HD and MHD modelling of the heliosphere

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September 13, 2011

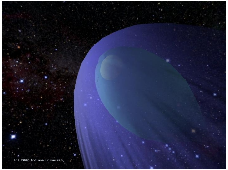


Figure: ...the geometry and flow inside our local astrosphere

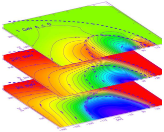


Figure: ... the transport of these particles

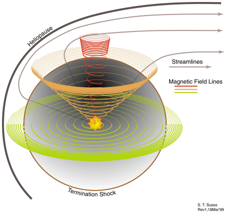
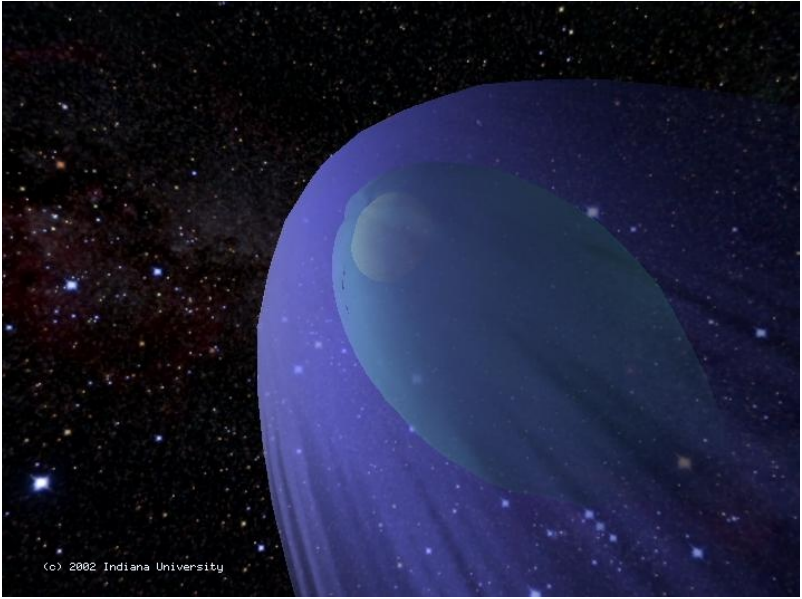


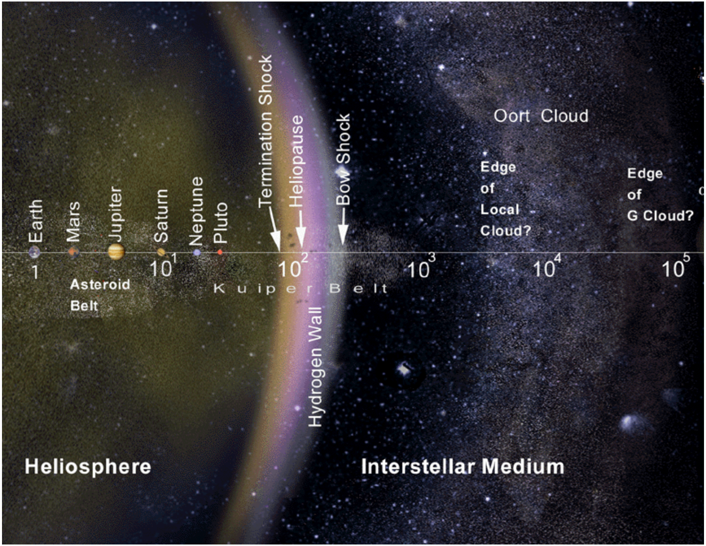
Figure: ....the magnetic field inside the heliosphere

Figure: ... influences life on Earth

Our local Astrosphere/Stellar Wind called the Heliosphere..

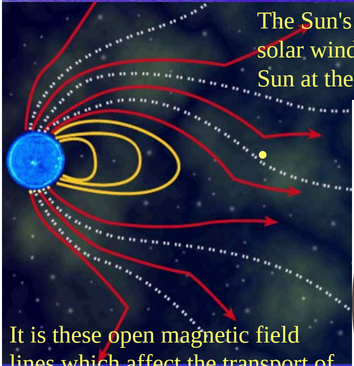


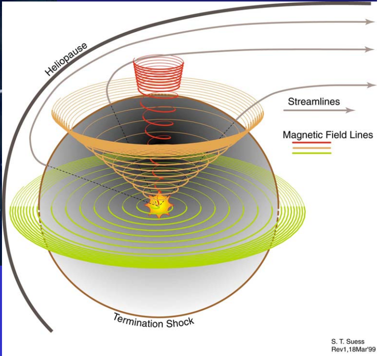
Our local Astrosphere/Stellar Wind called the Heliosphere..



