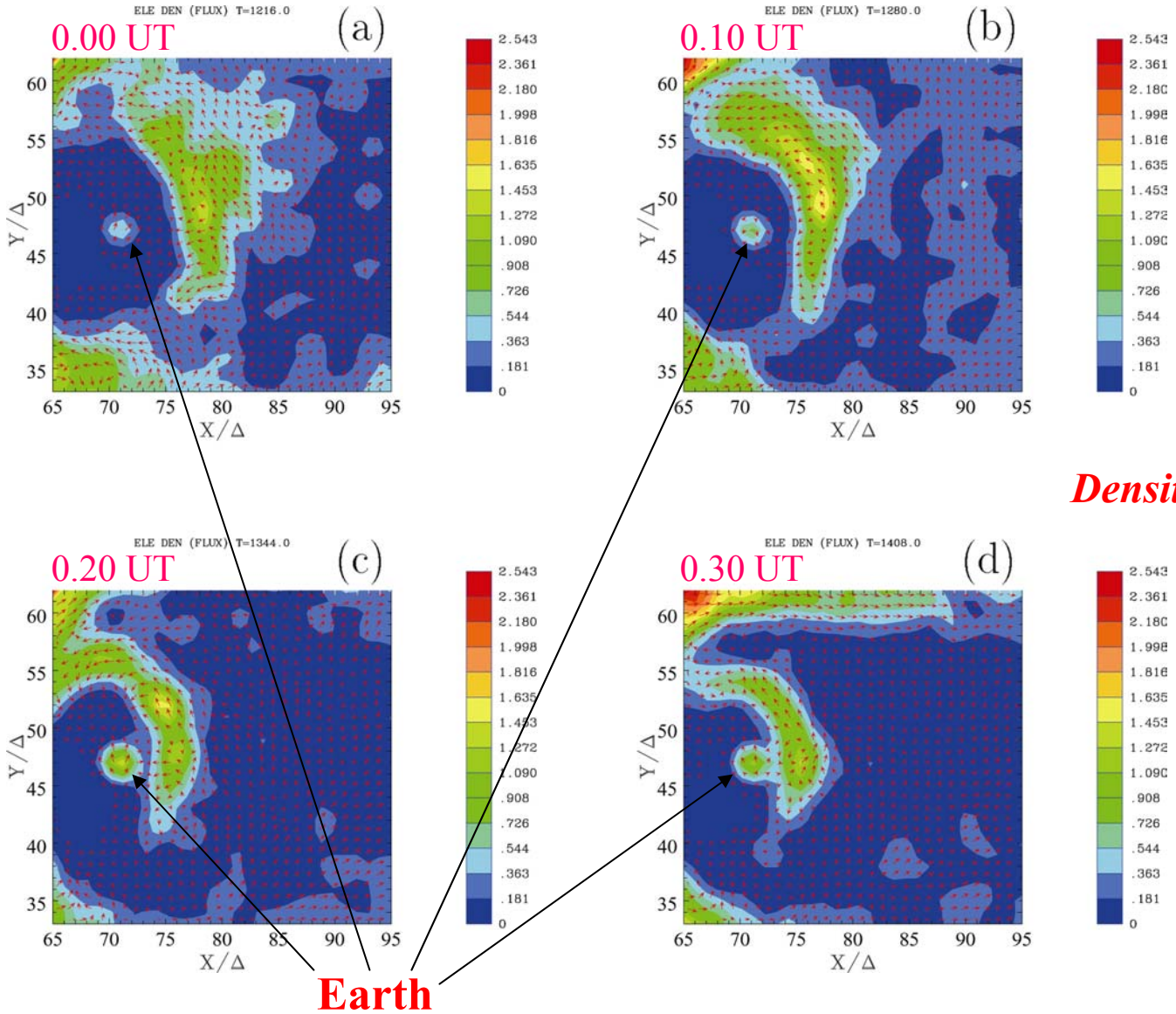
○ **Earth**

Particle injection at the equatorial plane

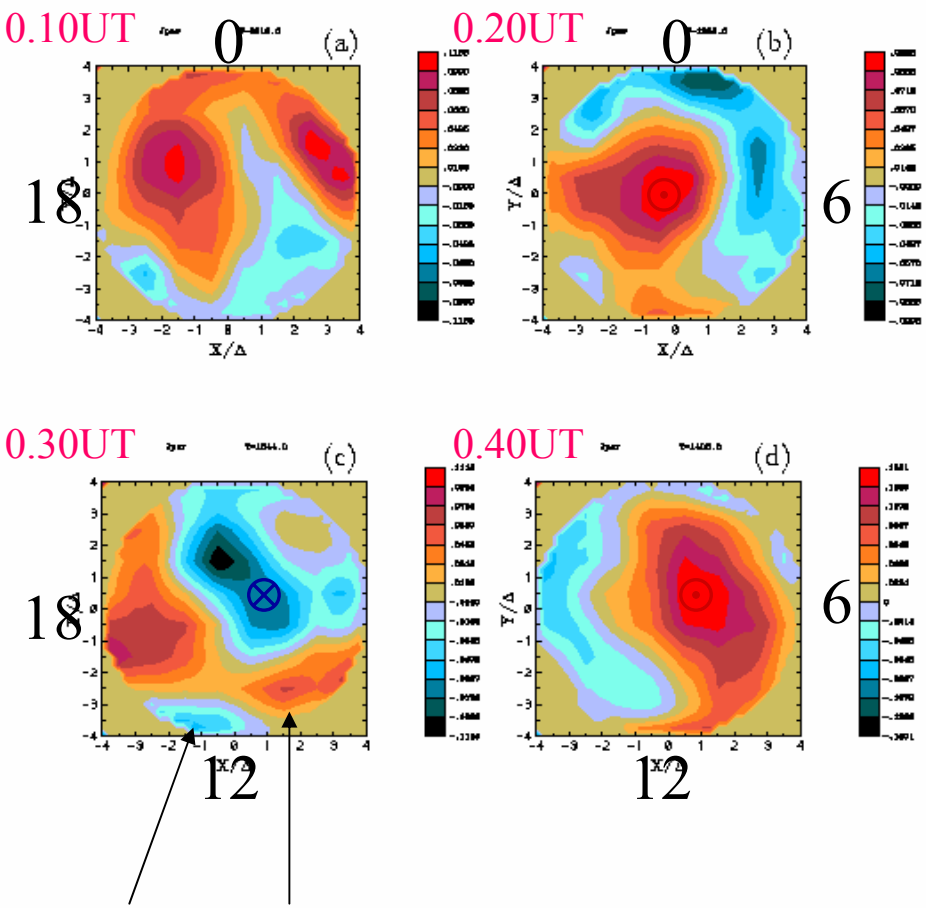
Electron density

Arrows: flux

Density: normalized



Field-aligned currents at the north pole at $r = 5\ R_E$



