Time-Distance Helioseismology of Deep Meridional Circulation

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Abstract A key component of solar interior dynamics is the meridional circulation (MC), whose poleward component in the surface layers has been well observed. Time-distance helioseismic studies of the deep structure of MC, however, have yielded conflicting inferences. Here, following a summary of existing results we show how a large center-to-limb systematics (CLS) in the measured travel times of acoustic waves affect the inferences through an analysis of frequency dependence of CLS, using data from the Helioseismic and Doppler Imager (HMI) onboard Solar Dynamics Observatory (SDO). Our results point to the residual systematics in travel times as a major cause of differing inferences on the deep structure of MC.

1 Introduction

Large-scale organisation of plasma flows in the convection zones of the Sun and sun-like stars is central to a host of problems related to stellar interior dynamics and magnetic dynamos. Poleward meridional flow, well observed on the solar surface through a variety of techniques, is recognised as a surface component of deep meridional circulation (MC), which traces back to a nearly century old prediction [Eddington(1925)]. There have been a good number of theoretical studies of MC with current numerical approaches recognising well that its understanding requires solving the complex fluid dynamical problem involving exchanges of energy and momentum between convection, rotation, thermal stratification and magnetic fields (see [Featherstone & Miesch(2015)] and references

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therein). Clearly, reliable helioseismic inferences of the deep structure of MC is crucial to make progress in this field [Toomre & Thompson(2015)]. Recently, helioseismology, especially time-distance helioseismology, has made significant progress in this direction, however with unsettling differences between the published results [Zhao et al.(2013), Jackiewicz et al.(2015), Rajaguru & Antia(2015), Chen & Zhao(2017), Mandal et al.(2018)]. A large part of these differences are thought to be related to the identification and accounting of a large systematics in travel-time measurements [Zhao et al.(2012)]. Here, in this article, we summarise these developments and show that further progress in this field depends heavily on understanding the origin of this systematics, fully characterising it and removing it reliably.

2 Time-distance Helioseismology of Deep MC: Current Results

Most of the inferences on the deep structure of MC have largely been from time-distance helioseismology [Duvall et al.(1993)]. Travel times of acoustic waves propagating in meridional planes are measured in deep-focus geometry for a range of travel distances Δ covering depths from the surface down to the base of the convection zone to capture the meridional flows and inverted, commonly, in ray theory approximation. Although different studies have followed the above basic method, we refer readers to respective publications for finer details of the measurement and inversion procedures adopted. We point out that Rajaguru & Antia (2015) implemented an in-built mass conservation constraint in terms of the stream function to invert travel times thereby determining both the meridional (u_θ) and radial (u_r) components of the flow. The data used by different authors are as follows: [Zhao et al.(2013)], [Rajaguru & Antia(2015)] and [Chen & Zhao(2017)] used first two, four and six years of SDO/HMI Doppler data respectively, [Jackiewicz et al.(2015)] used two years (2010 - 2012) of Global Oscillation Network Group (GONG) data, and [Lin & Chou(2018)] have used SOHO/MDI data.

