Helioseismic Measurements of Convective Power in Solar Cycle 24

J. T. Stefan [1], A. G. Kosovichev [1,2], A. Stejko [1], G. Guerrero [3]

[1] Department of Physics, New Jersey Institute of Technology, Newark, NJ
[2] NASA Ames Research Center, Mountain View, CA
[3] Department of Physics, Universidad Federal de Minas Gerais, Belo Horizonte, Brazil

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Abstract

Constraining the parameters under which convection in the solar interior operates has important implications for describing how energy is transported by plasma motions, and various physical models have been employed to provide some theoretical estimates on the expected power spectrum. Past attempts to measure the convective power distributed among large spatial scales have, however, found differing and incompatible values. Here, we present measurements of the convective power spectrum in the upper convection zone for Carrington rotations in Solar Cycle 24 obtained from the helioseismic signal corresponding to East-West flows. We also perform calibration on synthetic data using the global acoustic GALE code to make assessments of the flow velocities at various length scales without the need for performing inversions. This allows us to derive the convective power spectrum from the flow maps and to compare with the results from the raw travel times. These results are compared against predictions of convective power in global models of convection produced by the EULAG code. Finally, we show how the steps in our analysis procedure (for example data segmentation, filtering, etc.) affect our estimates of the convective power by comparing with the synthetic data from the GALE code.

Introduction

Initial attempts to describe the spatial scales of flows in stratified, convective media relied on the use of Mixing-Length Theory (MLT). The theory suggests that the flow spectrum peaks at some characteristic length-scale (the mixing length) and that this scale increases with depth. While MLT has been able to predict the dominant scale and magnitude of flows on the solar surface, it fails to describe the very large range of convective scales that have been observed since MLT's conception. Along with the dominant length scale identified by MLT (granulation, ~1.5 Mm), convection on larger scales (supergranulation, ~30 Mm) and intermediate scales (mesogranulation, 5-10 Mm) have been observed on the Sun. Furthermore, global magnetohydrodynamic (MHD) simulations have predicted convection on even larger scales than supergranulation, so-called giant cells, that have yet to be unambiguously identified in the Sun but whose existence would further contradict MLT. This raises the question: **is there a better theory than MLT that predicts the Sun's convective power spectrum?**

The spatial scales of convection in the Sun are of particular interest to dynamo theorists attempting to explain the Sun's magnetic cycle, as plasma motions are expected to be the main driver of this cycle. This has spurred many investigations, each using their own methods, to determine the convective power spectrum within the Sun. However, none of these methods (and in fact few simulations) agree on the convective power spectrum, leading to the so-called **convective conundrum** (Figure 8). A significant open question exists: **what is the true convective power spectrum within the Sun?**

This work is Part I of III in an investigation to replicate the results obtained by 3 independent methods, and to develop a better understanding of these methods by calibrating them on acoustic simulations performed by the GALE code [1] based on convective profiles obtained with the EULAG code [2]. Here, we focus on the method developed by Hanasoge+2012 [3] that uses acoustic wave travel time differences associated with East-West flows to estimate the convective power spectrum.

Methodology

The spherical harmonic transform can be applied to any function on the sphere to obtain a spectral representation of that function in angular degree ℓ and order m. We apply this transform to the travel time differences associated with East-West flows, adopting the convention that a positive shift corresponds to Westward flows. It can be shown (as in [3]), that an upper bound for the flow power spectrum can be measured from the travel time differences: $P_{\ell,m}(v) < P_{\ell,m}(\delta\tau)/C_\ell$. The calibration coefficients C_ℓ can be derived from simulations, where the true subsurface flow is known. In this section, we describe the calibration procedure for measurements at $0.96R_\odot$. First, we perform a simulation with flows that are sufficiently localized in radius and horizontal extent (Figure 1) such that spectral power is distributed across all spatial scales. Next, we perform a second, identical simulation without the flows. We apply the helioseismic analysis to both maps and subtract the travel time differences from the empty map to remove noise due to stochastic sources (Figure 2). Finally, we obtain the calibration coefficients (Figure 3) by performing a linear fit between $P_{\ell,m}(v)$ and $P_{\ell,m}(\delta\tau)$, and validate them using the input profile (Figure 4).

