Deviations in Peak Longitude of the Pickup Helium Focusing Cone Due to Transport Effects

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EMMREM

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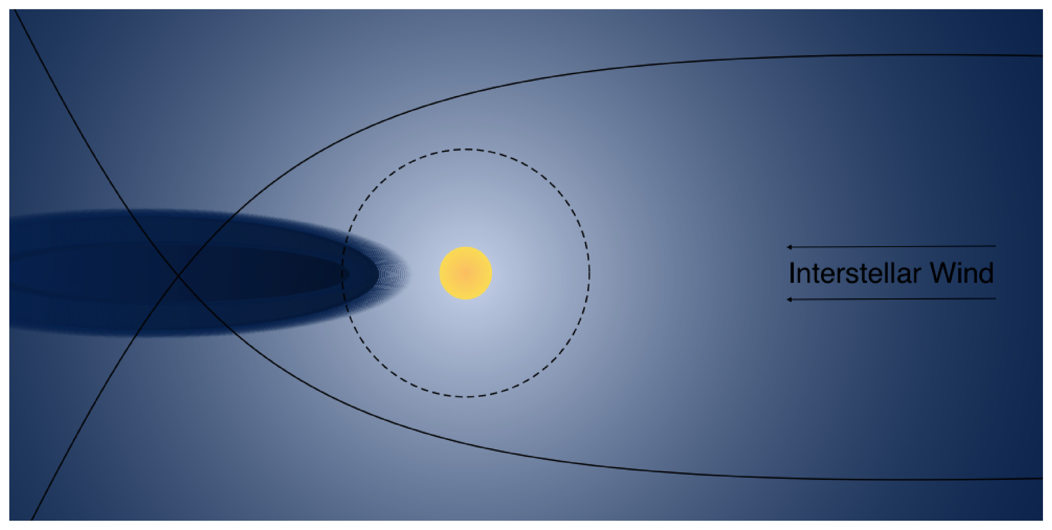
Motivation



Observations of the pickup helium focusing cone provide insight of the inflow direction of the interstellar wind by using the peak of the cone as an indicator. However the peak can shift due to the transport effects of the pickup ions. Recent observations measure the inflow longitude to be $77.4° \pm 1.9°$ from 1AU by STEREO/PLASTIC [Drews et al. 2012], $76.0° \pm 6.0°$ and $77.0° \pm 1.5°$ by MESSENGER/FIPS at 0.3AU and ACE/SWICS at 1.0AU, respectively [Gershman 2013]. In addition, IBEX – which detects neutral atoms directly – currently observes the inflow longitude at $74.5° \pm 1.7°$ [Leonard et al. 2015]. The aim of this study is to break down the different transport effects and see their individual contributions to the shift of the peak longitude. Under the conditions of recent studies, we hope to demonstrate that including transport effects may make the observations agree better with IBEX results.

Hot Gas Model

The hot gas model [Wu & Judge 1979] is used to obtain the density of neutral helium gas at any location within the heliosphere as it calculates the density of the interstellar neutral atoms as they penetrate the heliosphere and travel along hyberbolic trajectories due to solar gravitation and solar radiation pressure. The hot gas model is more accurate than the cold gas model since it takes the thermal velocities of the gas into account.

$$F = \frac{N_0}{\pi^{3/2} V_t^3} \exp\left[F_1 + F_2 \sin(\psi)\right]$$

where

$$F_1 = -\frac{V_b^2 + V_0^2 + 2V_b V_0 \cos\theta}{V_t^2} + \frac{2V_b V_0 \cos\theta}{V_t^2} \frac{(V_0 - V_r)^2}{V_r (V_0 - V_r) + Q^2} - \frac{\beta r_E^2 \theta'}{r V_\rho}$$

$$F_2 = \frac{2V_b V_0 V_\rho \sin\theta}{V_t^2} \frac{V_0 - V_r}{V_r (V_0 - V_r) + Q^2}$$