latitudes: 37°- 90°

blues: inward ⊗

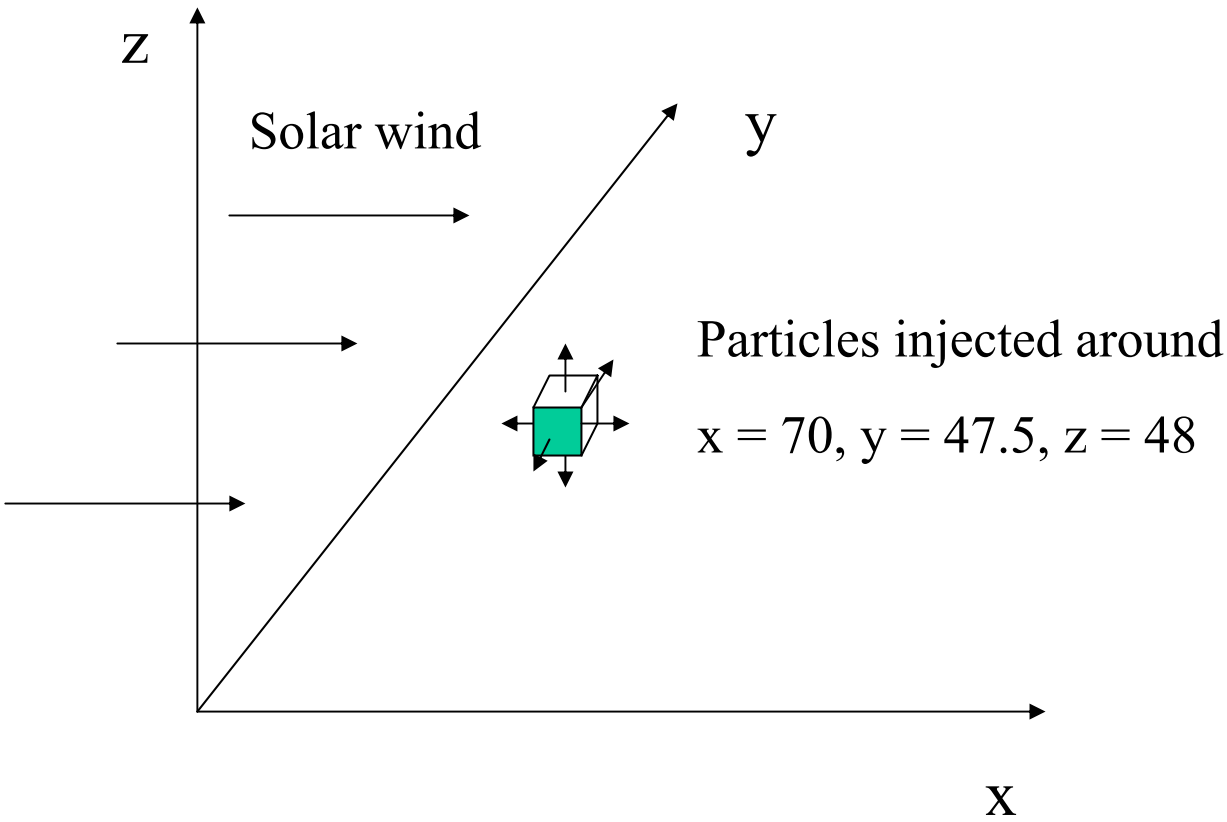
reds: outward ⊙

Figure 9 shows time evolution of the field aligned current at $r = 5\Delta$ ($\approx 5\ R_E$)) around the north pole (90° -- 36.9°) (projected on the equatorial plane and viewed from the pole). (a) 0.10 UT (1216), (b) 0.20 UT (1280), (c) 0.30 UT (1344), and (d) 0.40 UT (1408). The inward and outward currents are shown by blues and reds, respectively.

Self-consistent current generation

needs further improvements!