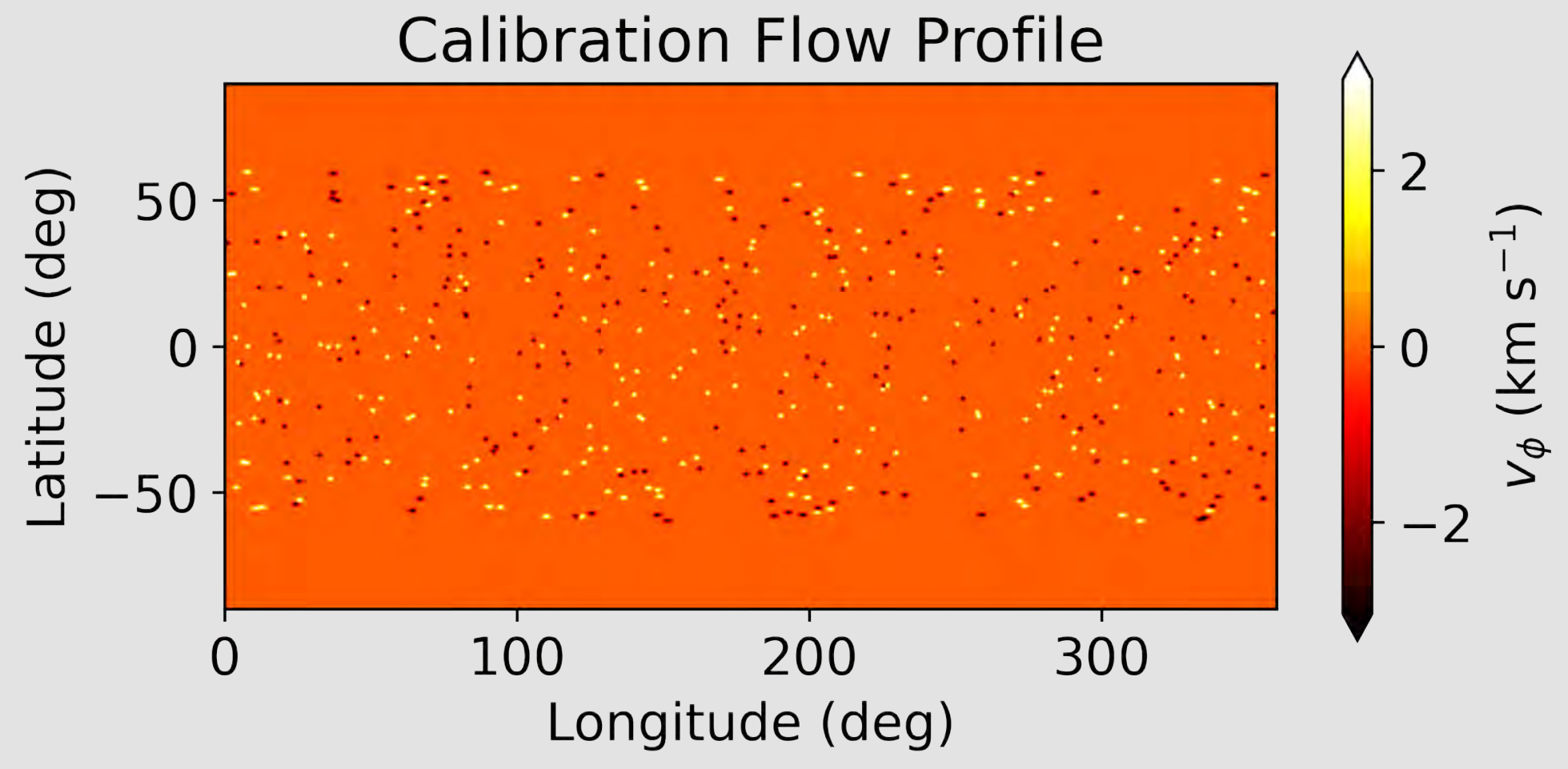


Figure 1: Calibration flow profile used as an input to the GALE simulation.

