37 International Cosmic Ray Conference 2021

Numerical Study the Effects of Corotating Interaction Regions (CIRs) on cosmic proton, and helium Transport

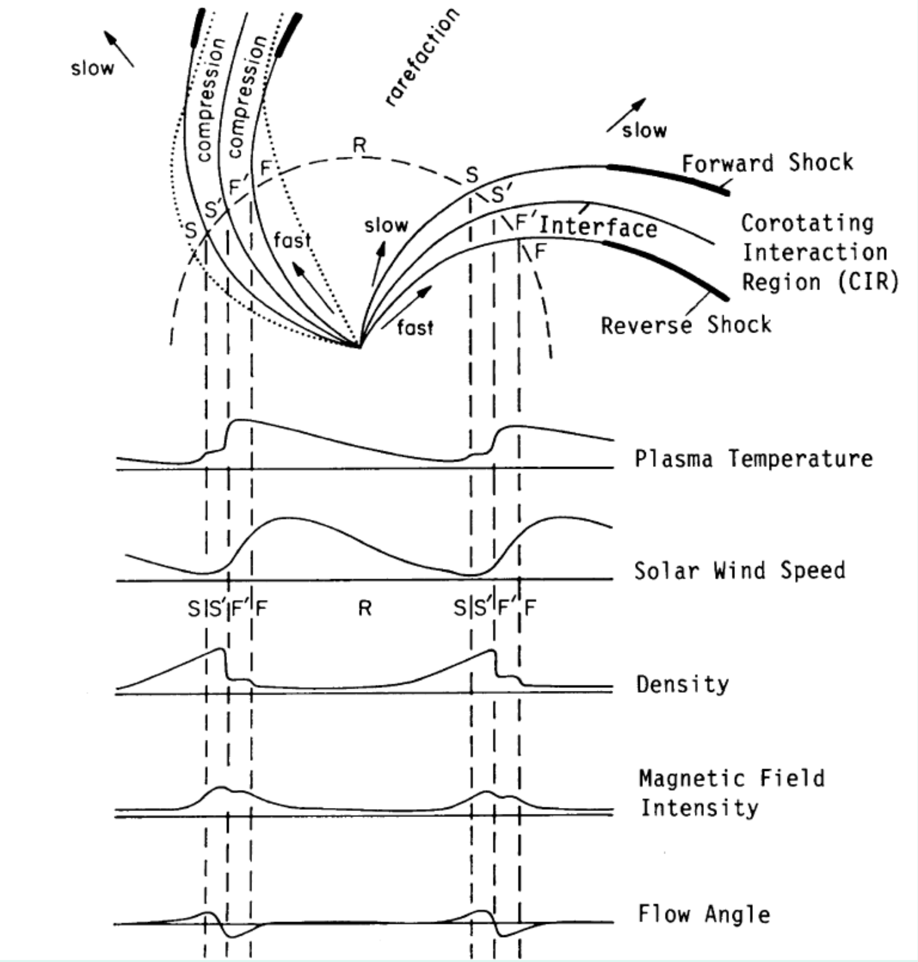
Xi Luo,[1] Marius Potgieter,[3] Xueshang Feng[2], Fang Shen[2] and Ming Zhang[4]

1. *Shandong Institute of Advanced Technology, Jinan, 250100 China*
2. *National Space Science Center, Chinese Academy of Science, China*
3. *Institute for Experimental and Applied Physics, CA University in Kiel, 24118 Kiel, Germany*
4. *Florida Institute of Technology, Melbourne, FL 32901, U.S.A*

Outline

- Background
- Numerical Model
- Simulation Results
- Summary

Motivation



Belcher and Davis (1971)

MHD simulation

$((V_r, V_\theta, V_\phi), (B_r, B_\theta, B_\phi), N, P)$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0$$

$$\frac{\partial \rho \boldsymbol{V}}{\partial t} + \nabla \cdot \left[\left(P + \frac{B^2}{2\mu_0} \right) \boldsymbol{I} + \rho \boldsymbol{V} \boldsymbol{V} - \frac{\boldsymbol{B}\boldsymbol{B}}{\mu_0} \right] = -\frac{\rho G M_s}{r^2} \frac{\boldsymbol{r}}{r} + \boldsymbol{V} \cdot \boldsymbol{f}$$