The HMF and heliosphere

The Sun's magnetic field is transported with the solar wind into space and their connection to the Sun at the one end of the field line is lost.





It is these open magnetic field lines which affect the transport of CR's in the heliosphere forming the HMF.

The heliosphere can be modelled (hydrodynamically) by solving the :

Euler

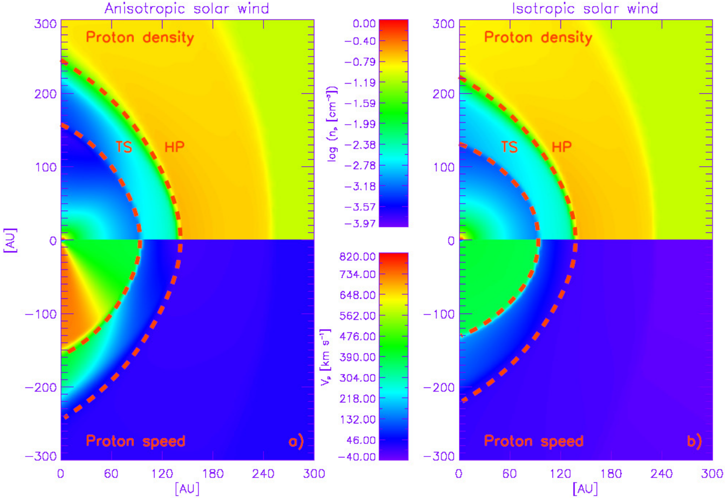
$$\frac{\partial}{\partial t}\rho_i + \nabla \cdot (\rho_i \vec{u}_i) = Q_{p,i}$$

$$\frac{\partial}{\partial t}(\rho_i \vec{u}_i) + \nabla \cdot (\rho_i \vec{u}_i \vec{u}_i + P_i \vec{I}) = Q_{m,i}$$

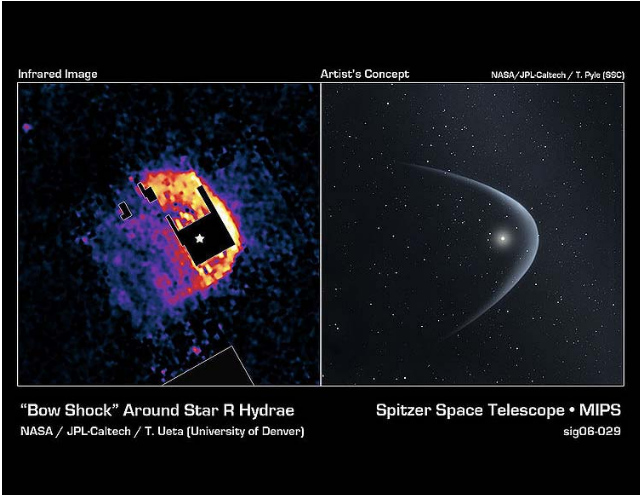
$$\frac{\partial}{\partial t}(\frac{\rho_i}{2}\vec{u}_i^{\,2} + \frac{P_i}{\gamma_i - 1}) + \nabla \cdot (\frac{\rho_i}{2}\vec{u}_i^{\,2}\vec{u}_i + \frac{\gamma_i \vec{u}_i P_i}{\gamma_i - 1}) = Q_{e,i}$$

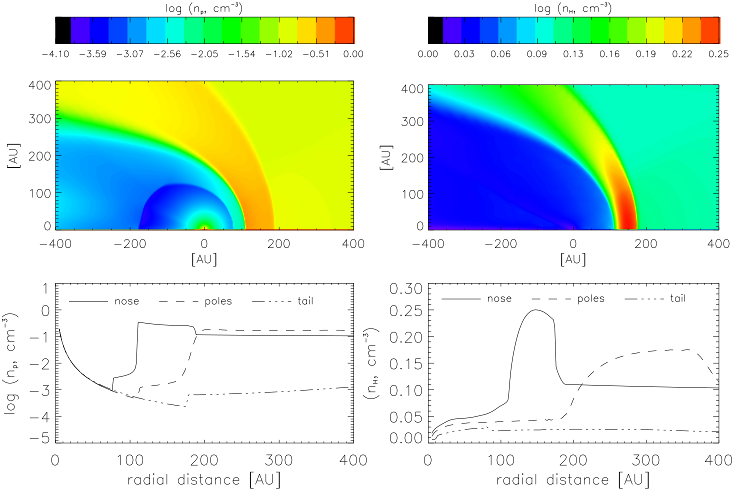
equation with mass density ρ_i, velocity $\vec{u}_i$, pressure P_i, γ_i the adiabatic indices and Q_i the sources related to the interaction between various species.