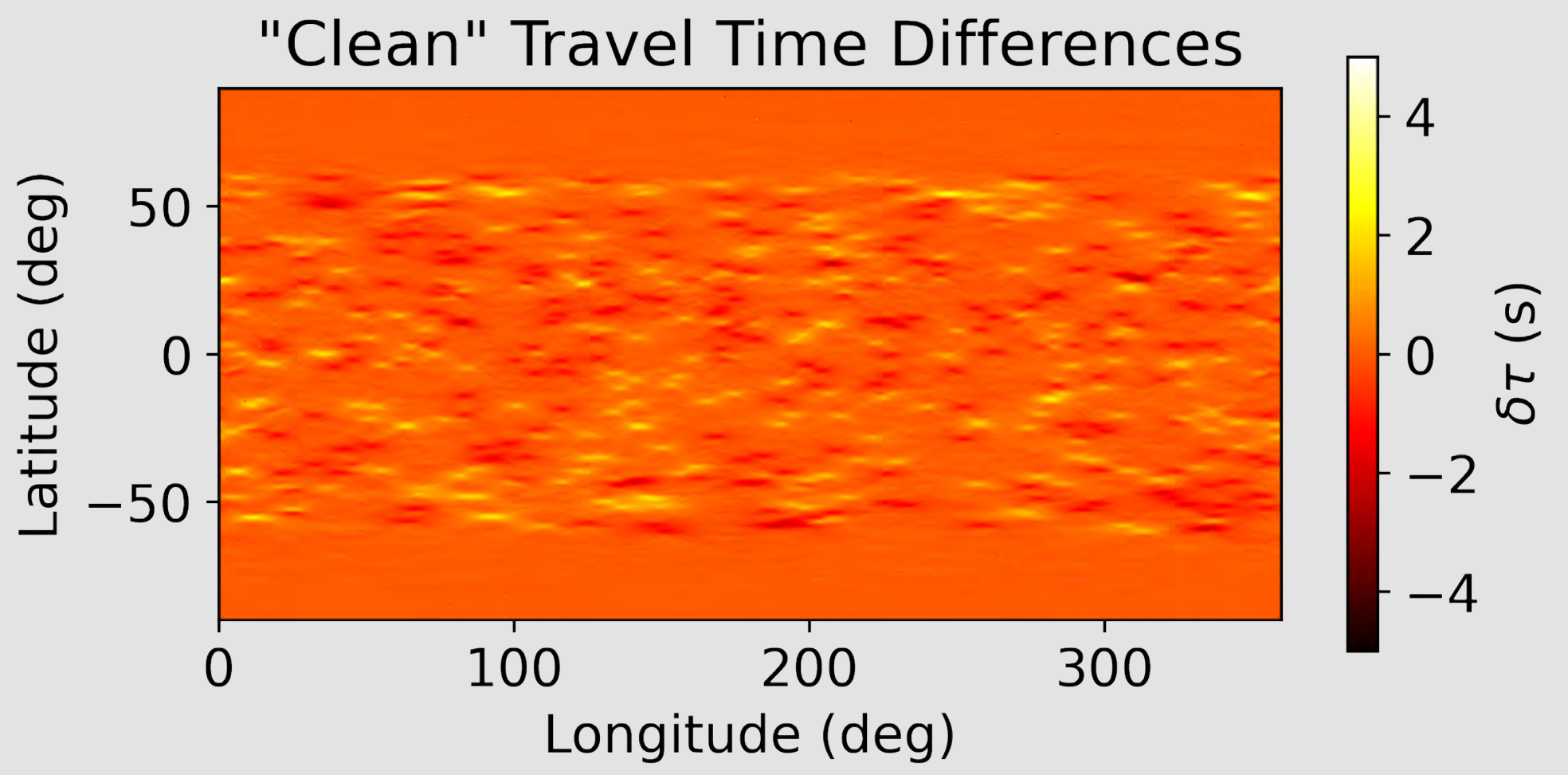
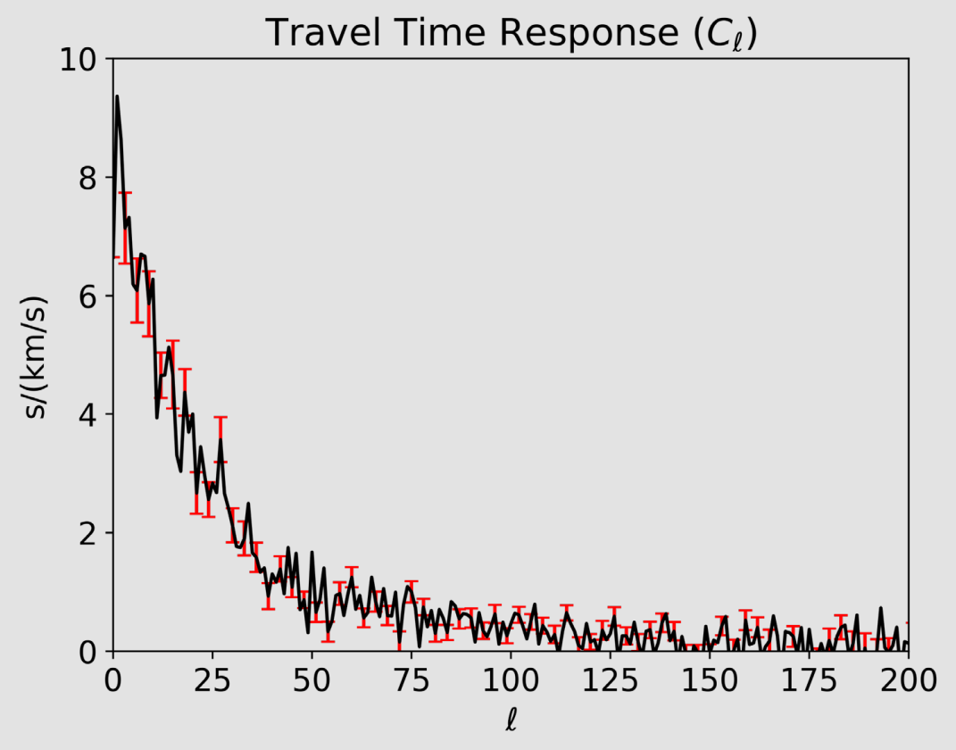


