Three-dimensional MHD simulation of the solar wind from the solar surface to 400 solar radius using REPPU (REProduce Plasma Universe) code

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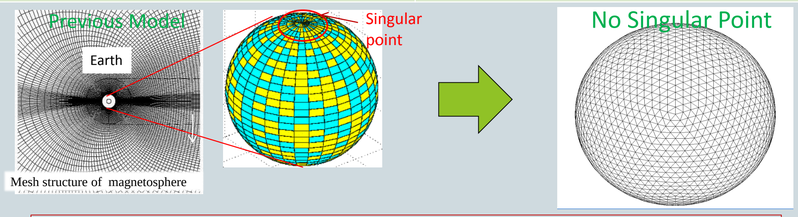
ABSTRACT

- Three-dimensional MHD simulation code, REPPU (REProduce Plasma Universe) code, is developed for modeling of space plasma phenomena, and is utilized for the solar surface and the global solar wind structure.
- The distinguishing features of this code is the 3-D grid system, which has no polar singularity though it is able to fit the spherical structure. This grid system makes it possible to set fine grids on the inner boundary of the inner simulation region which corresponds to the solar surfaceREPPU code achieved both the implementations for the fine grid structure on the inner boundary and for the wide range grids in global solar wind configuration.
- We extend the outer boundary to 400 solar radius, though the previous our model covered 200 solar radius. We split the simulation region at several 10 solar radius where the solar wind speed is super-sonic. This improvement made it possible to perform stable simulation in the outer region where rotational component of the solar wind velocity is high.

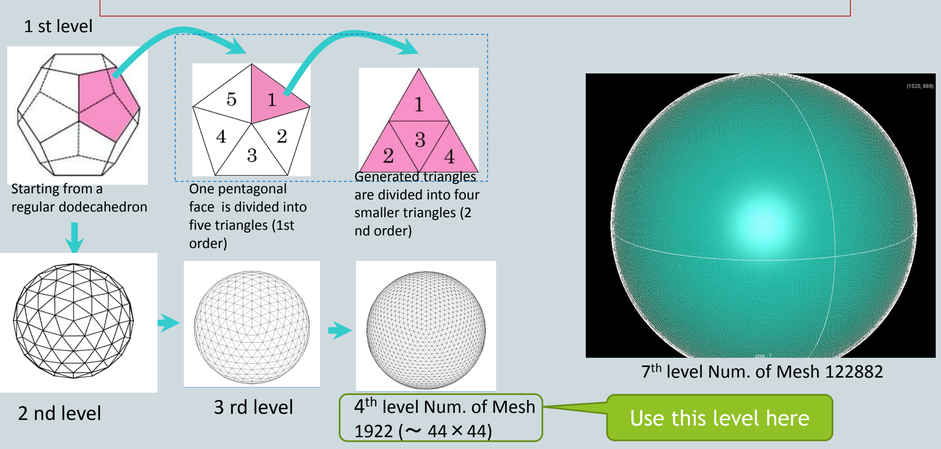
REPPU (REProduce Plasma Universe) code *[by Tanaka]*

Singular point-less coordinate system on a spherical surface

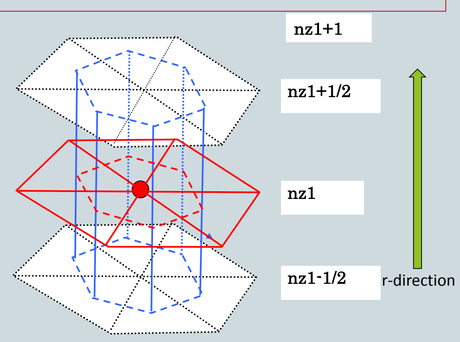
	Previous Model	Current Model
Grid	Modified spherical coordinate - the Singular Point of a pole	Unstructured grid - No Singular Point
Δt	determined by the grid size around the pole, which limits accuracy	determined by alphen velocity near the earth, not the grid size
Robustness	Weak when extreme data are input	Good. It is confirmed that Bastille event can be simuilated by using magnetosphere version of REPPU code