Initial simulation results with M2P2

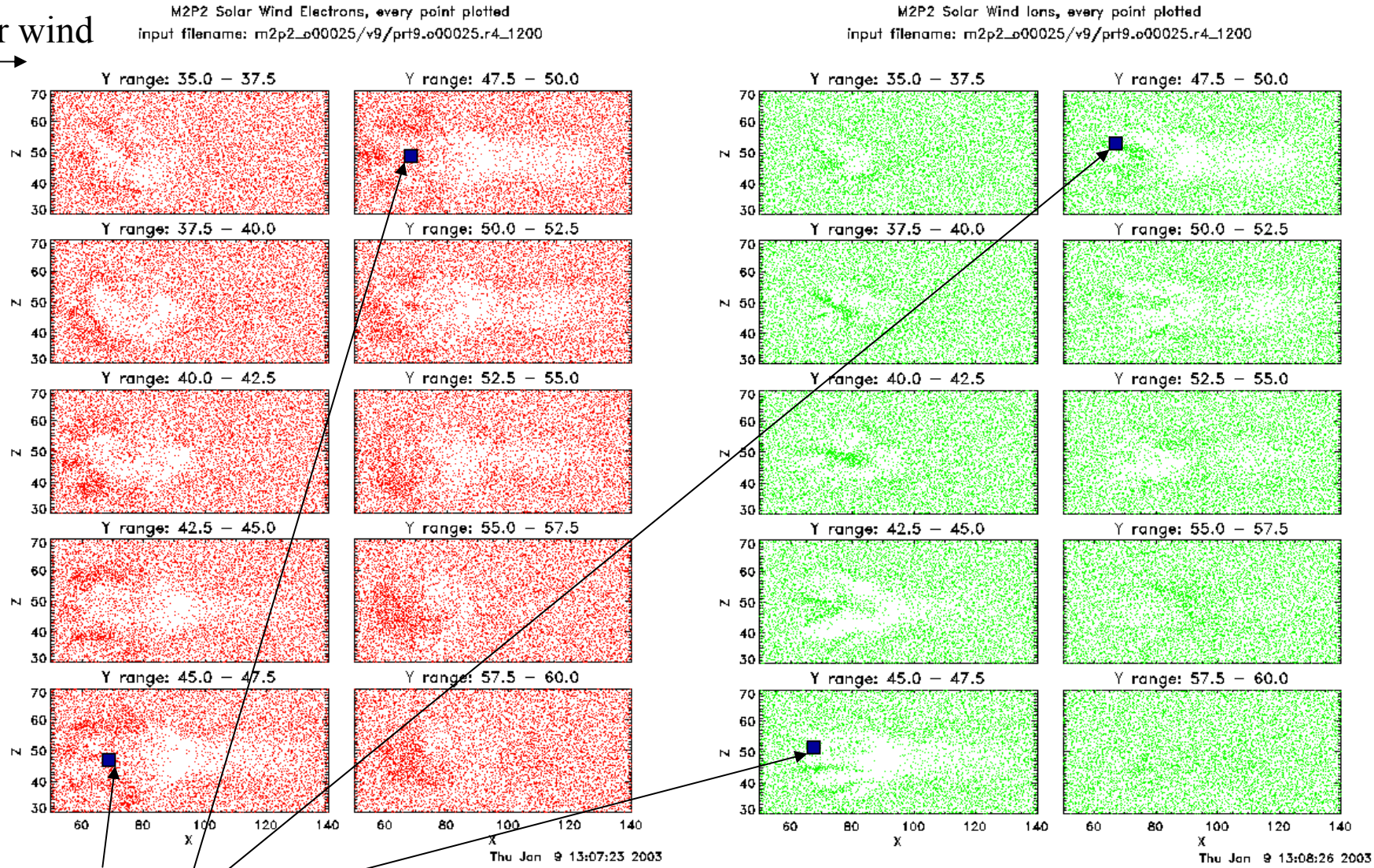


Solar wind particle distributions in y-slicing in x-z plane (local)