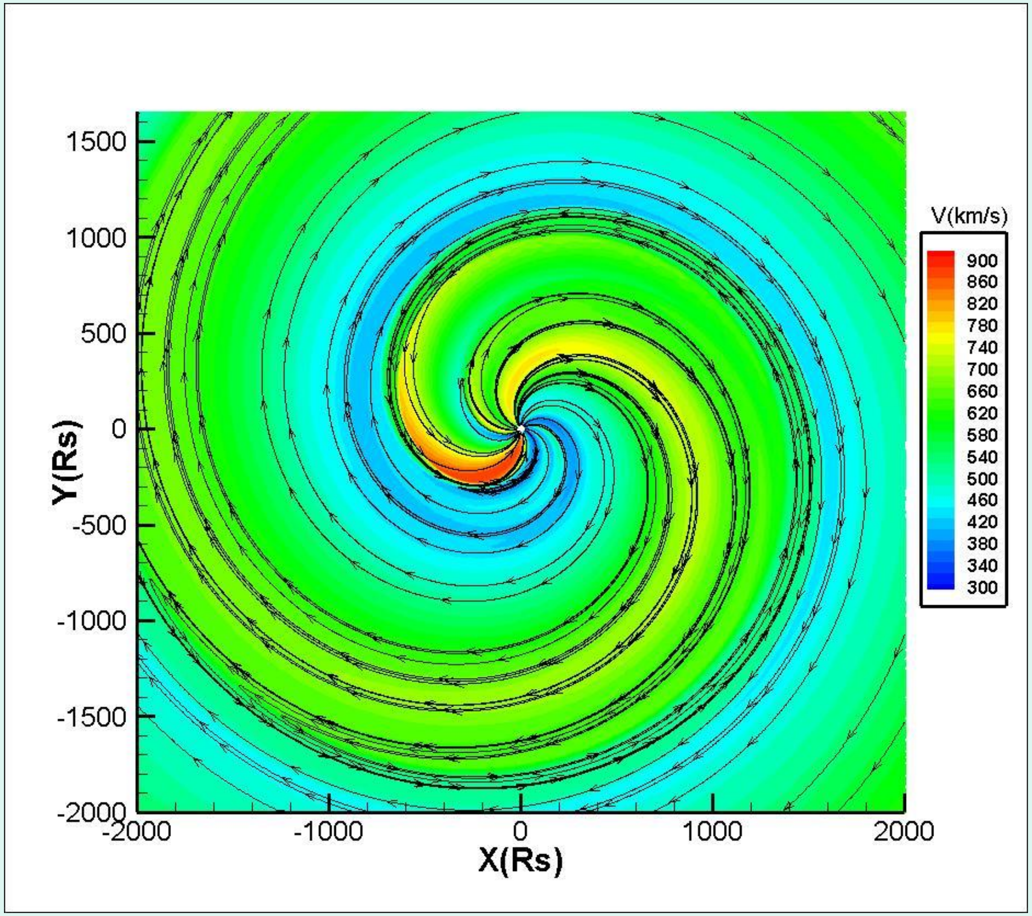
$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{V}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{V}) = 0$$

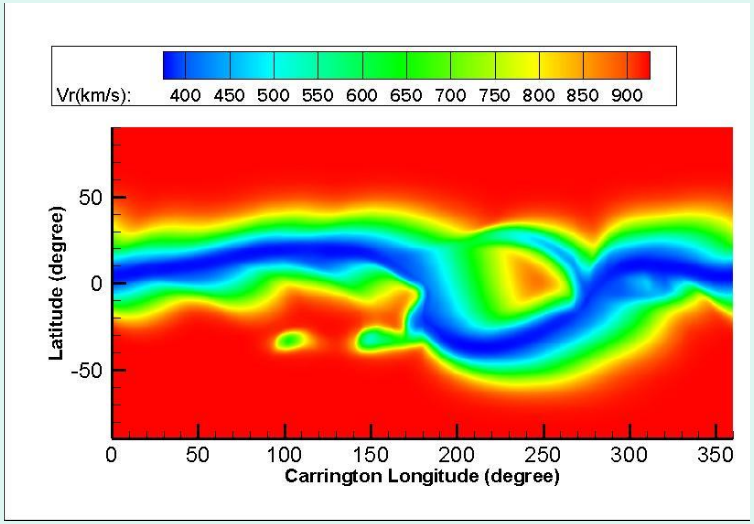
$$\frac{\partial P}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = -(\gamma - 1) P \nabla \cdot \boldsymbol{V}$$

