Periodic Density Structures from Ulysses

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Introduction

Periodic density structures (PDSs): number density variations found in solar wind plasma, both *in situ* [e.g., Viall+ 2008; Gershkovich+ 2022, 2023; Kepko+ 2024] and remotely [Viall+, 2010; Morton+, 2019]

PDSs are most likely related to the release mechanism of the solar wind [Viall & Borovsky 2020; Viall, DeForest, & Kepko 2021]

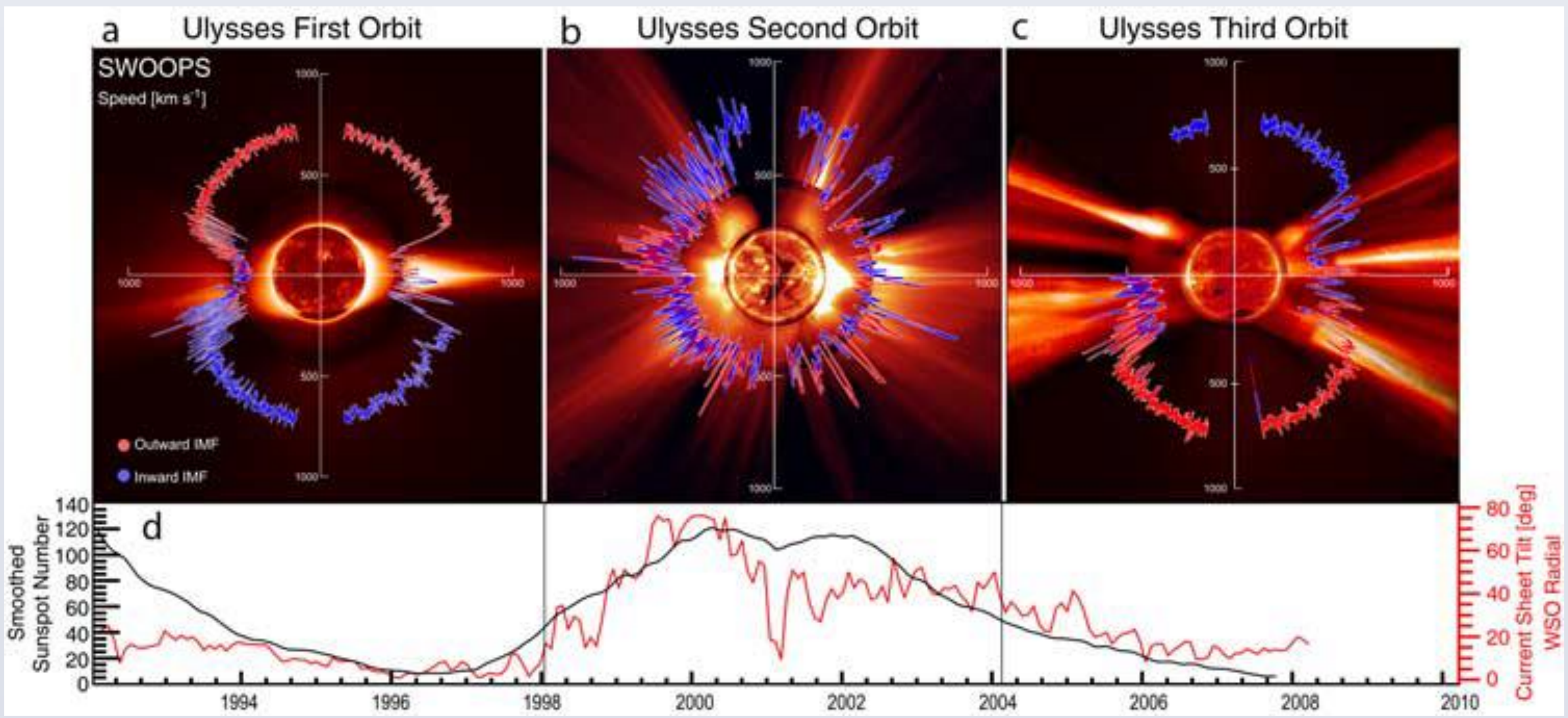
Recent results [Kepko+ 2024] have shown that there are likely two populations of PDSs at 1 AU in the ecliptic: the dominant one that peaks at a frequency of ~2 mHz (~8 min.), which corresponds to solar p-mode oscillations measured remotely [Morton+ 2019], and a smaller but still significant one at ~0.2-0.5 mHz (~30-90 min.), which is associated more with remote observations of the streamer belt [Viall+ 2010]