HD and MHD models



HD and MHD models

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log (n_H, cm^-3)
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nose
poles
tail
log (n_p, cm^-3)
(n_H, cm^-3)
radial distance [AU]
radial distance [AU]

The effect of neutrals...

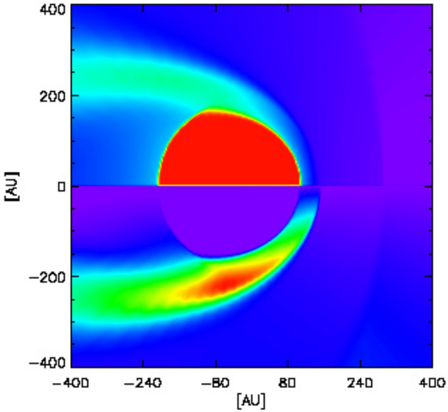


Figure: without neutral H

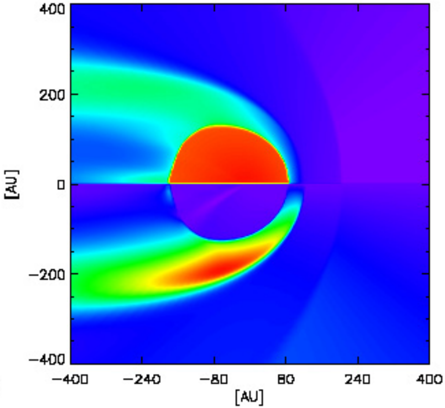
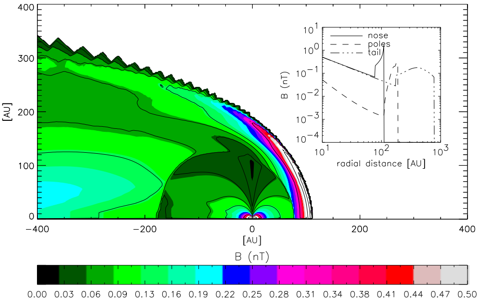


Figure: with neutral H

The magnetic field as a function of solar activity. To calculate this one can solve Faraday's law under the assumption of ideal MHD :

Faraday

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$



SOLAR WIND-LISM INTERACTION 539

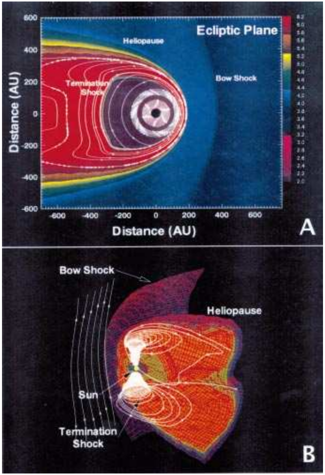
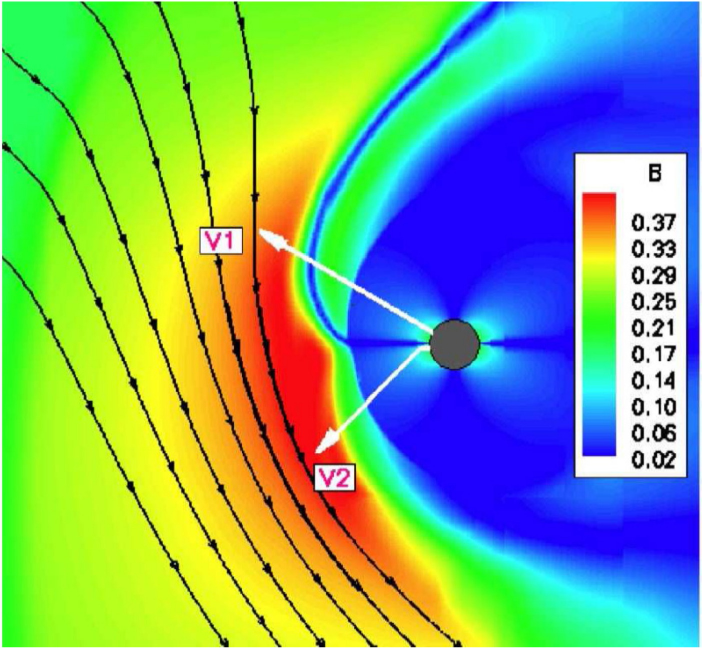