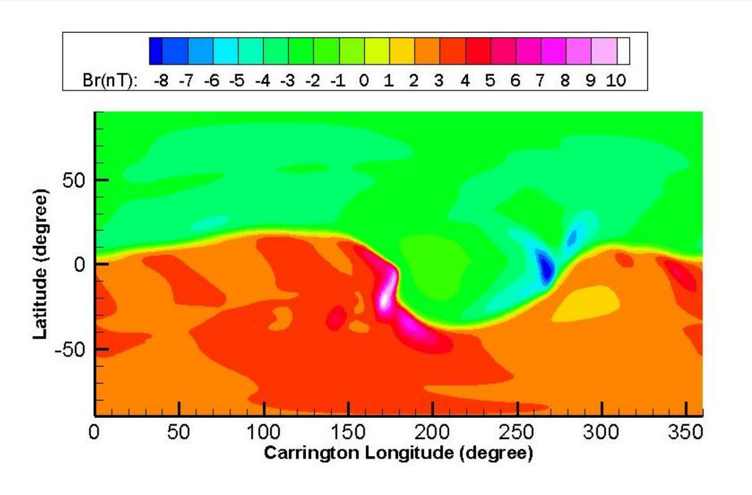
Expressed in the solar co-rotating frame.

MHD Simulation

Following two figures are the plasma parameters for 1 au.







Solve MHD equations to obtain plasma background for CR2066 (Jan. 2008).

(Shen et al. ApJ 2018)

CR transport plasma background

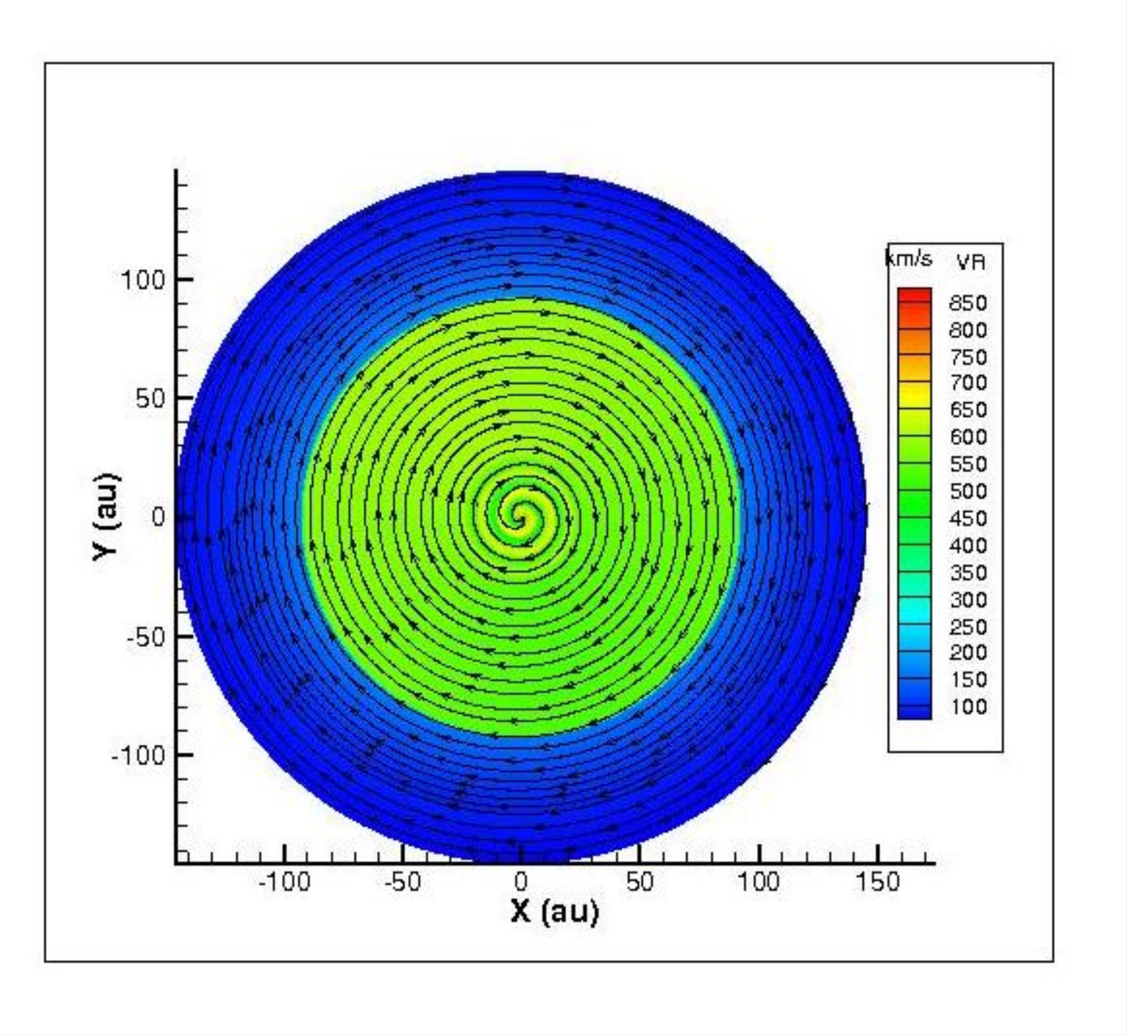
MHD simulation to 12 au; then use Parker HMF Model interpolated to 130 au.