and

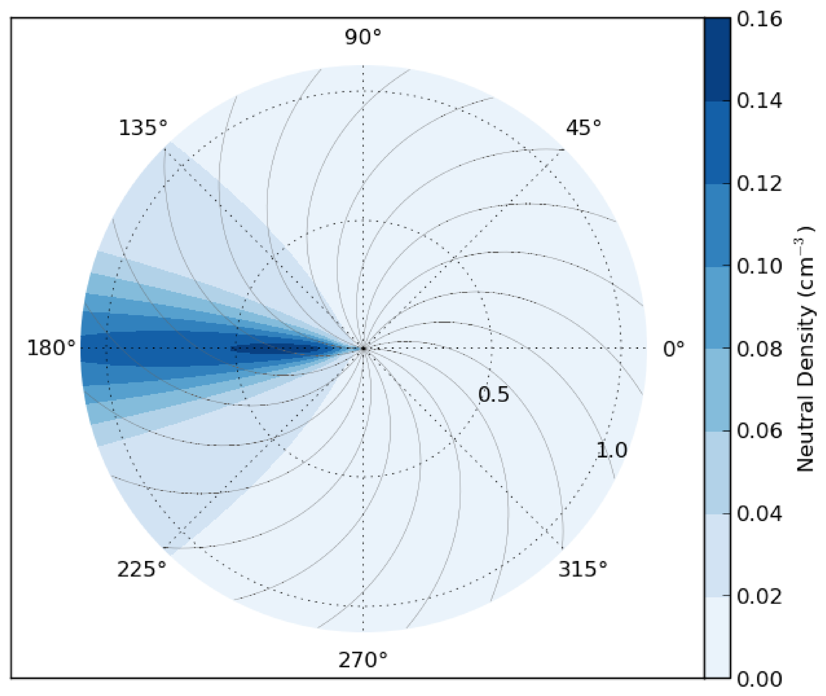
$$Q^2 = \frac{(1-\eta) GM}{r}$$
$$V_0 = \left(V_r^2 + V_\rho^2 - 2Q^2\right)^{1/2}.$$

To obtain the neutral density of atoms, the Maxwellian above is integrated.

$$N(r) = \frac{N_0}{\pi^{3/2} V_t^3} \int \left[\int_{V_{\rho_0}}^{\infty} \exp[F_1] V_\rho dV_\rho \int_0^{2\pi} \exp[F_2 \sin\psi] d\psi\right] dV_r$$

where

$$V_{\rho_0} = \begin{cases} \left(2Q^2 - V_r^2\right)^{1/2} & \text{if } V_r^2 < 2Q^2 \\ 0 & \text{otherwise.} \end{cases}$$



The above equation is solved numerically and sets up a map of neutral helium atoms for use by EPREM. The interstellar parameters used are according to [Witte et al. 2004]. The photoionization rate used is found in [Gershman et al. 2013]. The effects of electron impact have been ignored.

Parameter	Value
v_0	26.3 km s^{-1}
n_0	0.015 cm^{-3}
T_0	6300 K
β_{ph}	5.0×10^{-8} s^{-1}

The neutral cone is compared to the pickup cone by the general version of the isotropic distribution function derived by [Vasyliunas & Siscoe 1976] of the form

$$f(R,w) = \left[\frac{3}{4\pi\gamma v_{SW} v_{max}^3}\right] n(r = Rw^{3/\gamma}) \left[\frac{\beta_{ph} w^{-3/2}}{R}\right].$$

Here, R is the radial distance from the sun, $v_{max} = v_{SW} - v_{neutral}$, γ is the expansion factor and equals 2 for radial expansion, and n is the neutral density given by the hot gas model at a distance $r = Rw^{3/\gamma}$.

EPREM

The Energetic Particle Radiation Environment Module (EPREM) [Schwadron et al. 2010] is a sophisticated, three-dimensional, time-dependent numerical model of the transport of energetic particles within the heliosphere. The focused transport equation of the form [Kóta 2005] is solved along each magnetic field line and is of the form

$$\begin{aligned}
&\left(1 - \frac{\mathbf{V}\cdot\hat{\mathbf{e}}_b v\mu}{c^2}\right)\frac{df}{dt} && \text{(streaming)}\\
&+ v\mu\hat{\mathbf{e}}_b \cdot \nabla f && \text{(convection)}\\
&+ \frac{1-\mu^2}{2}\left[v\hat{\mathbf{e}}_b\cdot\nabla\ln B - \frac{2}{v}\hat{\mathbf{e}}_b\cdot\frac{d\mathbf{V}}{dt} + \mu\frac{d\ln\left(n^2/B^3\right)}{dt}\right]\frac{\partial f}{\partial\mu} && \text{(adiabatic focusing)}\\
&+ \left[-\frac{\mu\hat{\mathbf{e}}_b}{v}\cdot\frac{d\mathbf{V}}{dt} + \mu^2\frac{d\ln(n/B)}{dt} + \frac{1-\mu^2}{2}\frac{d\ln B}{dt}\right]\frac{\partial f}{\partial\ln p} && \text{(adiabatic change)}\\
&= \frac{\partial}{\partial\mu}\left(\frac{D_{\mu\mu}}{2}\frac{\partial f}{\partial\mu}\right) && \text{(pitch-angle scattering)}\\
&- \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f_0}{\partial p}\right) && \text{(stochastic acceleration)}\\
&+ Q. && \text{(particle source)}
\end{aligned}$$