Plate 6.1. (a) Shown in white are the interplanetary Parker magnetic field lines in the ecliptic plane. The colour corresponds to the Log[plasma temperature (K)] as a function of distance. The model heliosphere corresponds to the 3D isotropic gas dynamic simulations of Pauls and Zank (1996). (b) A 3D depiction of the interplanetary and LISM magnetic field showing the characteristic 'tornado'-like structure of the IMF. Of note is the repeated crossing of the termination shock by the spiral magnetic field. (Pauls and Zank, unpublished.)


B
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0.29
0.25
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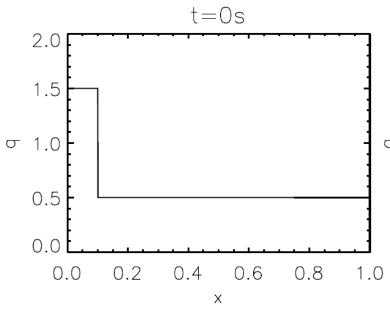
0.10
0.06
0.02
V1
V2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1.0
0.5
0.0
q
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0.2
0.4
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1.0
x
t=1s
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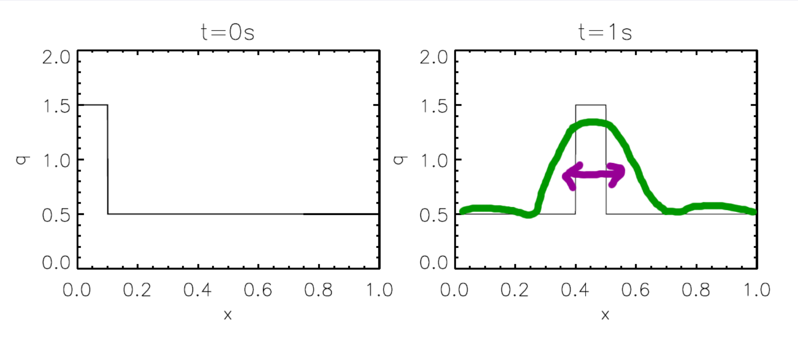
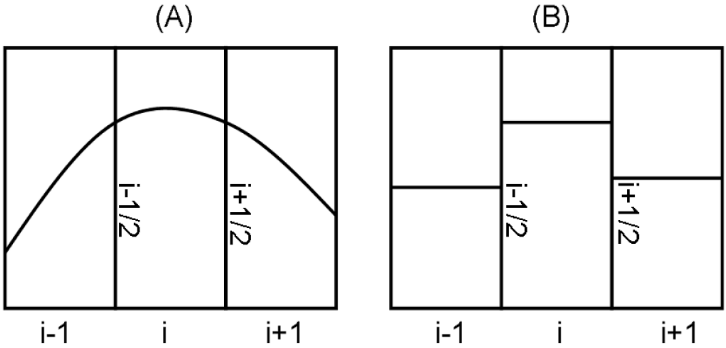


"...as sir Cyril Hinshelwood has observed.....fluid dynamicists were divided into hydraulic engineers who observed things that could not be explained, and mathematicians who explained things that could not be observed."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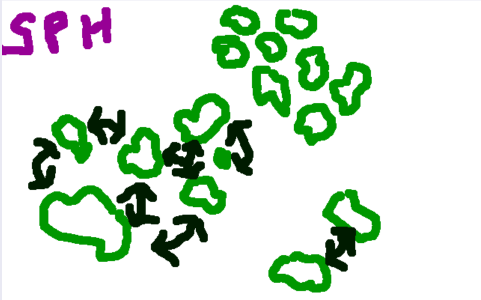
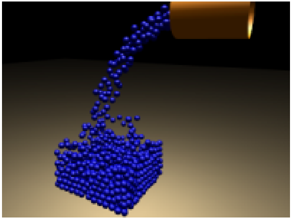
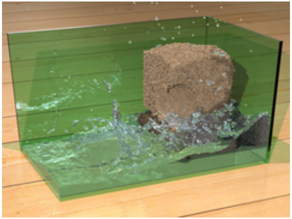


