Turbulence properties from brightness observations

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(1) Introduction

PUNCH will image macroscopic features of the inner heliosphere and also admit sufficiently high spatial resolution to probe scales of turbulence within the upper end of the inertial range, close to the integral scale. Because PUNCH is an imager, the measurements it will make relate differently to the underlying turbulent environment of the outer corona and inner heliosphere than do more familiar in-situ samples. We have previously observed (Pecora et al. 2024) using magnetohydrodynamic (MHD) turbulence simulations and synthesis of white-light data via the FORWARD code that the ``usual'' turbulence scalings are modified by the integration along the line of sight. Here, we present a preparatory study using Parker Solar Probe (PSP) WISPR data, to investigate the scaling of density power spectra in preparation for PUNCH observations.

(2) Previous results

We populate a cube which has sides of length 180 $R_\odot$ with multiple replicas of the simulation, tuning the simulation's spatial resolution to match PUNCH's requirements. The "extended" density field is processed using FORWARD modeling tool (Gibson et al. 2016) to create brightness maps similar to those provided by PUNCH. A radial falloff for the density to decrease as R^{-2} is included.

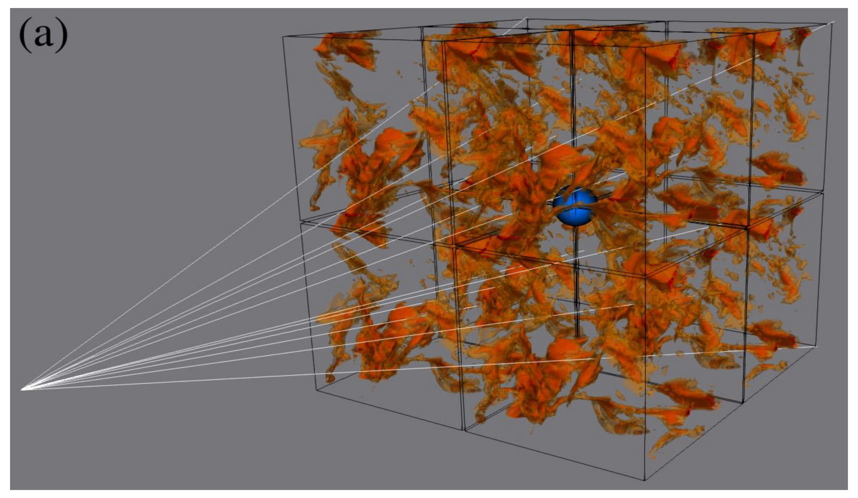

Fig. 1. Example of "Rubik's heliosphere". The Sun is the blue sphere in the center. Each cube is a replica of the cube in Fig. 1. Orange sheets represent regions of the highest density. White lines are LOS (line of sight) integration lines similar to PUNCH's.

To extract similar turbulence properties from the simulation and observations we
(i) average the simulation domain along one direction to mimic the integration along the field of view (FOV),
(ii) detrend PUNCH images to remove the radial falloff of the brightness caused by the Thomson scattering and the radial behavior of the density field.