Open questions:

- 1) Are these structures found not only at 1 AU in the ecliptic but also over the poles of the Sun?
- 2) If so, do they have the same frequency/length scale as those at low latitudes?
- 3) What do the answers to the previous questions mean for the formation of these structures?

Data & Methods

We use data from Ulysses/Solar Wind Over the Poles of the Sun (SWOOPS) [Bame+ 1992]. Ulysses was the first and only mission to explore the polar regions of the Sun, reaching ~80º heliocentric latitude. It discovered the bimodal speed distribution of the solar wind at solar minimum and its apparent disorder at solar maximum.



Credit: McComas+ 2008.

Specifically, we take the number density from Ulysses and perform a Fourier analysis using the Multi-Taper Method (MTM) detailed in Di Matteo+ [2020]. For the MTM, we use the following parameters:

Segments of 24 hours

- f_Rayleigh = 0.01 mHz
- Slide window every 1 hr

Sampled at a rate of once per 8 minutes (interpolated)

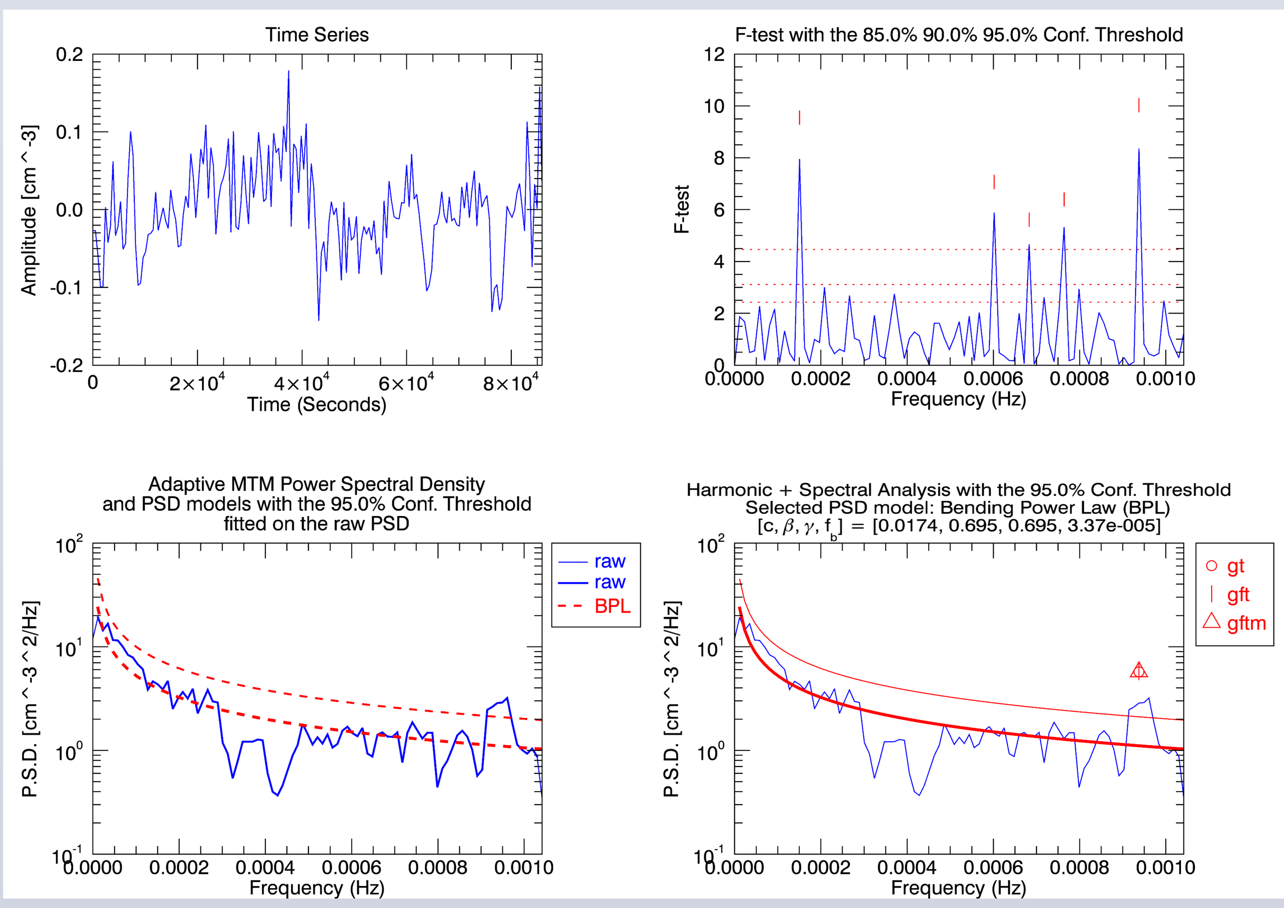
- f_Nyquist = 1.04 mHz

Example of output from the SPD_MTM routine (day 288 of 1994) →

Ulysses was at -76 deg. latitude

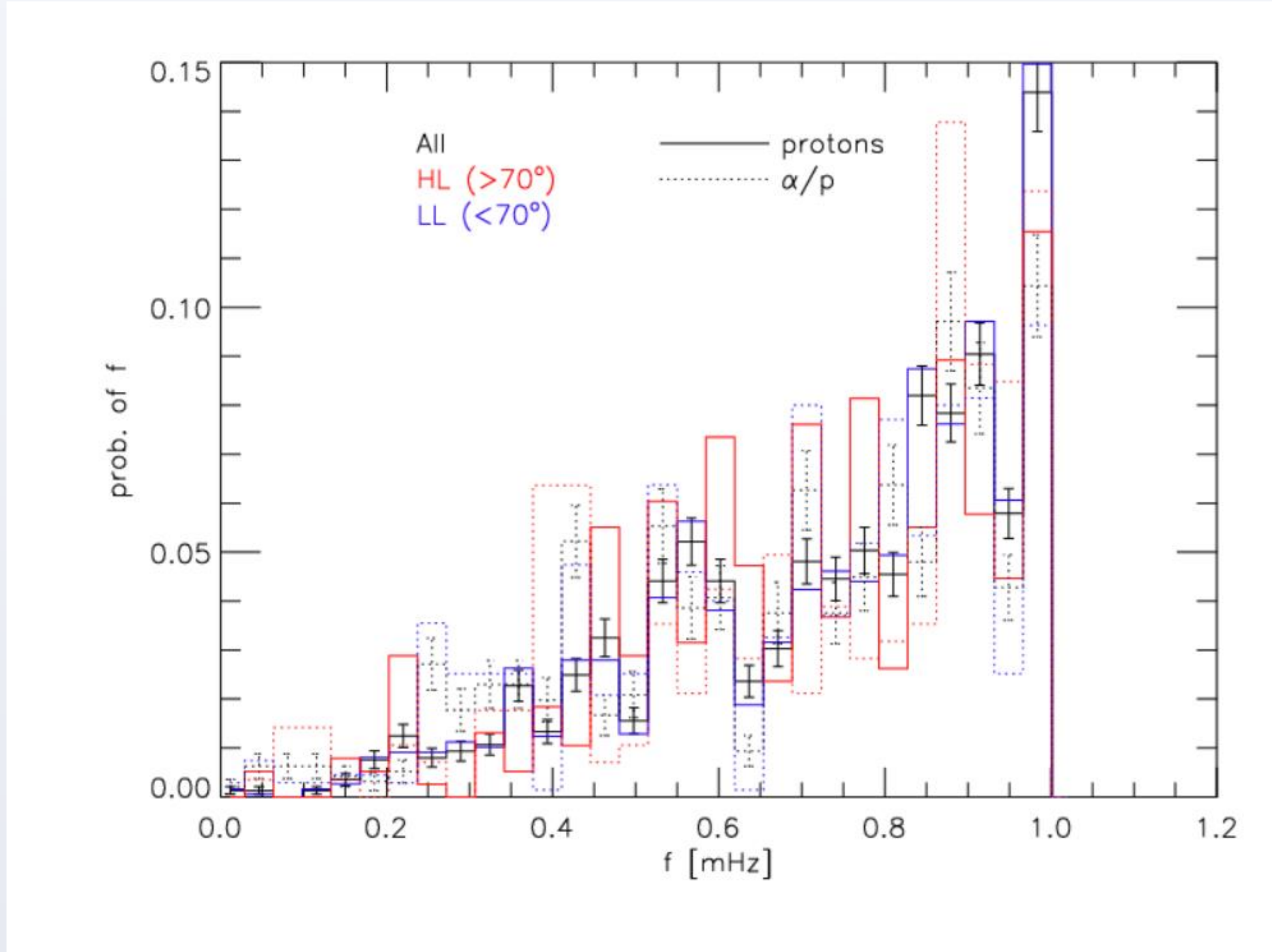
Found significant frequency (above background) at ~0.9 mHz