where the pitch angle diffusion coefficient is given by

$$D_{\mu\mu} = \frac{\left(1-\mu^2\right)v}{2\lambda_\parallel}$$

and $\lambda_\parallel$ is the parallel mean free path which is of the form [Li et al. 2003]

$$\lambda_\parallel = \lambda_0 \left(\frac{pc}{1\text{Gev}}\right)^{1/3}\left(\frac{r}{1\text{AU}}\right)^{2/3}.$$

STEREO/PLASTIC

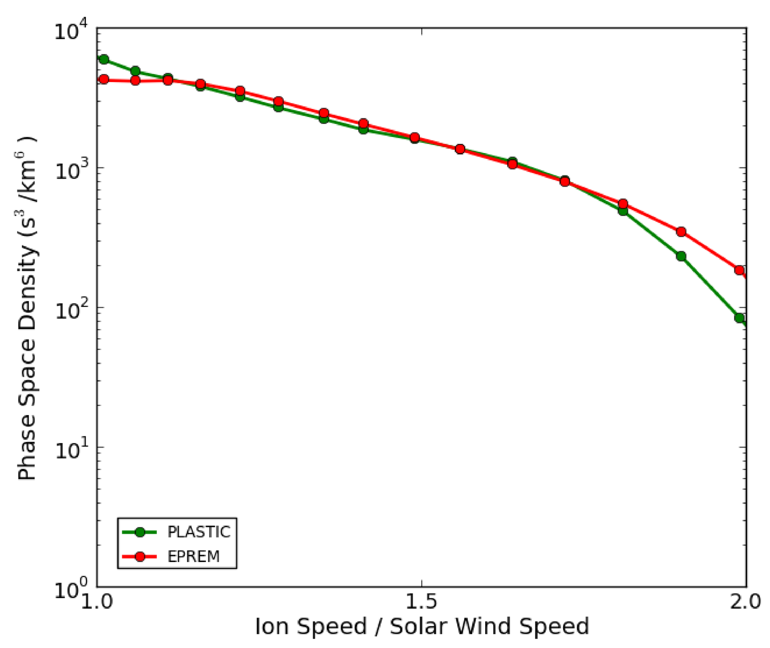
The Plasma and Suprathermal Ion Composition (PLASTIC) [Galvin 2008] instrument onboard the Solar Terrestrial Relations Observatory Ahead (STEREO A) spacecraft is a time-of-flight mass spectrometer with a stepped E/q analyzer to determine the mass, charge, and energy of ions. In this work, the Main Channel (MC) of the Solar Wind Sector (SWS) of PLASTIC is used to detect helium pickup ions. STEREO A resides at about 0.97 AU and orbits the sun with the SWS of PLASTIC facing radially inward at all times. The SWS has 32 linearly spaced angular bins between 22.5° in the ecliptic plane and 32 linearly spaced angular bins between 20.0° out of the ecliptic plane. There are also 128 logrithmically spaced energy bins ranging from ~0.3 keV/e to ~80.0 keV/e.

For each angular bin and energy bin, a transformation is done from the spacecraft frame to the solar wind frame then averaged over all angular bins.