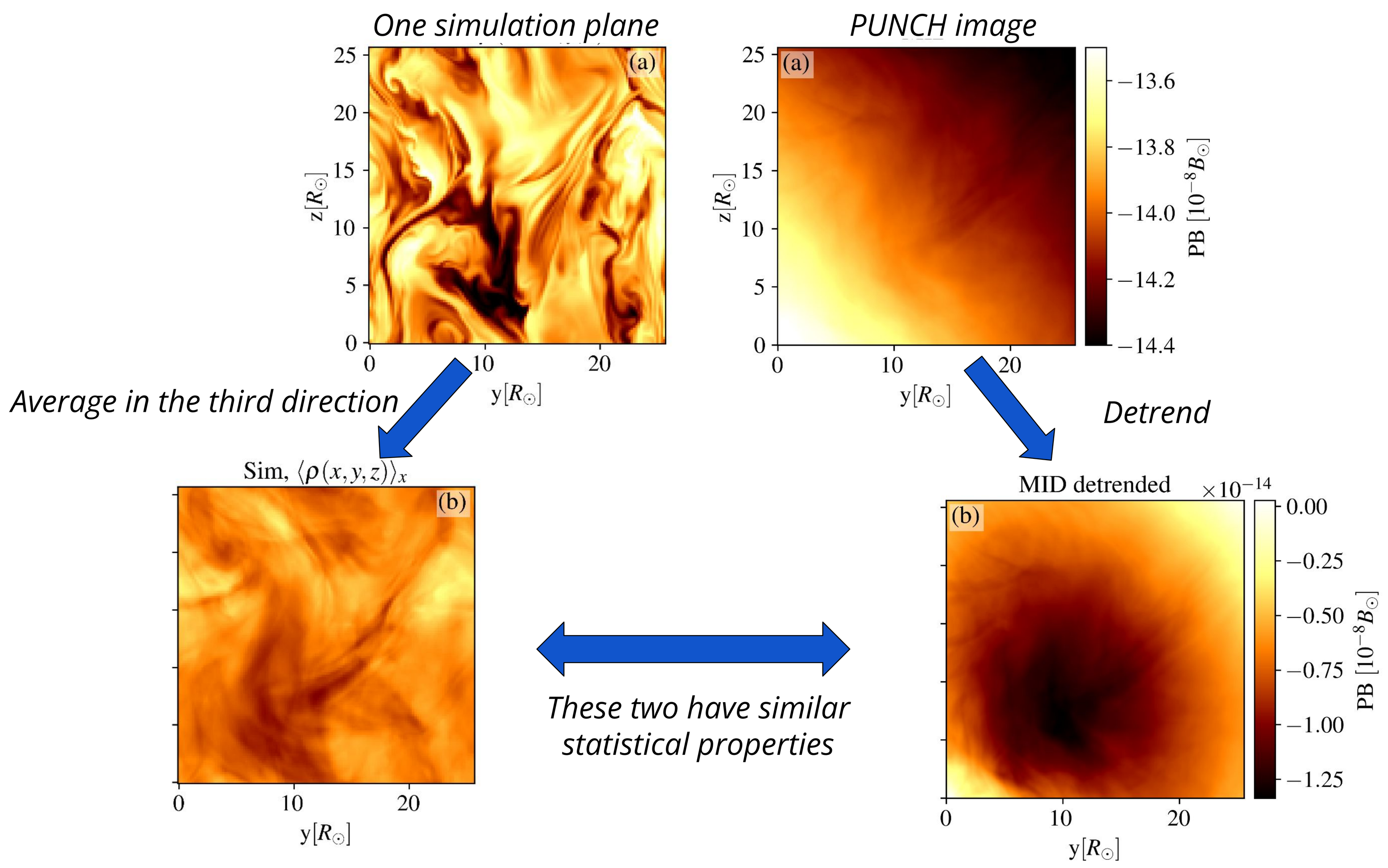

Fig. 2. Procedure to compare the properties of the simulation and PUNCH fields. Even though the bottom two figures look different, their statistical properties are now similar.

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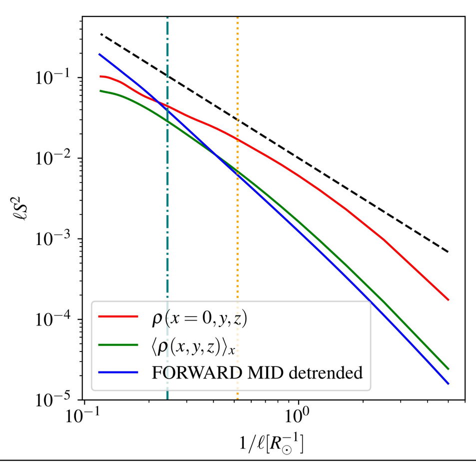

Fig. 3. Comparison of the equivalent spectra for the original simulation (red) and the modified (average) simulation (green) and PUNCH image (blue). Now the spectral properties of the latter two are similar.