Generation of unstructured grid system



Control volume for the FVM (Finite Volume Method) *[Tanaka, 1994]*



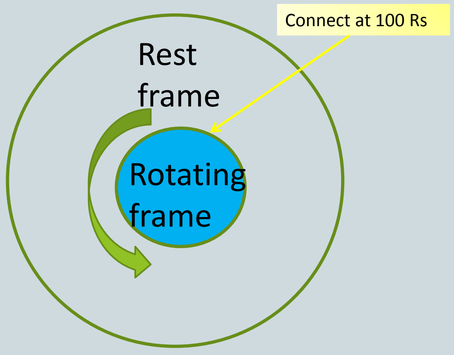
Computational scheme

Finite Volume Method (FVM)
Flux
TVD (Total Variation Diminishing), and Monotonic Upstream Scheme for Conservation Laws (MUSCL) interpolation with Van-Leer's differential scheme

Simulation Model

・The inner boundary is set at 1Rs.
=> Phenomena occurred on the solar surface can be simulated seamlessly toward the earth orbit.
・The outer boundary is extended to **400 solar radii**, though the previous our model covered 200 solar radii.
・We split the simulation region about several 10 solar radii (here 100 solar radii) where the solar wind is super-sonic.
- **The inner region** is developed in **a rotational frame** and the observed magnetic field data are input on the solar surface as the inner boundary.
- **The outer region** is simulated in **a fixed frame** and simulated data in the inner region are set on the inner boundary of this code.

Calculation frames for the inner and the outer simulation regions



Equations of Motion

[Nakamizo, Tanaka + , JGR, 2009]

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot \left(\rho \mathbf{v}\mathbf{v} + P\mathbf{I} + \frac{B^2 - B_0^2}{2\mu_0}\mathbf{I} - \frac{\mathbf{B}\mathbf{B} - \mathbf{B}_0\mathbf{B}_0}{\mu_0} \right)$$

$$= -\rho \frac{GMs}{r^2}\hat{\mathbf{r}} - 2\rho\Omega \times \mathbf{r} - \rho\Omega \times (\Omega \times \mathbf{r}) + S_M ,$$

$$\frac{\partial \mathbf{B}_1}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

$$\frac{\partial U_1}{\partial t} + \nabla \cdot \left[\mathbf{v} \cdot \left(U_1 + P + \frac{B_1^2}{2\mu_0} \right) - \frac{\mathbf{B}_1 (\mathbf{v} \cdot \mathbf{B}_1)}{\mu_0} - \frac{\mathbf{B}_0 (\mathbf{v} \cdot \mathbf{B}_1)}{\mu_0} + \frac{\mathbf{v}(\mathbf{B}_1 \cdot \mathbf{B}_0)}{\mu_0} \right]$$

$$= \rho \mathbf{v} \cdot \left(-\frac{GMs}{r^2}\hat{\mathbf{r}} \right) - \rho V \cdot [\Omega \times (\Omega \times \mathbf{r})] + S_E ,$$

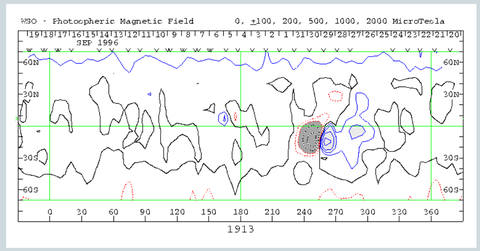
$\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_1$, $U_1 = \frac{\rho v^2}{2} + \frac{P}{\gamma - 1} + \frac{B_1^2}{2\mu_0}$ $\mathbf{B}_0$ the potential magnetic field, $\mathbf{B}_1$ the perturbed component

$\gamma = \frac{5}{3}$ S_M the momentum source term

S_E the energy – source term

Input data

Observed the line-of-sight photospheric magnetic field data provided by Wilcox Solar Observatory.
We calculate a Dirichlet problem for the 3D potential magnetic field.



Solar wind acceleration model

$$S_E = Q \exp(-R/L_Q) + \nabla \left(\xi T^{2.5} \frac{\nabla T \cdot \mathbf{B}}{B^2} \right) \cdot \mathbf{B}$$

volmetric heating func. + thermal conduction term

Q the intensity, L_Q decay length of heating,

ξ the coeff. of the parallel thermal conductivity

$Q = Q_0 \cdot \frac{1}{f_s}$, $f_s = \left(\frac{R_s}{R} \right)^2 \frac{B_{Rs}}{B_R}$. f_s expansion factor