Figure 2: Resulting travel time differences after removing the contribution from stochastic source noise.



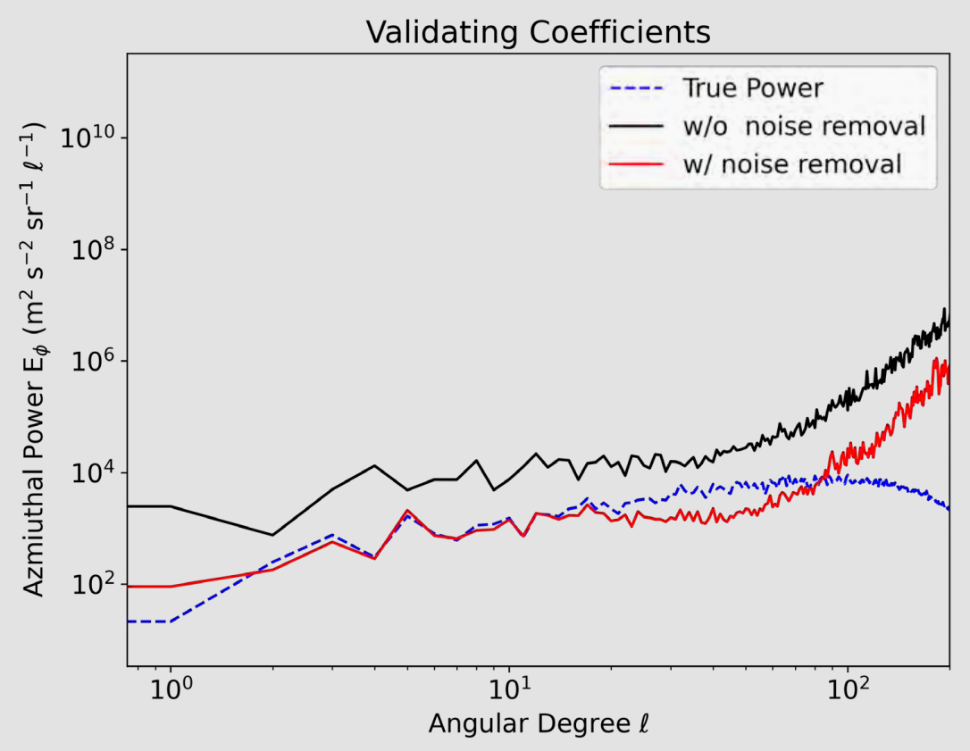


Figure 3 (left): Calibration coefficients derived from the linear fit of the SHT coefficients of velocity and travel time, visualized as the travel time response to 1 km/s flows at each spatial scale.

Figure 4 (right): Validation of the derived coefficients by applying them to the raw travel time map (black) and the "clean" travel time map.