(3) Getting brightness data from PSP's WISPR

The goal here is to obtain total brightness time series from regions that have the same distance from the Sun, to avoid the convolution of spectral features with the radial scaling of density. During PSP perihelia, there exist points in the field of view of WISPR instrument that fulfill this requirement.

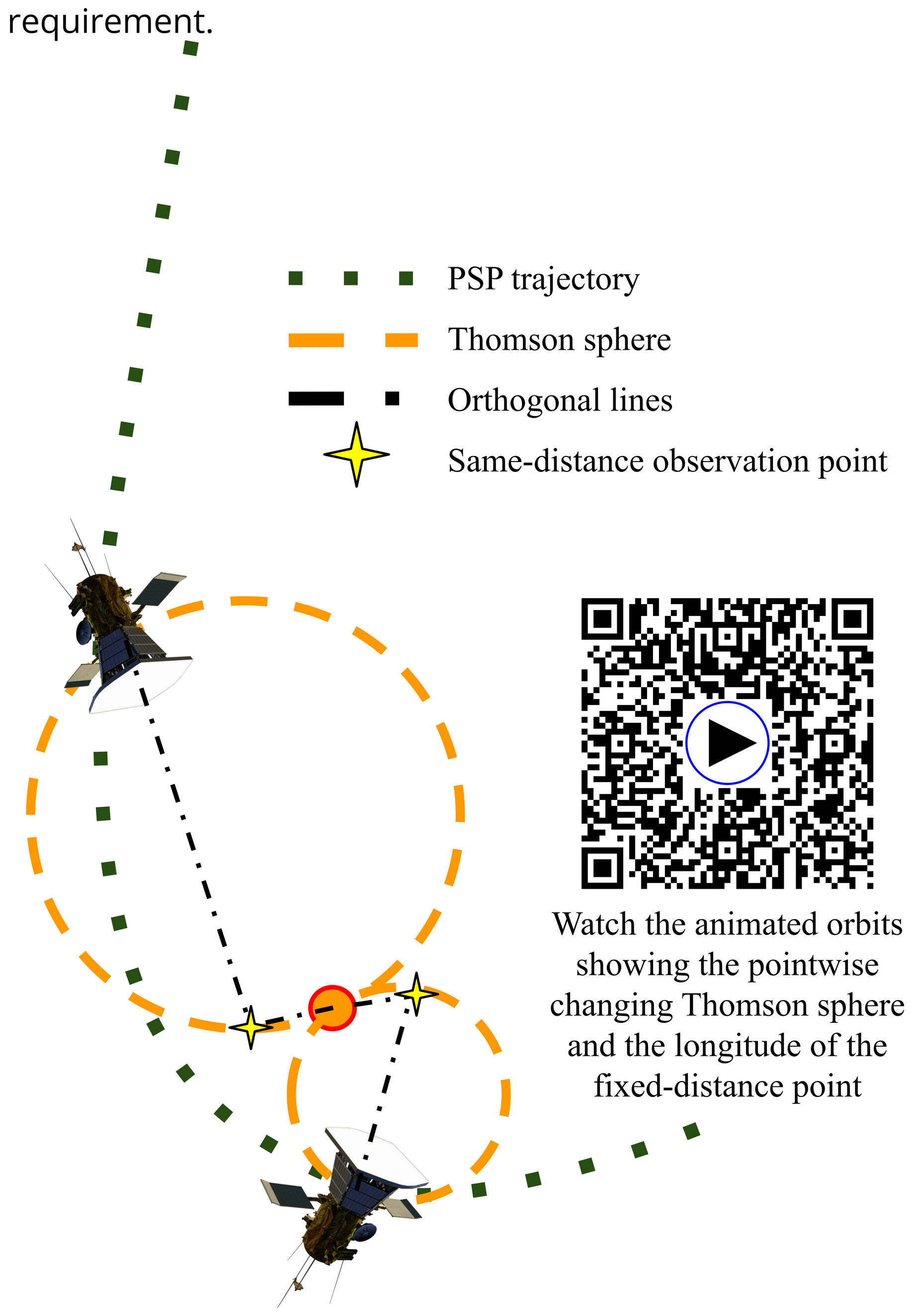

Fig. 4. Schematic representation of data sampling. Brightness can be sampled at the same distance from the Sun by geometrically tracking individual points within WISPR's FOV.

