The Single Radial Isorotation Surface in the Bulk of the Solar Convection Zone: Implications for the Solar Dynamo

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5.1. HMI Contour Map in Larson & Schou (2018): Single Interpolated Radial Bulk-CZ Isotach

Systematic errors in data recorded with HMI since 2010 were corrected in Larson & Schou (2018). The isorotation contours of a 2dRLS inversion of the corrected data are shown in their Figure 30. The data are averaged "over the first six years of the HMI 72-day analysis" (2010-2016). In this contour map, up to the confidence limit at $\lambda = 80°$ there are eight isotachs, with 20-nHz spacing. In the bulk of the convection zone, between $\lambda \approx 20°$ and $\lambda \approx 65°$, an approximately-rectilinear segment is well fit on each of the five displayed isotachs I_1 to I_5 by a straight line, spanning $\approx 0.21\ R_\odot$ from $\approx 0.74\ R_\odot$ to $\approx 0.95\ R_\odot$ (this paper). Over the defined depth span of $\approx 0.21\ R_\odot$ on the five cited quasi-rectilinear isotach segments, five distinct constant conical inclinations are observed vs. the rotation axis. These inclinations are, with rising λ : $\theta\ I_1 \approx 23.5° \pm 1°$ (450 nHz), $\theta\ I_2 \approx 34.5° \pm 1°$ (430 nHz), $\theta\ I_3 \approx 28.3° \pm 1°$ (410 nHz), $\theta\ I_4 \approx 23.5° \pm 1°$ (390 nHz), and $\theta\ I_5 \approx 38.5° \pm 1°$ (370 nHz).

In this contour map featuring 20-nHz spacing, interpolation is necessary to narrow down the location of a radial isotach segment, if any. The most radial isotach inclination is found to be on, or very close to the interpolated isotach for 380 (380) nHz between the displayed I_4 (390 nHz) and I_5 (370 nHz) isotachs. This interpolated segment's inclination is found to be bracketed by $\theta\ I_4 \approx 23.5° \pm 1°$ on the 390 nHz isotach, and by $\theta\ I_5 \approx 38.5° \pm 1°$ on the 370 nHz isotach. The average of the two values yields an interpolated radial inclination $\theta_{RAD} = (\approx 23.5° + \approx 38.5°) / 2 \approx 31.0° \pm 1°$, i.e. a radial latitude $\lambda = 59.0° \pm 1°$.

Overall, the above data witness unambiguous inward isotach divergence, locally approaching either a slanted-parallel pattern or a non-radial outward-divergence pattern. This finding suffices to rule out a plurality of radial isotachs in the HMI rotation profile under scrutiny. The variance of 15° between inclinations on the 390 nHz and the 370 nHz isotachs calls for consideration of additional data, in which interpolation can be avoided or minimized, to secure accurate estimates of θ_{RAD} with higher confidence. No HMI contour map with isotach-spacing narrow enough to require no interpolation at all for our purposes could be found in the literature during the present research. But the following contour map with 10-nHz spacing requires less interpolation.

5.2. HMI Contour Map in Linton et al. (2021): Single Interpolated Radial Bulk-CZ Isotach

Linton et al. (2021) gave, in their Figure 7.18, "the average of 2dRLS inversions of 45 72-days periods of HMI data from 2010 to 2018." Contours consist in fourteen isotachs with 10-nHz spacing up to $\lambda = 75°$.

In this contour map, a unique radial isotach segment can be interpolated between I_8 with $\theta\ I_8 \approx 29° \pm 2°$ and I_9 with $\theta\ I_9 \approx 37° \pm 2°$. The two isotach segments to be interpolated extend over a depth span of $\approx 0.17\ R_\odot$ from $\approx 0.78\ R_\odot$ to $\approx 0.95\ R_\odot$. The interpolated radial segment is inclined at the angle $\theta_{RAD} = 33° \pm 2° = (\approx 29° + \approx 37°) / 2$. The latitude of the radial isotach is thus $\lambda = 57° \pm 2°$. The variance between inclinations on the two interpolated isotachs is only 8 nHz, i.e. about half that in the HMI contour map in Larson & Schou (2018). Separately, the clear overall isotach inward-divergence in the contour map in Linton et al. (2021) confirms the absence of a plurality of radial isotachs in the HMI data under scrutiny.

The central-value latitude of the single radial isotach I in contour maps of current HMI data is $\lambda = 57°$ in Linton et al. (2021), and $\lambda = 59°$ in Larson & Schou (2018). The radial latitude in current HMI data is below the $\lambda = 70°$ uncertainty threshold given by Solanki et al. (2020).

6. The Observed Pattern in MDI Data: a Single Radial Bulk-CZ Isotach

6.1. Single Interpolated Radial MDI Isotach in Larson & Schou (2018)

Larson & Schou (2018) first extended the analysis of MDI data to "unsmoothed, full-resolution" full-disk observations, as opposed to the "low-resolution data (..) with a resolution one-fifth that of the full-disk data". A 2dRLS rotation-inversion of the MDI full-disk contours observed from 1996 to 2010 is displayed in the contour map which is Larson & Schou (2018)'s Figure 29. In this contour map, up to the confidence limit at $\lambda = 80°$ there are eight isotachs, with 20-nHz spacing. Nearly rectilinear segments can be defined on each of the displayed five isotachs from $\lambda \approx 23°$ to $\lambda \approx 64°$. Two segments on isotachs in mid-latitudes span a depth of $\approx 0.15\ R_\odot$ from $\approx 0.80\ R_\odot$ to $\approx 0.95\ R_\odot$, with inclinations $\theta\ I_1 \approx 26° \pm 1°$ (450 nHz) and $\theta\ I_2 \approx 25.5° \pm 1°$ (430 nHz). Two segments on higher-latitude isotachs span a depth of $\approx 0.20\ R_\odot$ from $\approx 0.75\ R_\odot$ to $\approx 0.95\ R_\odot$, with inclinations $\theta\ I_3 \approx 28.5° \pm 1°$ (410 nHz) and $\theta\ I_4 \approx 25° \pm 1°$ (390 nHz). The highest-latitude rectilinear isotach segment (370 nHz), spanning only $\approx 0.13\ R_\odot$ ($\approx 0.82\ R_\odot$ to $\approx 0.95\ R_\odot$), is inclined at $\theta\ I_5 \approx 40.5° \pm 1°$.

In this MDI map with 20-nHz spacing, interpolation is necessary to narrow down the location of a radial isotach segment, if any. The most radial isotach inclination is found to be on, or very close to the interpolated isotach for 380 nHz between the displayed 390 nHz and 370 nHz isotachs.

This interpolated segment's inclination is found to be bracketed by θ I_4 ≈ 25° ± 1° (390 nHz), and by θ I_5 ≈ 40.5° ± 1° (370 nHz). The average of the two values yields an interpolated radial inclination θ_{RAD} = (≈ 25° + ≈ 40.5°) / 2 ≈ 32.75° ± 1°, i.e. a radial latitude λ ≈ 57.25° ± 1°.

As in the case of HMI data, the MDI data in Larson & Schou (2018) reveal unambiguous overall inward isotach divergence, with limited local parallel and non-radial outward patterns. These findings suffice to rule out a plurality of radial isotachs in the MDI rotation profiles under scrutiny.