Results

We apply the derived calibration coefficients to travel time maps obtained from two Carrington rotations at the rising and falling phases of Solar Cycle 24: CR 2106 (beginning 20 Jan 2011) and CR 2184 (beginning 16 Nov 2016) respectively. Due to the limited nature of solar observations, we must take additional steps to apply the previous methodology. First, it is not currently possible to produce natural synoptic maps, so we artificially create them by stitching together travel time maps. We choose to use 24 individual maps of width 15 deg; such a division works well with our chosen resolution of 0.25 deg/pixel so that an integer number of pixels fills each division. Second, travel time measurements near the poles (and East/West limbs) become increasingly inaccurate due to foreshortening and reprojection. We therefore limit our analysis to ±73.75 deg to remove the anomalous polar regions; this specific limit (as opposed to 60 deg or 65 deg) is chosen as it works well with our spatial resolution. This artificially decreases the overall power and so we correct for this by scaling the power spectrum by the missing area. We show the artificial synoptic maps for CR 2106 in Figure 5, for CR 2184 in Figure 6, and compare the power spectra from the two maps in Figure 7. We find no significant differences in the convective power between the rising and falling phases of the solar cycle.

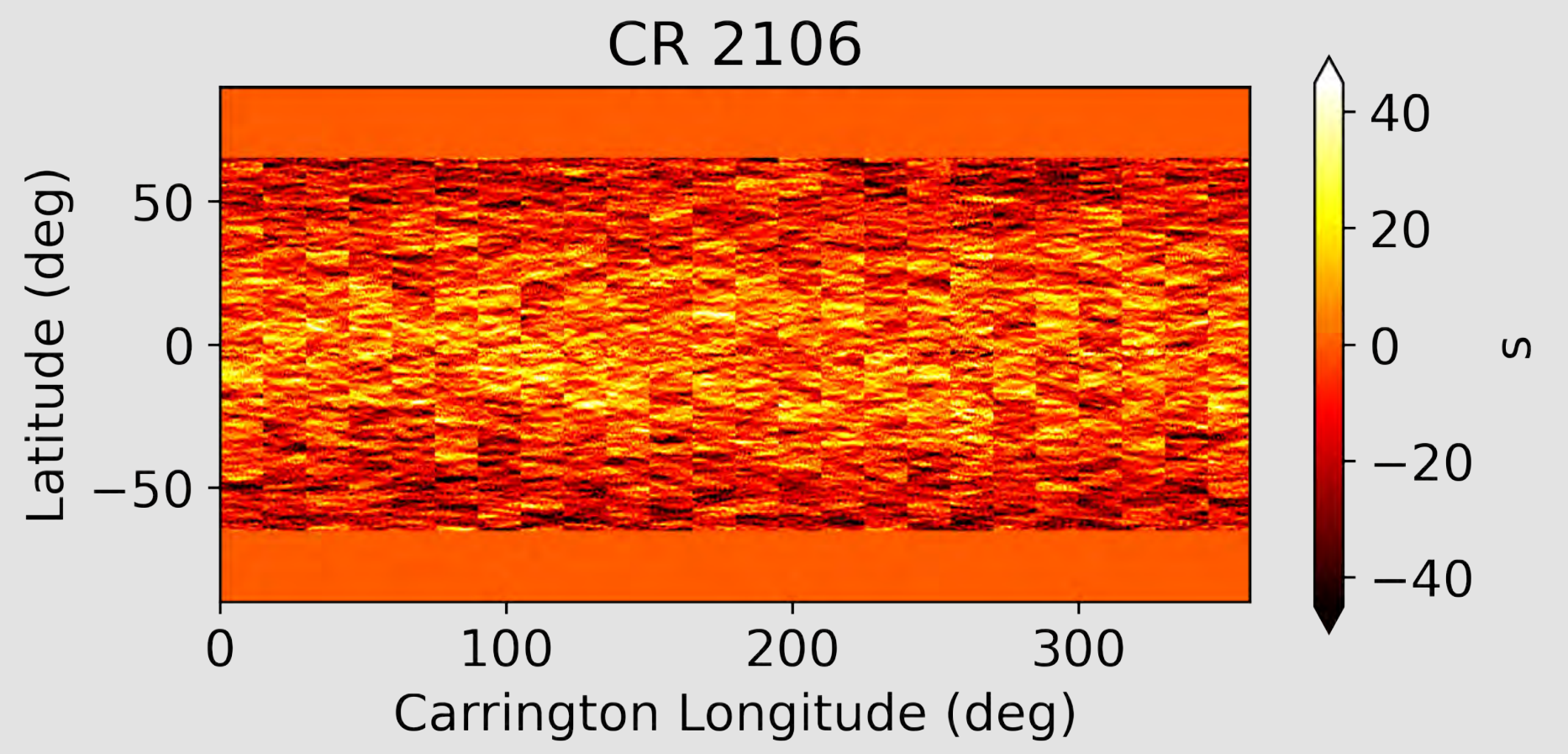


Figure 5: Artificial synoptic travel time map for CR 2106.