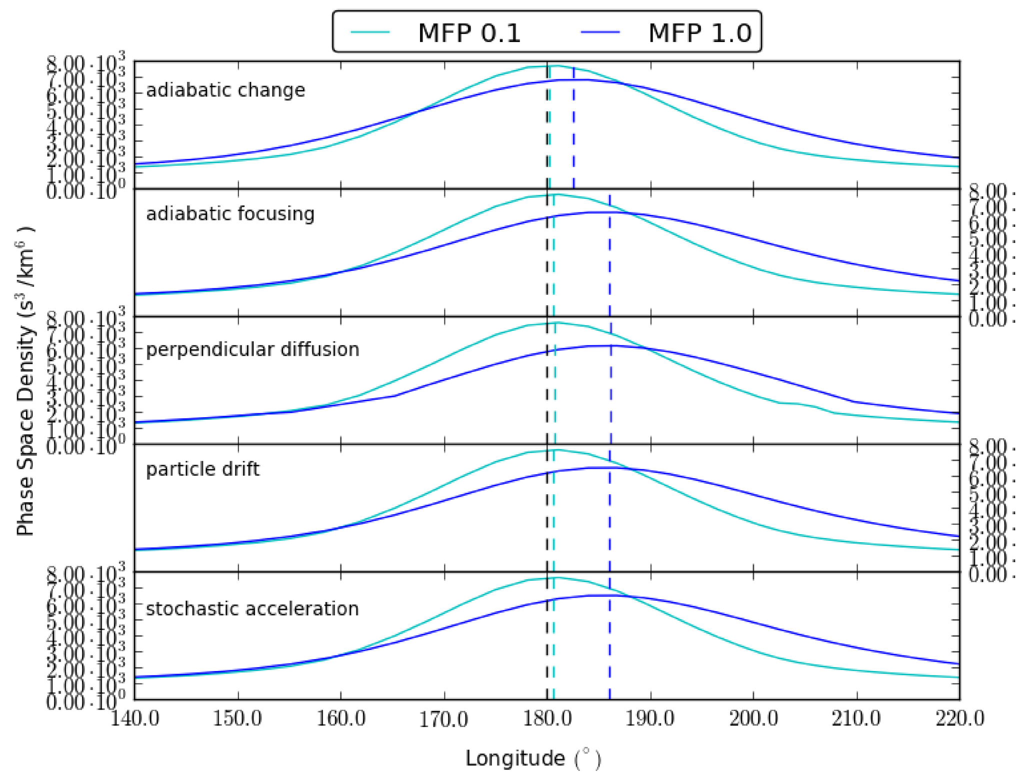
$$v_{SW} = \sqrt{v_{SC}^2 + u^2 - 2uv_{SC}\cos\alpha\cos\beta}$$
$$\mu = \frac{1}{v_{SW}}\left[v_{SC}\cos\psi\cos\beta\cos\alpha + v_{SC}\sin\psi\cos\beta\sin\alpha - u\cos\psi\right]$$

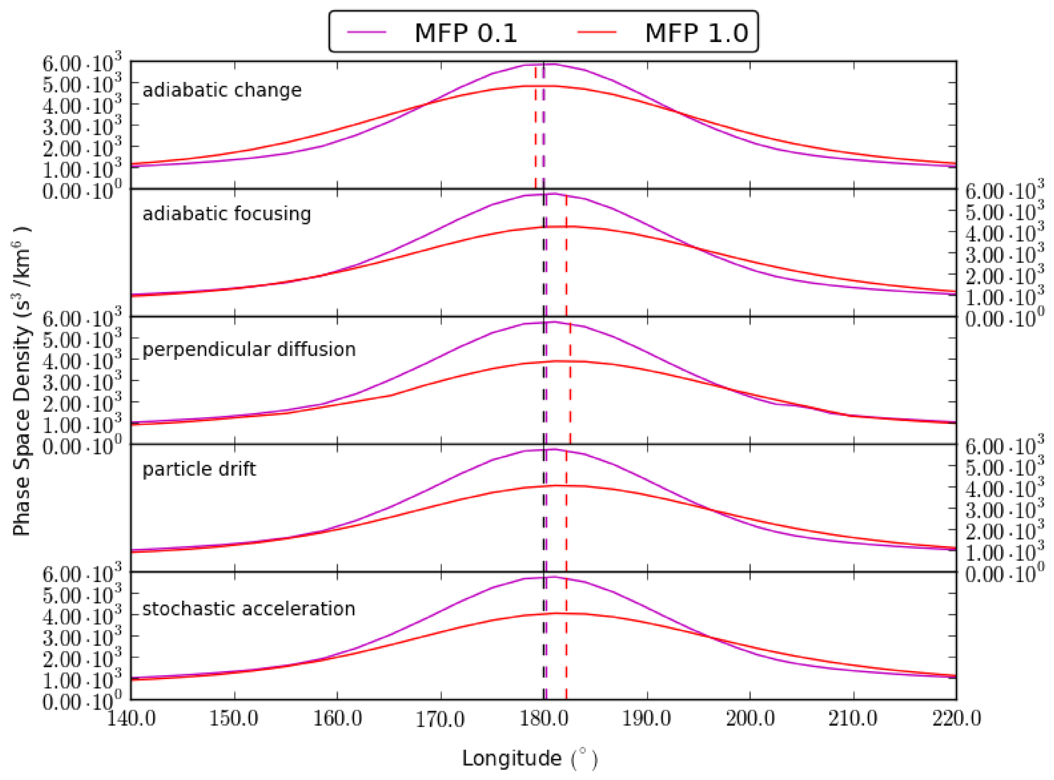
where u is the solar wind speed and ψ is the angle between the radial direction and the magnetic field vector.