Analysis was repeated for the ratio of the alpha particle, or He⁺⁺, density to the proton density

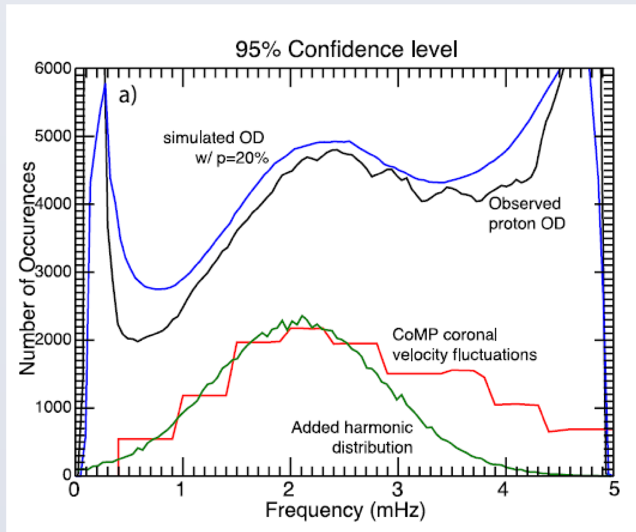


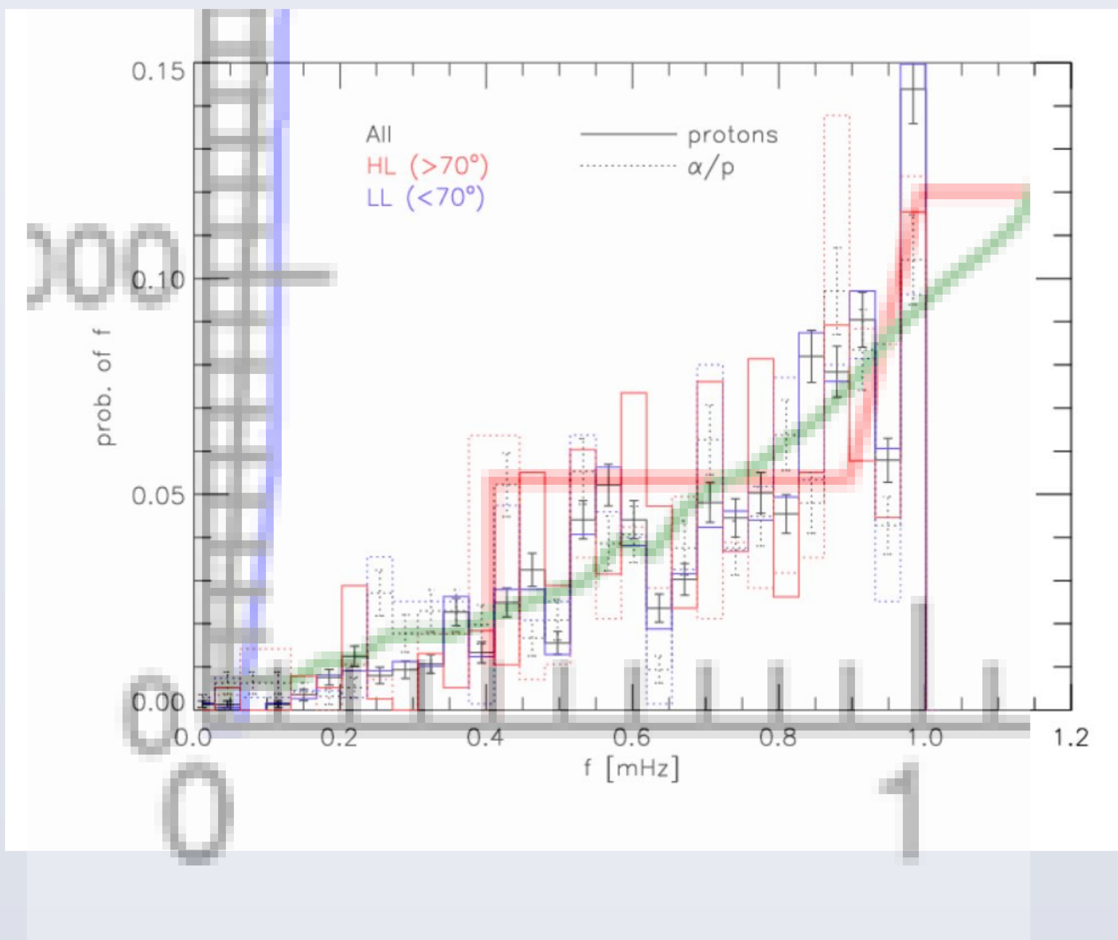
Main Results & Discussion

We took all the data (~20 years) from Ulysses and made a distribution of frequencies found over the entire mission at all latitudes and solar conditions (black), at high latitudes during solar minimum and when the current sheet tilt was low, i.e., 1992-1998 and 2006-2009 (red), and low latitudes plus high latitues at solar maximum or when the current sheet tilt was high, i.e., 1991 and 1998-2006 (blue). Protons are solid lines while alpha-to-proton ratio are dotted lines. Error bars are based on Poisson statistics (only shown for protons at all times as a representative of all others). Shape of the distribution is consistent with Kepko+ [2024] results (after false positive removal) that shows a peak at 2 mHz.