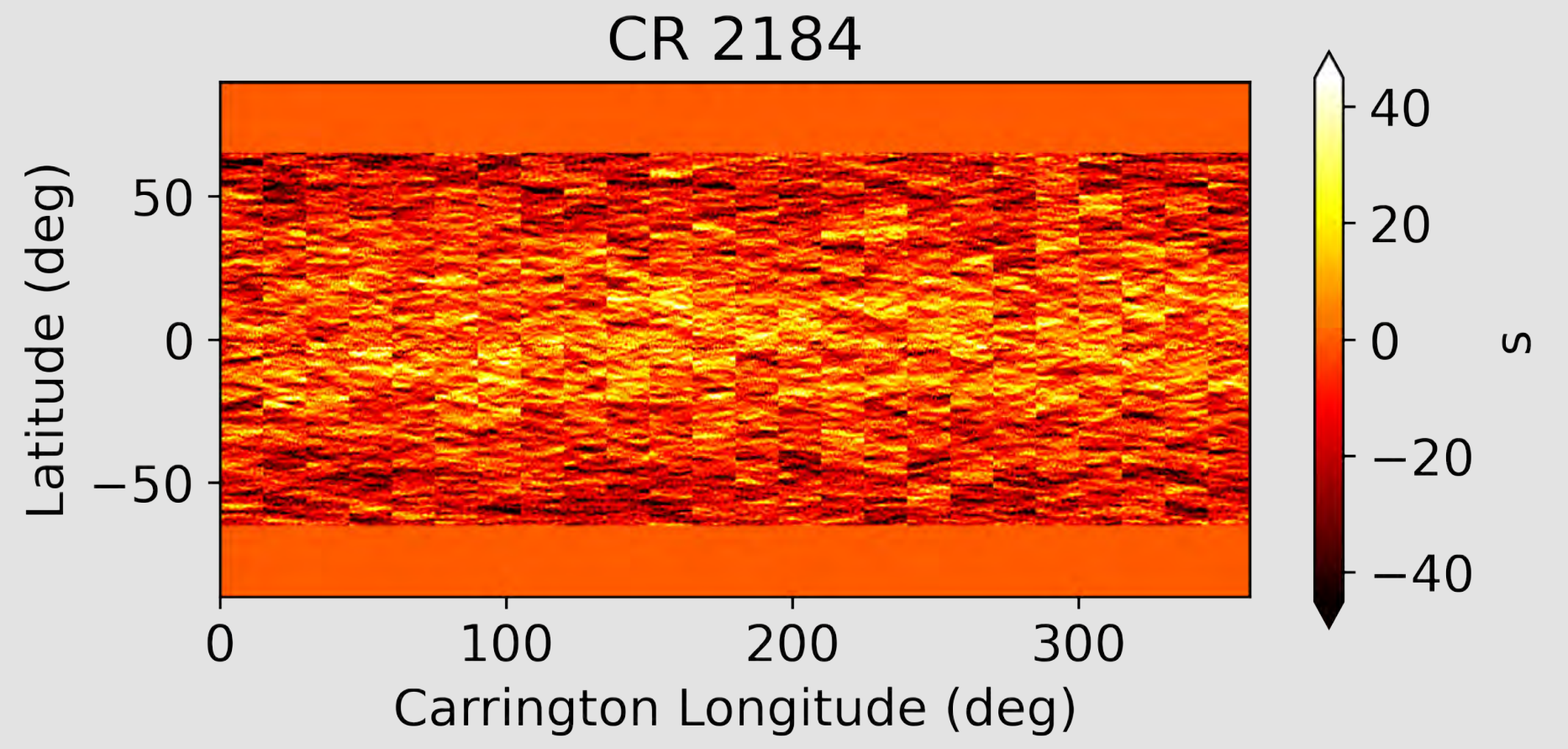


Figure 6: Artificial synoptic travel time map for CR 2184.