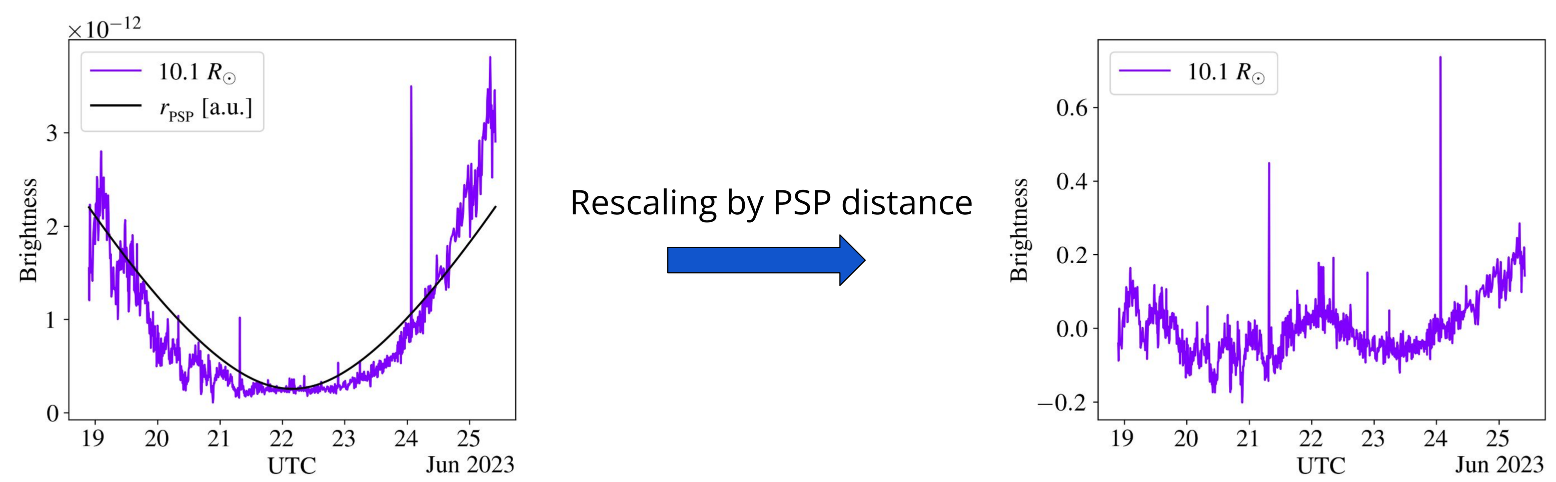

Fig. 5. (Left) time series of brightness sampled at constant 10.1 solar radii. Superimposed is the square distance of PSP from the Sun (in arbitrary units). (Right) brightness normalized by the inverse square of PSP distance. This corrects the luminosity change due to PSP motion.

By looking at different positions within WISPR's FOV, we can sample brightness at different distances from the Sun. This allows us to infer if there is any evolution of spectral properties in the inner regions of the heliosphere, birthplace of the solar wind.