$$b_r(r) = b_r(r_0)(\frac{r_0}{r})^2$$

$$b_\varphi(r) = b_\varphi(r_0)\frac{r_0}{r}$$

$$\varphi(r_0) = \varphi(r) - \frac{r - r_0}{v_{sw}}\Omega$$

The termination shock and heliopause have also been included in the simulation domain.



Combined MHD & CR transport model

The MHD simulation

$$\vec{B} \qquad \vec{V}_{sw}$$

Diffusion Tensor

$$\vec{\vec{\kappa}} = \kappa_{\perp}\vec{\vec{I}} + (\kappa_{\parallel} - \kappa_{\perp})\hat{b}\hat{b}$$

$$\kappa_{\parallel} = \left(\kappa_{\parallel}\right)_0 \beta\left(\frac{p}{1GeVc^{-1}}\right)^{0.5}\left(\frac{B_e}{B}\right)$$

$$\kappa_{\perp} = (\kappa_{\perp})_0 \beta\left(\frac{p}{1Gevc^{-1}}\right)^{0.5}\left(\frac{B_e}{B}\right)$$

Drift Speed

$$\vec{V}_d = \frac{pv}{3q}\vec{\nabla} \times \left(\frac{\vec{B}}{B^2}\right)$$

Solar Wind Speed

$$\vec{V}_{sw}$$

$$d\vec{\mathbf{x}} = \sqrt{2\vec{\vec{\kappa}}} \cdot d\vec{\mathbf{w}}(s) + (\nabla \cdot \vec{\vec{\kappa}} - \vec{\mathbf{V}}_{sw} - \vec{\mathbf{V}}_d)ds$$