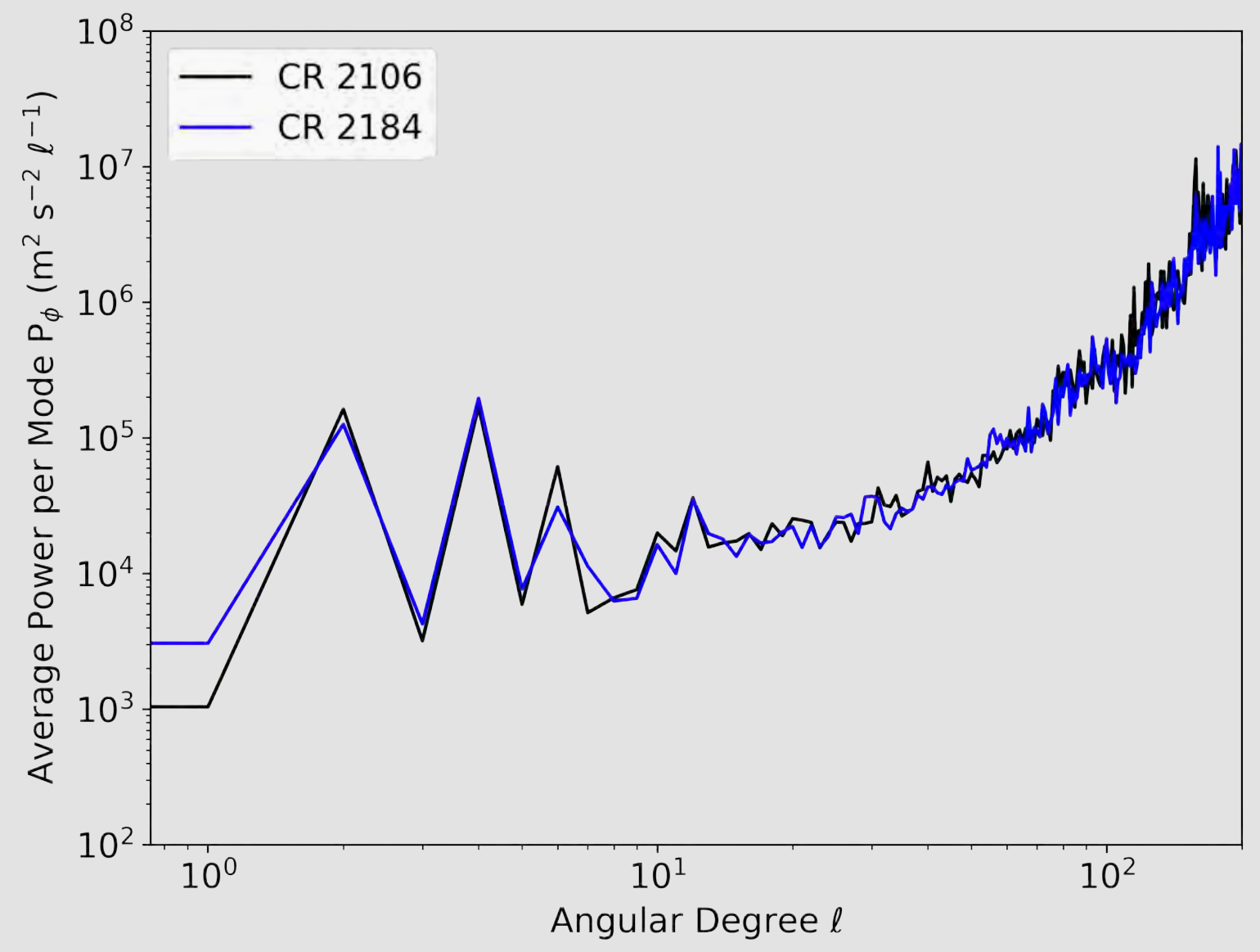


Figure 7: Comparison of the average power per mode for CR 2106 (black) and CR 2184 (blue).