$$S_M = M(R - 1.0)\exp(-R/L_M)$$

M the intensity of the momentum addition, L_M the decay length

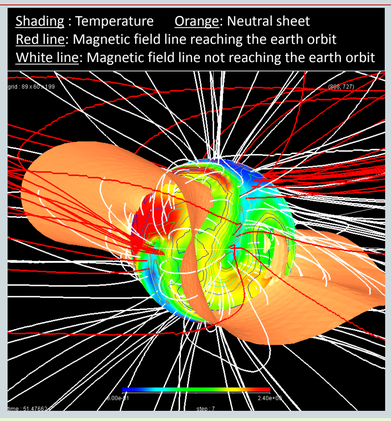
$$M = M_0 \cdot \frac{1}{f_s}$$

$Q_0 = 3.3 \times 10^{-6}\,\mathrm{Jm^{-3}s^{-1}}$ $M_0 = 5.3 \times 10^{-14}\,\mathrm{Nm^{-3}}$ $L_Q = L_M = 0.9Rs$

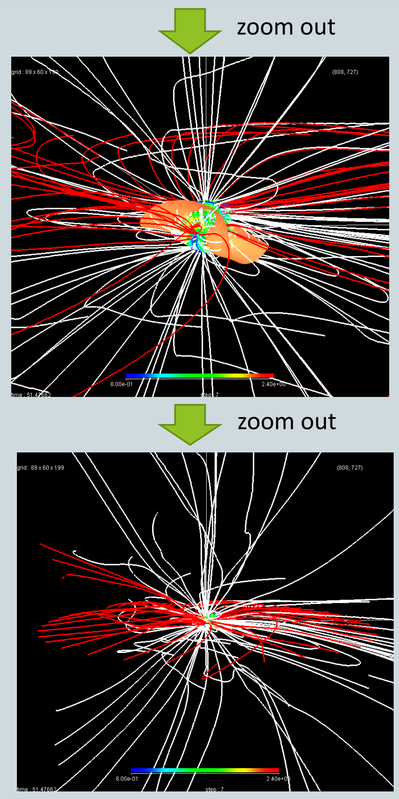
References Tanaka, T. (1994), *J. Comp. Phys., 111,* 381.
Nakamizo, A., Tanaka, T. + (2009), *J. Geophys. Res., 114,* A07109.
Please see other references in my proceedings.

Simulation Results

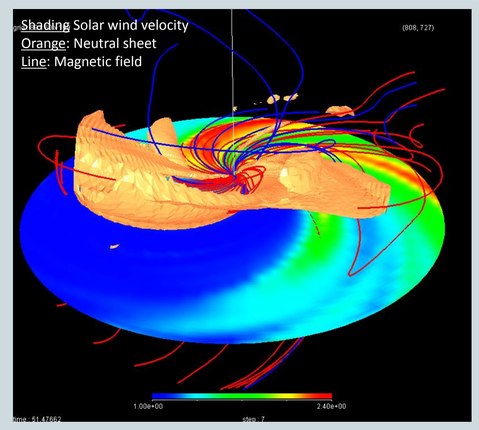
From near solar surface to outer region



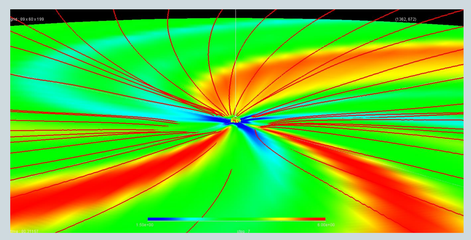
It is interesting that curved neutral sheet is concerned with the CH at the low latitude.
Many red lines start from the low latitude region, however, there are the red lines originating from the CH located at the high latitude.
This means that not only the CHs placed at the low latitude also the CHs at the high latitude could have an effect on the environment near the earth.