$$dp = \tfrac{1}{3}\nabla \cdot \vec{\mathbf{V}}_{sw} p\, ds$$

Proton V.S. Helium Transport

β**:** $$\beta = \frac{R}{\sqrt[2]{(R)^2+(A/Z)^2mc^2}}$$

Proton: mc^2 = 0.938 GeV

Helium: mc^2 = 3.727 GeV

Different Beta Value for Same Rigidity

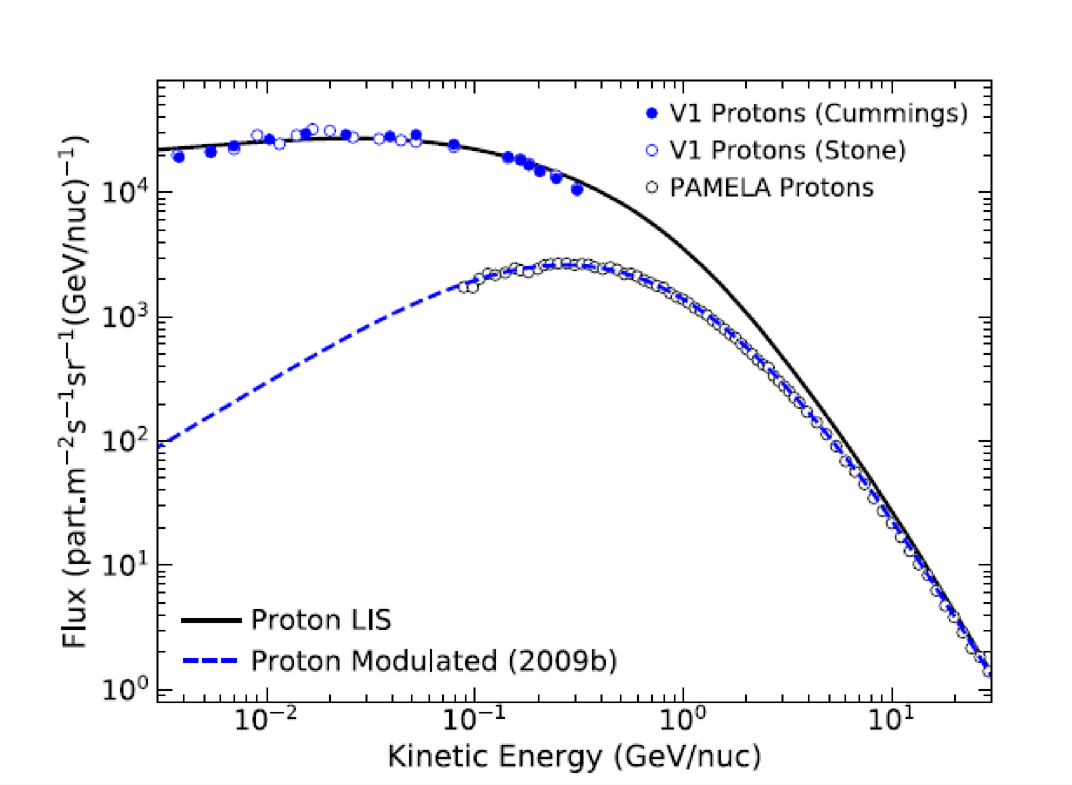
Diffusion coefficients:

$$\kappa = \kappa_0 \cdot \beta \cdot G(R) \ / \ \mathrm{B}$$

Proton: $q = e \ \ \mathrm{A} = 1$

Helium: $q = 2e \ A = 4 \ or \ 3$

Proton Local Interstellar Spectrum



$$J_{\mathrm{p}}(E) = 2620.0\,\frac{1}{\beta^2}\left(\frac{E}{E_0}\right)^{1.1}\left(\frac{(E/E_0)^{0.98}+0.7^{0.98}}{1+0.7^{0.98}}\right)^{-4.0} + 30.0\left(\frac{E}{E_0}\right)^{2}\left(\frac{E/E_0+8.0}{9.0}\right)^{-12.0},$$

D. Bisschoff et al. ApJ 2019

Helium Isotopes Local Interstellar Spectrum

$$J_{\mathrm{He}}(E) = 163.4\,\frac{1}{\beta^2}\left(\frac{E}{E_0}\right)^{1.1}\left(\frac{(E/E_0)^{0.97} + 0.58^{0.97}}{1 + 0.58^{0.97}}\right)^{-4.0}$$

D. Bisschoff et al. ApJ 2019

Unit of J(E) is $counts/(m^2 \cdot s \cdot sr \cdot \left(\frac{GeV}{nuc}\right))$, E is $\frac{GeV}{nuc}$