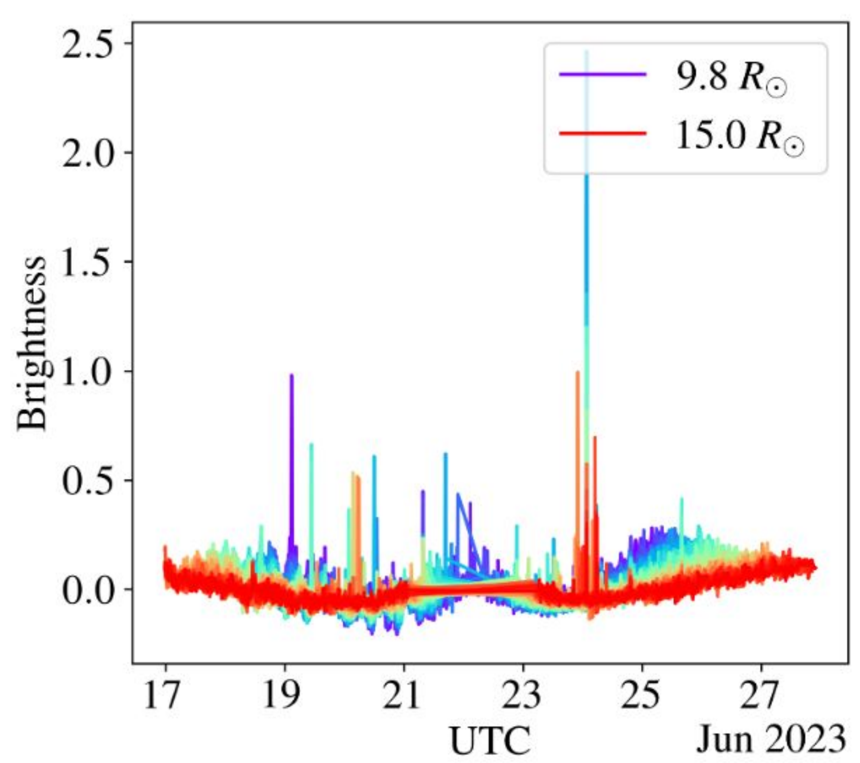

Fig. 6. Collection of time series sampled at distances from 9.8 to 15 $R_\odot$. We finally collected the data we are interested in!

(4) Spectral evolution

Of the different brightness time series in Fig. 6, we can compute the power spectral density using the Blackman-Tukey technique, suitable for non-periodic data sets.

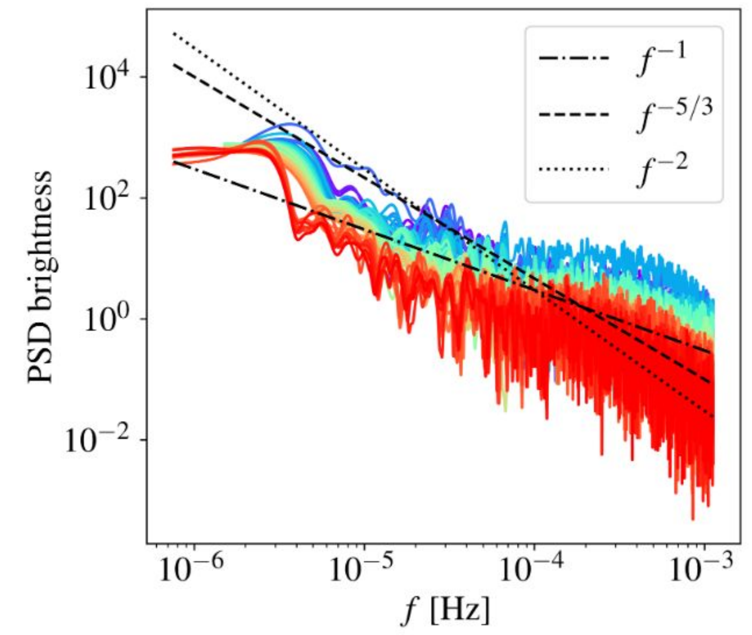

Fig. 7. Power spectral density of brightness time series shown in Fig. 6. For reference are indicated nominal power laws commonly observed in turbulence. f^{-1} is related to large-scales, $f^{-5/3}$ is generally observed in the turbulence inertial range, f^{-2} is the modification of the -5/3 slope due to the integration along the line of sight, as observed in Pecora et al. 2024. There is an overall trend for the spectra steepening from closer to the sun (blue) to farther away (red).