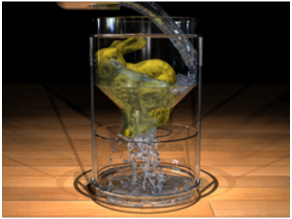
Movie: heliospheremovie

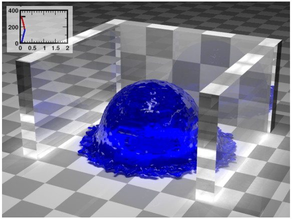
Movie: denmovie **Movie: mov**

Smooth Particle Hydrodynamics (SPH)









- Basic idea of SPH method (Lucy 1977; Gingold and Monaghan 1977) lies in representing the fluid elements by N_g particles. These act as interpolation centres to determine the value of any variable $f(\mathbf{r})$.
- In order to smooth out statistical fluctuations interpolation is performed with a smoothing (or kernel) function W. For example for some function f we can write

any function

$$\langle f(\mathbf{r})\rangle = \int f(\mathbf{r}')W(\mathbf{r}-\mathbf{r}', h)\mathbf{dr}' \tag{1}$$

$$\langle f(\mathbf{r})\rangle \approx \sum_{j=1}^{N} m_j \frac{f_j}{\rho_j} W(\mathbf{r}-\mathbf{r}', h) \tag{2}$$

with h the smoothing length e.g. the smoothing scale for the interpolating kernel W

e.g. with the most common (but not widely used), Gaussian kernel :

kernel

$$W(r,h) = \frac{1}{h\sqrt{\pi}} e^{-\frac{r^2}{h^2}} \tag{3}$$

- This kernel maybe more natural but has the disadvantage that the region of each SPH particle is infinite.
- Other kernel functions are availiable which have a very strictly defined outer edge. This property saves an enormous amount of computer time, with the sum reducing to only particles with distances less than h

Given that W is differentiable we can find the gradient of f as

gradient

$$\langle \nabla f(\mathbf{r}) \rangle \approx \sum_{j=1}^{N} m_j \frac{f_j}{\rho_j} \nabla W(\mathbf{r} - \mathbf{r}', h) \tag{4}$$

For example for density

density

$$\rho(\mathbf{r}_i) = \sum_{j=1}^{N} m_j W(r_{ij}, h_i, h_j) \tag{5}$$

- where $r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$, m_j is the mass of particle j and h_k is the smoothing length for particle k, which specifies the size of the averageing volume.
- Every particle's smoothing length h_k must be updated so that each particle has a constant number of neighbours. The smoothing length is then defined as

smoothing length

$$h_k = \frac{1}{2}|\mathbf{r}_k - \mathbf{r}_{kf}| \tag{6}$$

where $\mathbf{r}_{kf}$ is the position of particle k's most distant neighbor.

For the momentum equation we consider

momentum

$$D_t \mathbf{v}_i = -\left(\frac{\nabla P}{\rho}\right) \tag{7}$$

but we can write

$$\frac{\nabla P}{\rho} = \nabla\left(\frac{P}{\rho}\right) + \frac{P}{\rho^2}\nabla\rho \tag{8}$$

momentum

$$\frac{d\mathbf{v}_i}{dt} = -\sum_{j=1}^{N} m_j\left(\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2} + \prod_{ij}\right)\nabla_i W_{ij} \tag{9}$$

The artificial velocity between particles i and j (Monaghan abd Gingold (1983); Balsara (1995)):

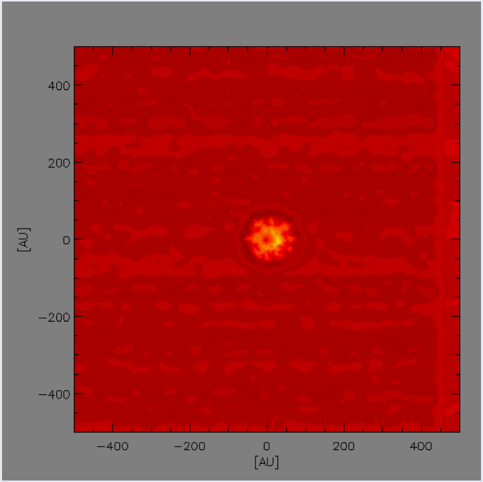
artificial viscosity

$$\prod_{ij} = \frac{\alpha v_{sig}\mu_{ij} + \beta\mu_{ij}^2}{\rho_{ij}^k} \tag{10}$$