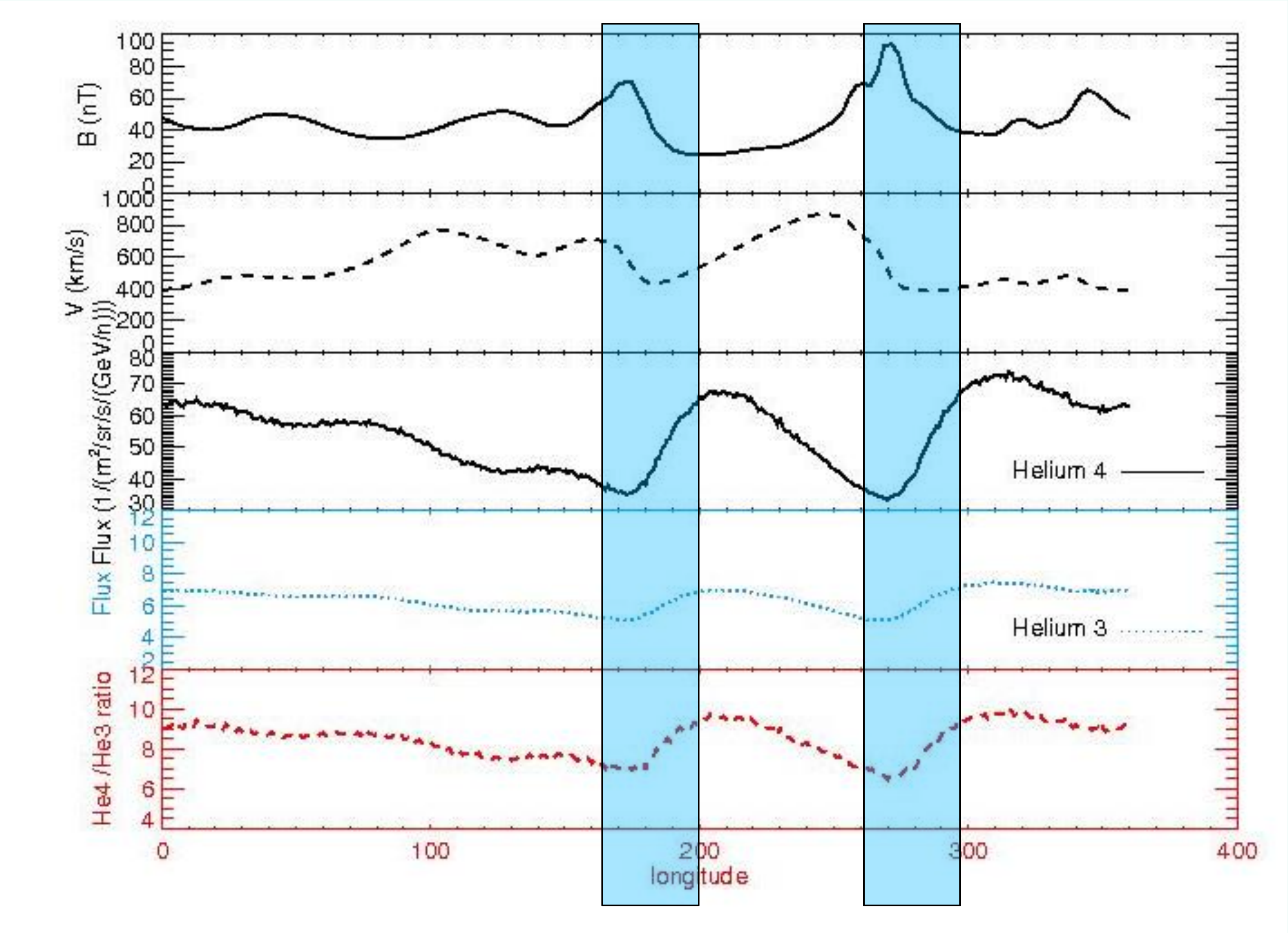
$For\ E < 1.41 GeV/nuc$

$$\frac{J_{He3}(E)}{J_{He4}(E)} = -0.0718 \times E^4 + 0.3518 \times E^3 - 0.666 \times E^2 + 0.6055 \times E^1 - 0.0012$$