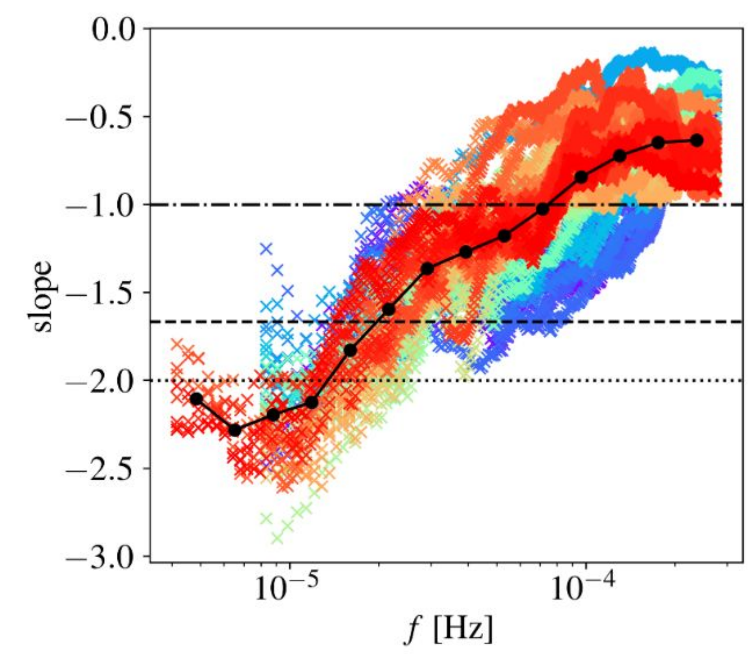

Fig. 8. Spectral slopes measured by fitting each spectrum in running windows of 1 decade in frequency. The only range of frequencies giving stable results is for $f < 2\times10^{-5}$ Hz. In this range, the slope is close to -2.2, similar to the prediction of the previous paper where simulations and synthetic models were used. In this same range, no particularly significant radial trend is observed though.

(5) Discussion & Conclusions

1. We can obtain brightness measurements at fixed distances from the sun exploiting PSP: This is a complementary approach to what will be used with PUNCH in a similar dichotomy as in Lagrangian vs Eulerian sampling.
2. By keeping the distance fixed, we avoid the envelope due to the density scaling as the inverse square distance from the sun. PSP brightness measurements need also to be corrected to take into account the instrument getting closer to the source.
3. The power spectral density of the brightness time series show a spectral slope close to -2 for frequencies smaller than 2x10-5 Hz.
4. This is consistent with the modification to the inertial range slope due to the line-of-sight integration. However, here it appears at frequencies larger than the inertial range.

STILL TO BE INVESTIGATED

1. What is the effect of the F-corona removal filter on the power spectra?
2. Will using L2 or L3 data affect the results?
3. What if instead of pointwise brightness (subject to strong variability), we use an averaged value about the observed point?
4. Thoughts? Comments? Let me know!

WAITING FOR PUNCH

1. PUNCH will avoid the problem of geometrical corrections. The spatial orbits of PSP will be substituted for temporal observations.
2. PUNCH's enormously larger FOV provides full annular coverage. More points, more statistics. But also, more points, more systematic investigation of the equatorial and polar solar wind separately.
3. PUNCH observations are subject to longer paths of integration along the line of sight. Comparison with more in-situ (or shorter integration) can help determine how strong this effect is for turbulence studies.

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