if $\mathbf{v}_{ij}\cdot\mathbf{r}_{ij} < 0$ else 0 otherwise, and $\mathbf{v}_{ij} = \mathbf{v}_i - \mathbf{v}_j$ and $\rho_{ij}^k = \frac{1}{2}(\rho_i + \rho_j)$, with $\alpha = 1$ and $\beta = 2$ the artificial constants and μ_{ij} is defined as

$$\mu_{ij} = -\frac{\mathbf{v}_{ij}\cdot\mathbf{r}_{ij}}{h_{ij}^k}\frac{1}{r_{ij}^2/h_{ij}^2 + \eta^2} \tag{11}$$

with η=0.1 and $h_{ij} = \frac{1}{2}(h_i + h_b)$ and the signalvelocy $v_{sig} = \frac{1}{2}(c_a + c_b)$ the sound speed of particles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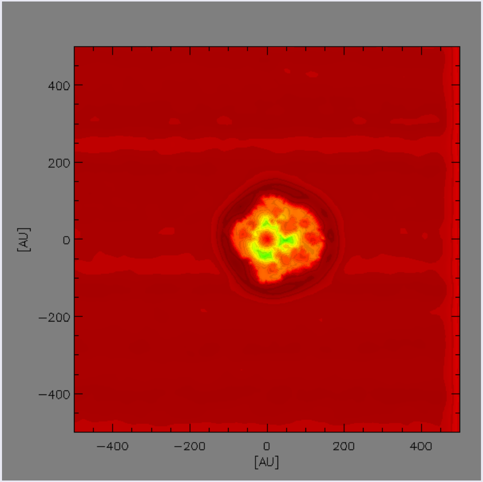
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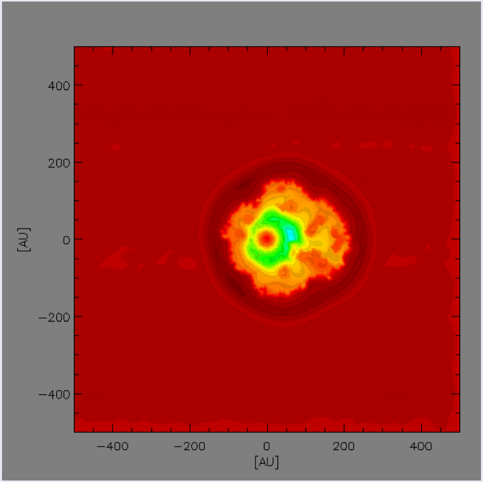
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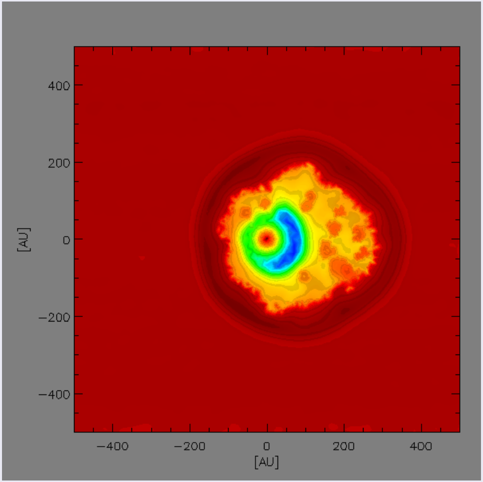
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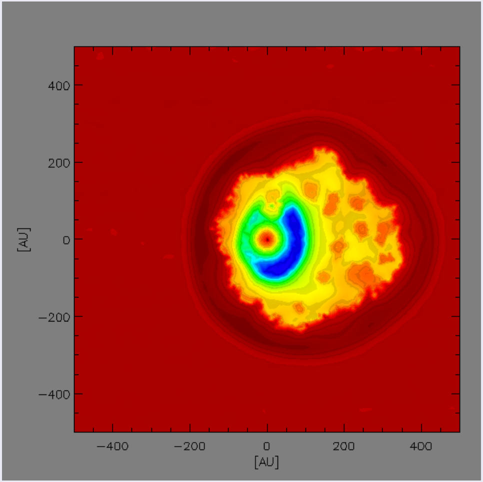