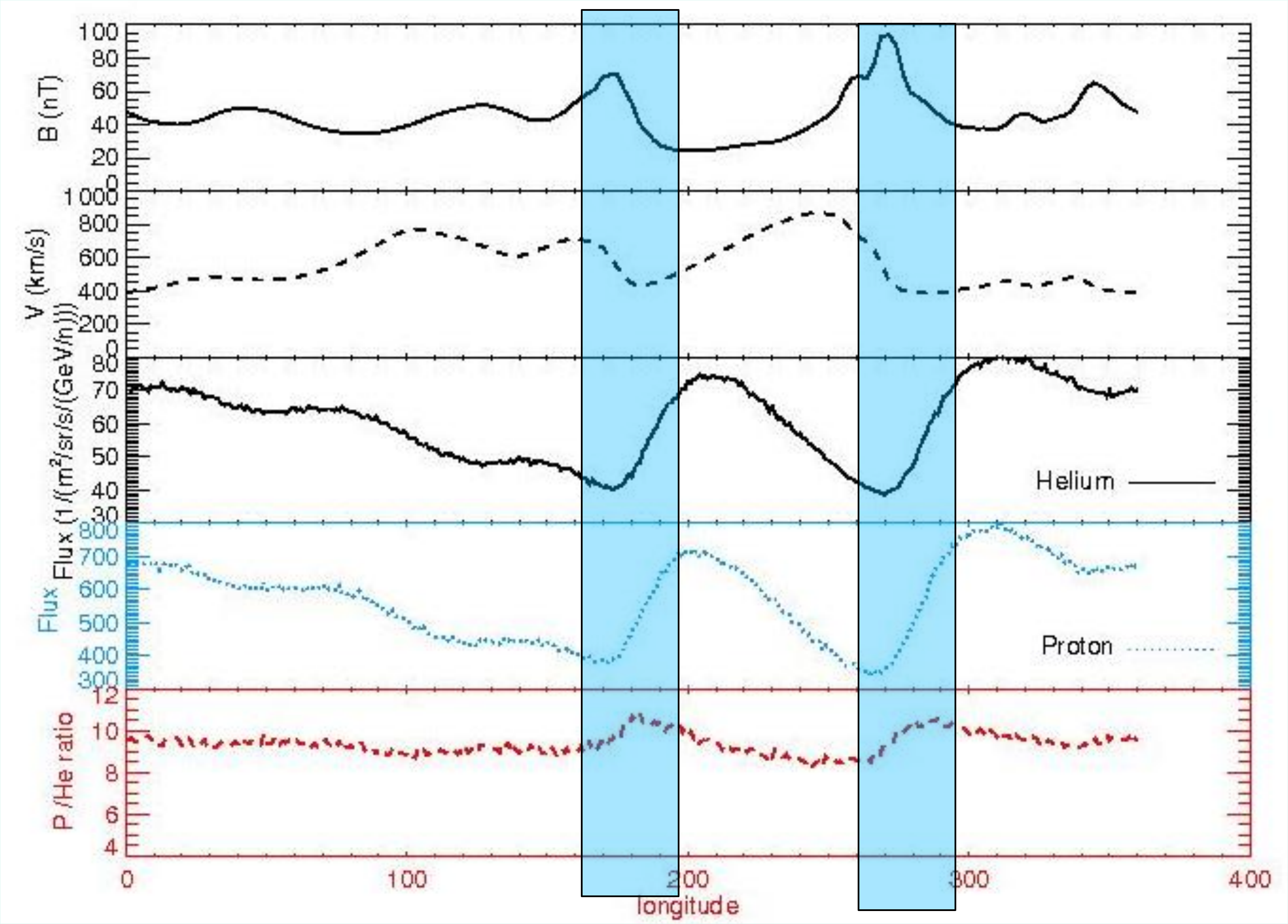
$For\ E \geq 1.41 GeV/nuc$

$$\frac{J_{He3}(E)}{J_{He4}(E)} = 0.00000002 \times E^4 - 0.000004 \times E^3 + 0.0003 \times E^2 - 0.0093 \times E^1 + 0.2412$$

Simulation Results
(0.3 GV Helium Isotopes longitude variation)