Solar wind electrons

Solar wind ions

Solar wind



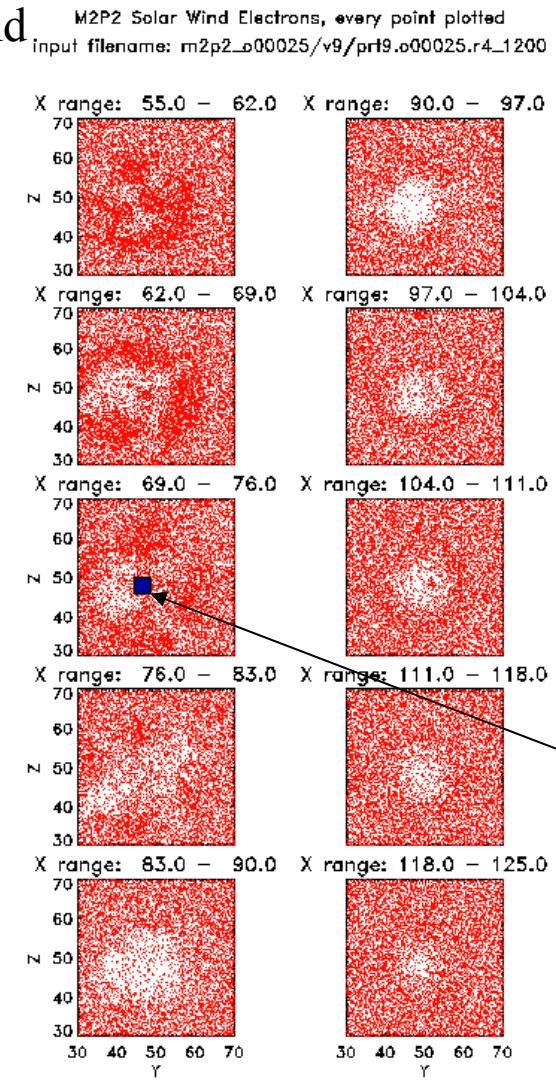
vehicle

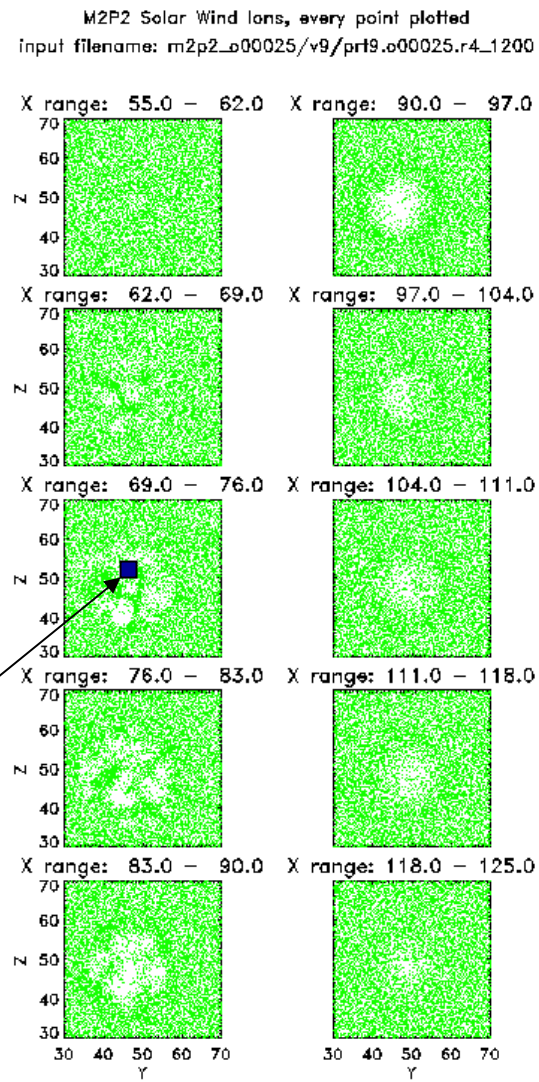
Solar wind particle distributions in x-slicing in y-z plane (local)

Solar wind electrons

Solar wind ions

Solar wind ⊙





■ Vehicle

Brief summary of simulation results with M2P2

- After particles are injected from the vehicle, the solar particles are partially reflected and penetrated into the bubble
- Solar wind electrons and ions interact with the bubble differently
- To understand these complicated particle dynamics requires intensive simulations with theoretical analysis and other simulations
- Current systems need to be investigated to understand the magnetic fields around the bubble
- IMFs need to be included for further simulation studies
- Mass ratios need to be changed in order to estimate dynamics in more realistic mass ratio
- Behind the vehicle a cavity was created, which suggests that solar wind particles transfer their momentum to the bubble created around the vehicle