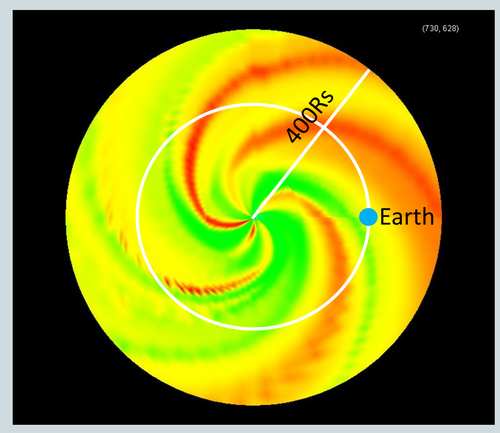
Global solar wind structure



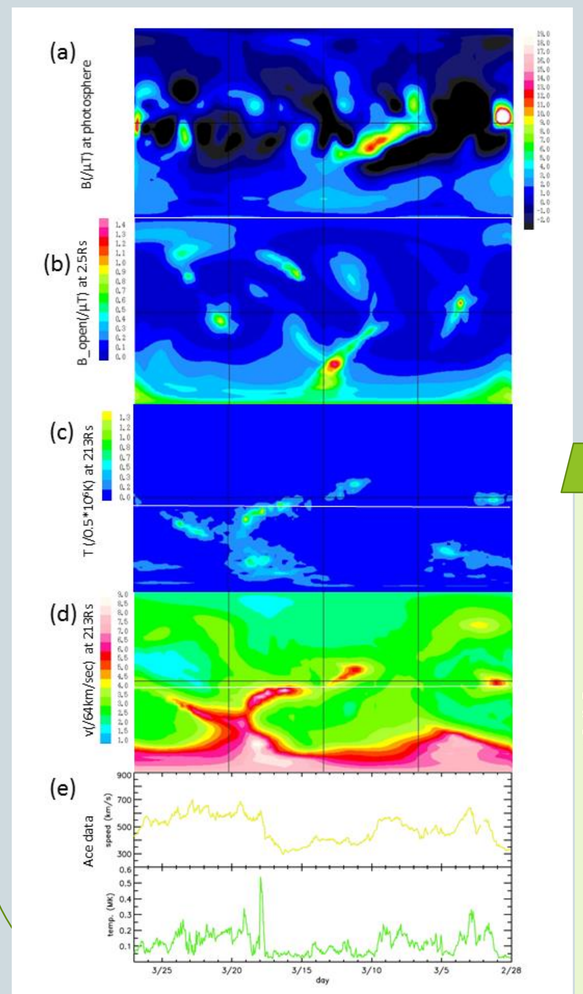
Solar wind structure (color contour) and interplanetary magnetic field (line)



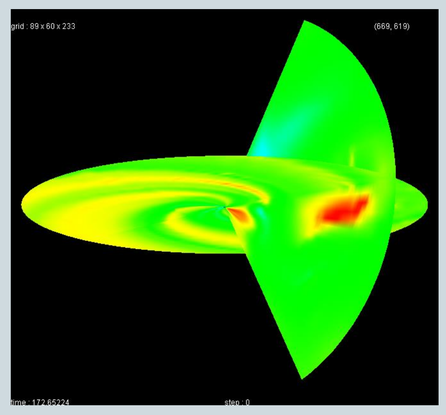
Solar wind structure in the wide region : 1 ～ 400 Rs (an equatorial plane)



Synoptic chart for CR2161 (2/28-3/26), when St. Patrick's event (3/17) occurred



Solar wind structure in the wide region : 1 ～ 400 Rs (a meridian and an equatorial plane)



Verification

- One of features is that the period for high-speed solar wind continued for about 6 days, comparatively long term and is thought to be one of cause of the long geomagnetosphere disturbance initiated as St. Patrick's Day event.
- That high-speed stream seemed to be ejected from the coronal hole (CH) on the southern solar surface and we can see that high-speed region in southern hemisphere starting on March 16 in Fig. (d).

(It is noted that simulation data on the white horizontal line indicating about 7 degree solar latitude in southern hemisphere in (c) and (d) should be compared with the observation data when taking account of the inclination of a plane of revolution.)

- Figure (c) showed that the high-speed region almost agreed with high temperature region, and this indicates that the origin of the stream was the CH.
  The corresponding region can be seen in Fig. (b), which is also consistent with the high-speed stream origin.
- Beginning of the high-speed stream is earlier about one day and that stream lasting period is shorter than the observation data.
  That difference might be due to the ambiguities in the acceleration model of the solar wind and to that our simulation does not include the effect of coronal mass ejections (CMEs) at current state.

Summary and Future work

- We developed the 3D MHD simulation model, REPPU code, for the solar surface and the global solar wind structure. Simulation can be **updated once a day** though our simulation region includes both near solar surface and the wide region beyond the earth orbit, 400 Rs.
- Simulation results including the period when St. Patrick event occurred were presented. Our code could identify that the source of the stream might be the CH in southern surface of the sun since our model could simulate from the solar surface.
- We are peparing for operation to forecast the solar wind condition.
- We will input CME models in order to model propagation of CME and predict the arrival time of shock wave associated with the CME.