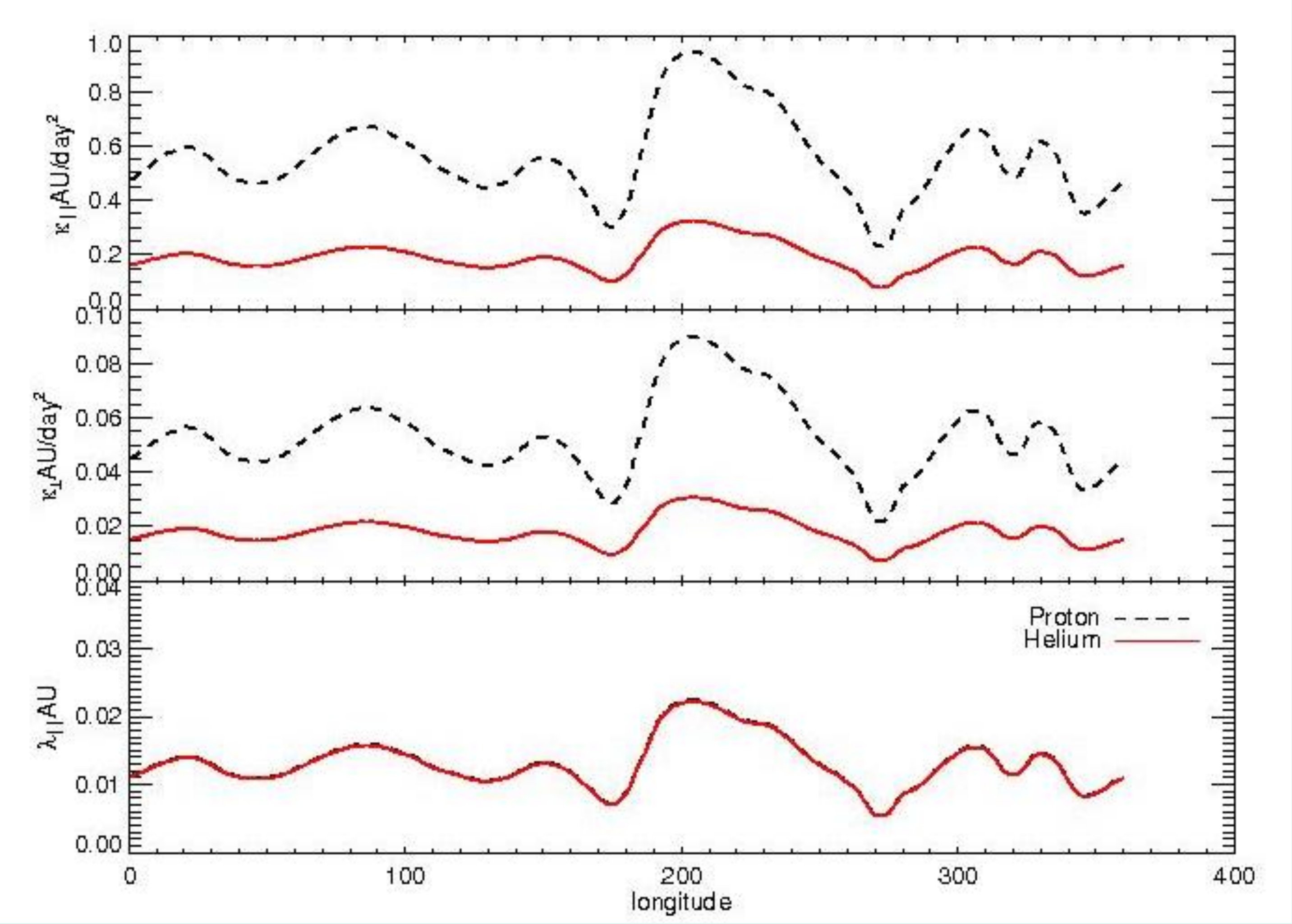


Simulation results
(0.3 GV Proton and Helium longitude variation)



Simulation results

(1 GV Proton, Helium 4 Mean Free Path Longitude Variation)



Black: Proton
Red : Helium 4

Conclusion & Summary

- Proton and two Helium isotopes studied at 0.3 GV are modulated by the CIR so that their flux levels are depressed inside the CIR;
- The manner in which the two helium isotopes responds to the presence of the CIR is different as a function of longitude; similar to proton and total helium;
- The flux ratio at 0.3 GV of He-4 to He-3 and proton to total helium vary inside the CIR;
- Possible reason is that their LIS forms and mass charge ratio are different.

Thank You!