Comparison with Prior Estimates

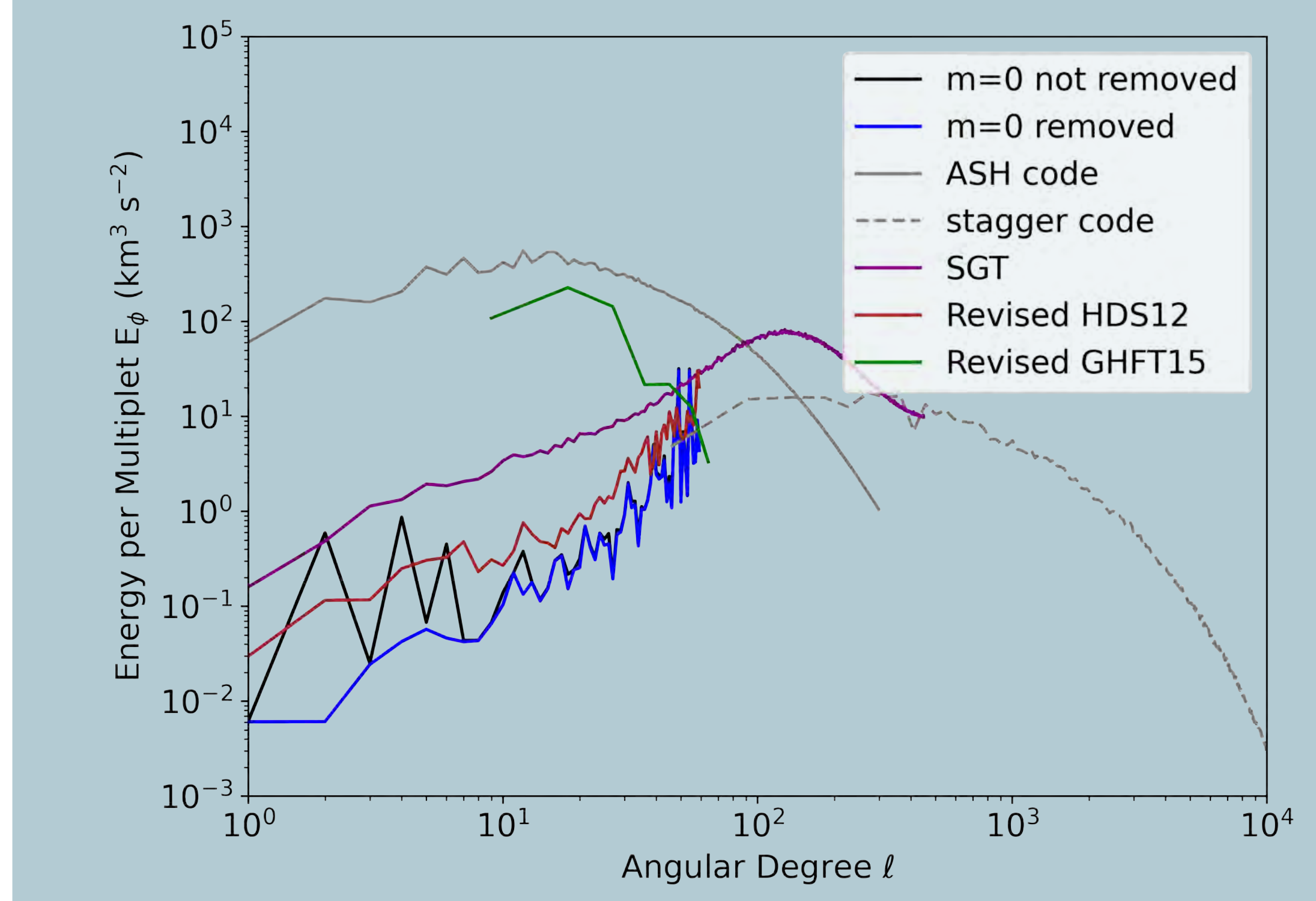


Figure 8: A summary of the convective conundrum as it currently stands, with our new estimates added (black and blue).

Prior estimates have been made in units of energy per multiplet, where the power from each angular order m is summed instead of averaged. We show the results of our analysis in this format in Figure 8 for a one-to-one comparison. Among these estimates are the predicted spectra from the ASH [4] and stagger [5] codes, as well as the spectra measured by Hanasoge+2012 [3] using a time-distance method and Greer+2015 [3] using a ring diagram method, both revised by Proxauf [6] who identified inaccuracies in the respective methodologies. The spectrum derived from surface granulation tracking (SRT) [7] is also shown.

Questions to Resolve

1. Why does the sensitivity decrease so strongly at $\ell \approx 50$, which is a significantly larger length scale than both the input resolution and the minimum resolvable length scale?

2. How does segmentation into many individual panels affect the derived power spectrum (both theoretically and quantitatively), particularly for small spatial scales? [This is in progress…]

3. Removing the m=0 component also removes the excess energy at even angular degrees; this excess energy likely comes from differential rotation, but the hypothesized giant cells (also called banana cells) are expected to strongly contribute to low, even angular degrees. Is it possible to distinguish between the DR and giant cell contributions? How much of this excess power comes from giant cells?

References

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