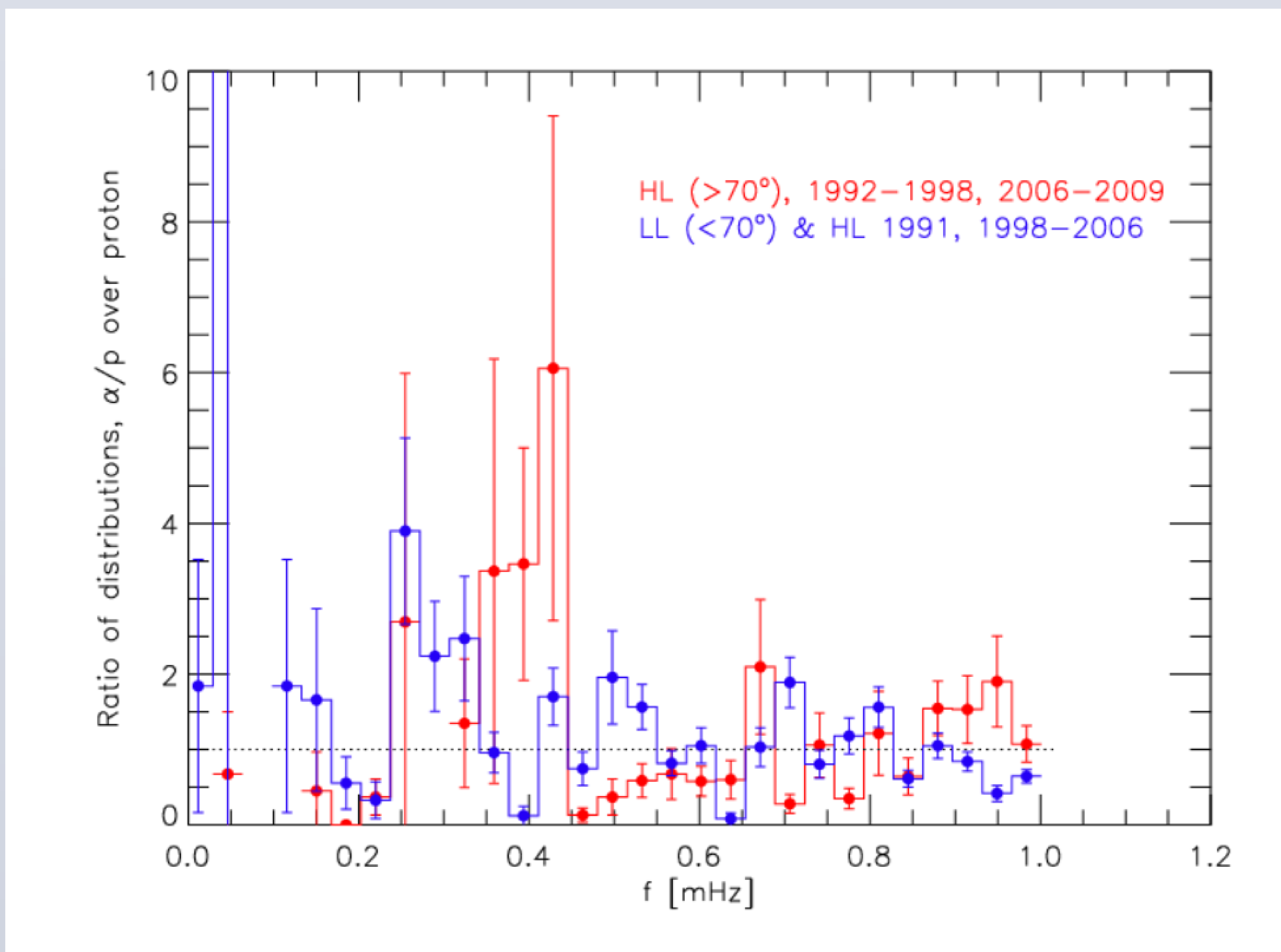


Since this population has been associated with p-modes that are over the Sun at all latitudes, there is no inconsistency with finding them equally at high latitudes with Ulysses.





We then took the ratio of the distributions representing the alpha-to-proton ratio and the protons alone, to look for variations that are present in the alpha-to-proton ratio, which is strongly coupled to the source region of solar wind plasma. We find a peak between 0.25 and 0.45, with the pristine fast wind (red) at slightly higher frequencies. This agrees moderately well with results from Kepko+ [2024] (see Figure 9) that performed the same analysis at 1 AU in the ecliptic.



The fact that our analysis of pristine fast wind at the highest heliolatitude solar wind ever measured shows similar results to those found in the ecliptic calls into question the source of the ~90-minute oscillations as being due to streamer belt wind, which originates at low latitudes. Another possibility is related to the coincidence that 90 minutes converted to a length scale is around 2-4e6 km, assuming wind speeds of 400-800 km/s. This roughly corresponds to the size of supergranules (30 Mm on the photosphere [Rouillard+ 2021]) that have expanded in size due to an assumed purely radial expansion factor of 215 at 1 AU to 6.5e6 km or 6500 Mm.

However, these structures have only been found to leave an imprint in the solar wind through the presence of magnetic switchback patches from Parker Solar Probe data [Fargette+ 2021], and it is not known if they have an imprint on the density and/or if they make it to 1 AU and beyond.