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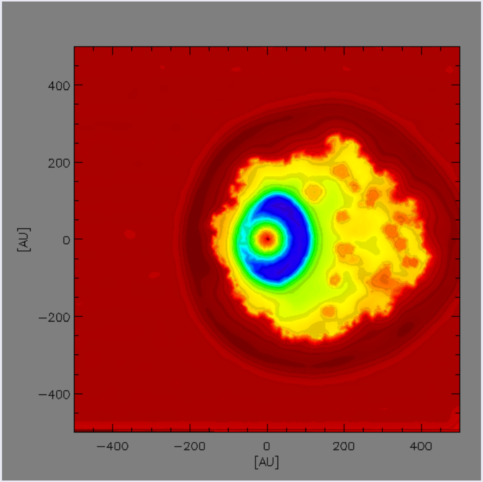
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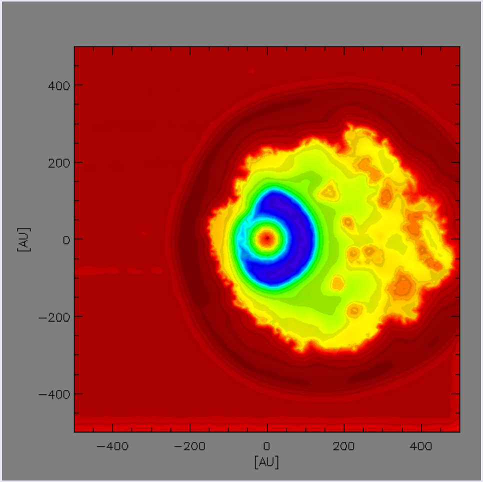
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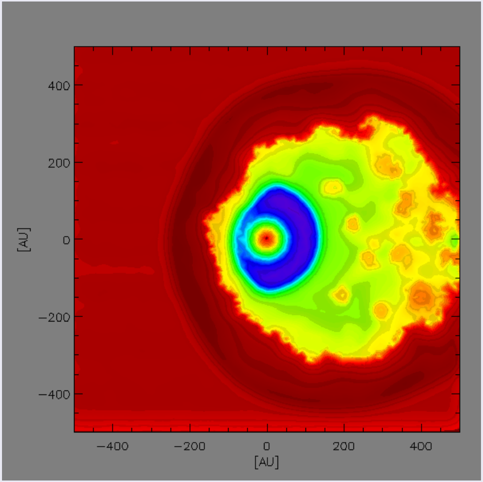
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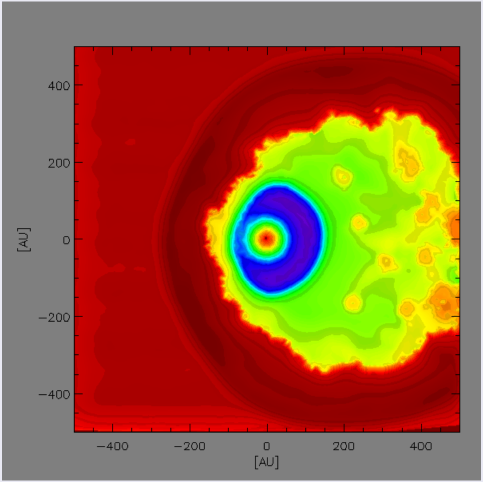
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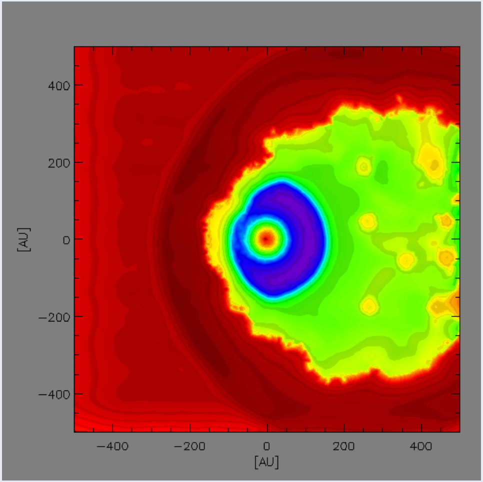

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Summary and Conclusions

HD and MHD models provide a good description of the background plasma and magnetic field of the heliospheric structure.

Output from these models can be used in cosmic ray transport models to calculate the cosmic ray distribution inside the heliosphere.

Next phase is to focus on details, e.g. Heliospheric Current Sheet beyond the termination shock, instabilities, turbulence, etc.