Hourly averaged helium pickup ions observations from PLASTIC within the first three orbits were used – dating from March 2007 to February 2010 – for the energy range of $1.5 < w < 2.0$ where w is the ratio of ion speed to solar wind speed. The average solar wind speed for this time range was approximately 406 km/s.



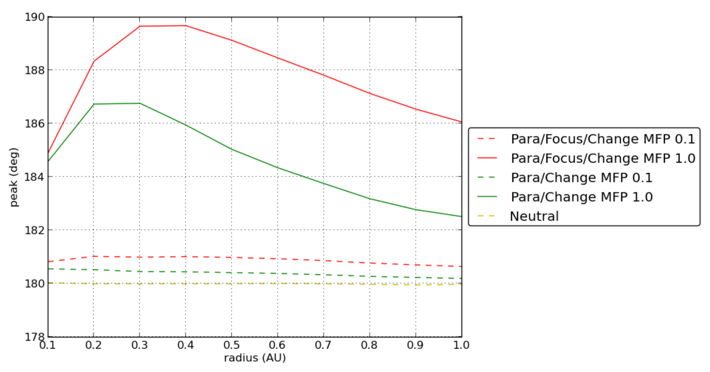
Results

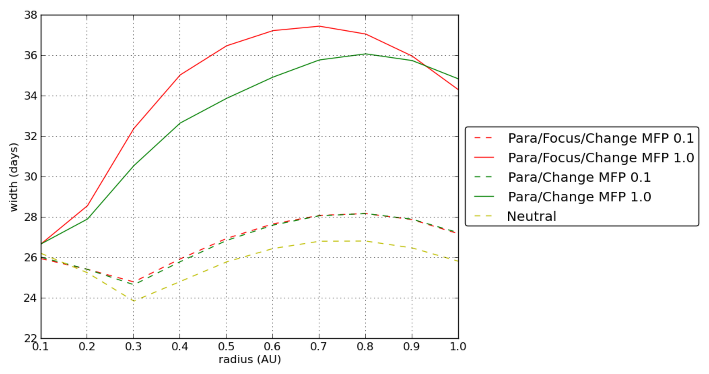


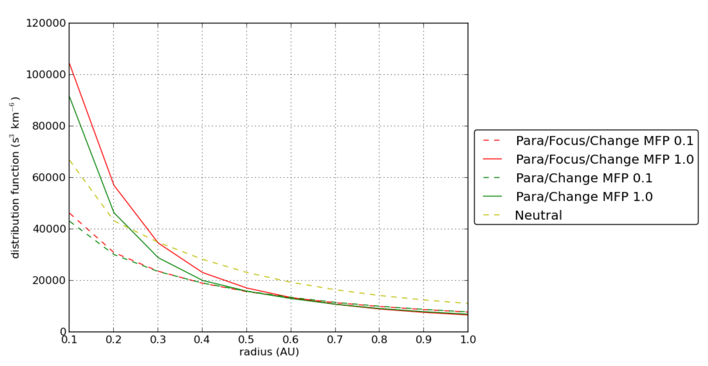


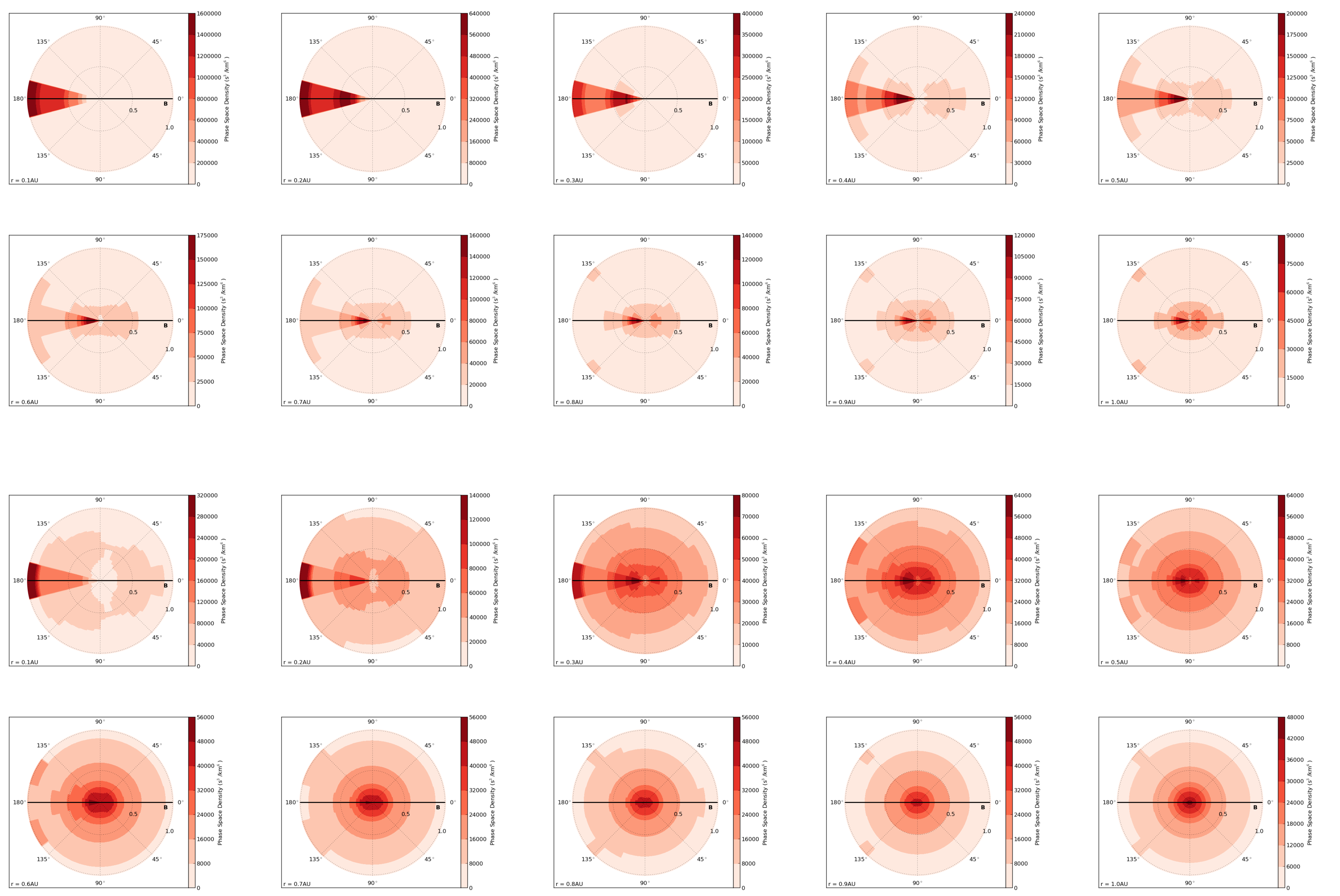
Transport Effects	Peak Longitude Shift (°) MFP 0.1 AU	MFP 1.0 AU
Para Diff	-	-
Para Diff, Ad Ch	0.22	2.54
Para Diff, Ad Ch, Ad Focus	0.67	6.09
Para Diff, Ad Ch, Ad Focus, Perp Diff	0.73	6.23
Para Diff, Ad Ch, Ad Focus, Particle Drift	0.67	6.09
Para Diff, Ad Ch, Ad Focus, Stoch Acc	0.67	6.09

Transport Effects	Peak Longitude Shift (°) MFP 0.1 AU	MFP 1.0 AU
Para Diff	-	-
Para Diff, Ad Ch	-0.06	-0.72
Para Diff, Ad Ch, Ad Focus	0.29	2.16
Para Diff, Ad Ch, Ad Focus, Perp Diff	0.34	2.58
Para Diff, Ad Ch, Ad Focus, Particle Drift	0.29	2.16
Para Diff, Ad Ch, Ad Focus, Stoch Acc	0.29	2.16









Future Work

To complete this current study, we plan to further investigate the radial dependence of the shift of the peak longitude and the impact it may make on observations. A comparison will be made to works done using STEREO/PLASTIC, specifically [Drews et al. 2012].

In this work, the solar wind conditions were neglected by taking the average values for the time range under concern. For a future project, we plan on considering how the peak longitude of the pickup helium focusing cone shifts under certain solar wind conditions such as varying solar wind speed and regions such as the compression and rarefaction regions of CIRs.

References

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