All the different results from the above studies are summarised in Figure 1. Here, meridional flow profiles obtained by different authors have been hemispherically symmetrized and plotted. A prominent feature in the results of [Zhao et al.(2013)] and [Chen & Zhao(2017)] is a double-cell MC in depth covering most of the latitudes with the outer cell having a rather shallow return flow at about $0.9 R_\odot$. Results of [Jackiewicz et al.(2015)] agree with this shallow return flow but fail to reproduce the deeper second cell of MC. Distinct from the above inferences is a single cell deep MC derived by [Rajaguru & Antia(2015)], with a depth of $\approx 0.77 R_\odot$ for a large-scale reversal of flow. The results of [Lin & Chou(2018)] cover only the low latitudes ($< 30°$) and show a double-cell structure. It is also worthwhile to note that all the profiles in Figure 1 indicate a complicated flow structure at low latitudes ($< 20°$) with two or more reversals of flows over depth, corresponding to two or more cells.
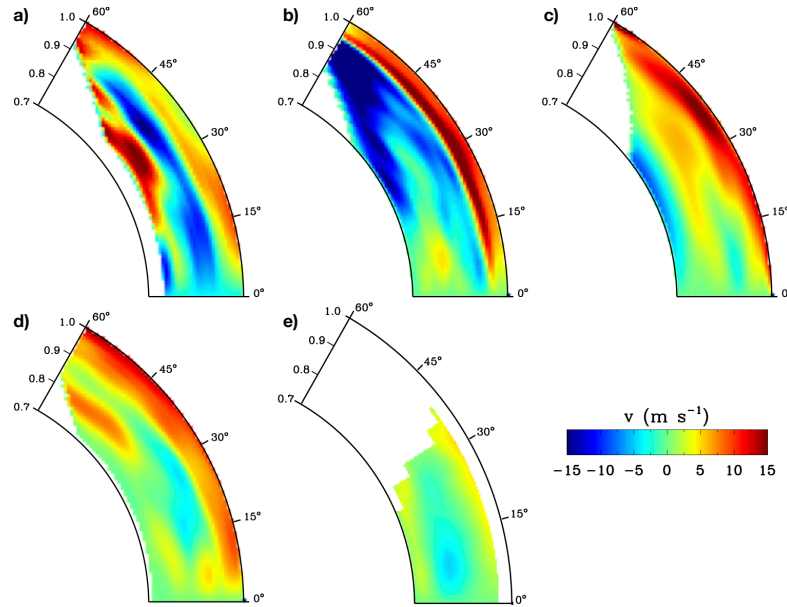
Fig. 1 Hemispherically symmetrized meridional flow profiles obtained from time-distance helioseismic inversions by (a) Zhao et al. (2013), (b) Jackiewicz et al. (2015), (c) Rajaguru & Antia (2015), (d) Chen & Zhao (2017), and (e) Lin & Chou (2018). Poleward flows are postive and equatorward flows are negative. Figure courtesy of Junwei Zhao.

The above differences among the different studies, employing basically the same method and in some cases even the same data set, obviously demand a thorough relook at the analysis procedures, signals and systematics in the measurement. The major difference pertaining to the large-scale flow profile, viz. single- or double-cell profiles of MC, may, at a basic level, be taken as due to the implementation or not of mass conservation constraint in the inversion. However, inaccuracies in the identification and separation of signals from systematics could have large impacts in the inferences and we focus on these in the rest of this artcile.

3 Systematics and Signals in Travel Times

A major development that led to the above presented time-distance helioseismic studies of MC, in the first place, has been the identification and removal of a large systematic center-to-limb effect in the measurements [Zhao et al.(2012), Zhao et al.(2013)], especially improving the identification of flow signals in the deeper layers [Zhao et al.(2013), Rajaguru & Antia(2015), Jackiewicz et al.(2015)]. As shown by [Zhao et al.(2012)], the above effect is a large systematic increase in

travel time differences against angular distance from the solar disk center mimicking a radial outflow from the centre towards the limb, and which increases as Δ increases. This large center-to-limb systematics (CLS) in travel times is still of unknown origin, although the analyses of [Zhao et al.(2012), Zhao et al.(2013)] involving comparisons of travel times from different observables (corresponding to different heights of formation in the solar atmosphere) from the SDO/HMI as well as with that from another instrument (SOHO/MDI) pointed to possible physical causes in the solar atmosphere related to observation height differences. A study by [Baldner & Schou(2012)] showed that the near-surface granular convection could affect the wave-propagation in the observable layers leading to a similar effect as the CLS in travel times. An empirical correction procedure was suggested by [Zhao et al.(2012)]: estimate CLS from waves traveling in W-E direction over an equatorial belt as a function of center-to-limb distance (*i.e. longitude*) and subtract it from N-S travel times measured against latitude. This prescription was tested using different observables and also validated by comparing with direct surface measurements of meridional flows by [Zhao et al.(2012)].

3.1 Wave-Frequency Dependence of Systematics and Signals

Given that we do not understand the origin of CLS, hence lack a model to remove it from the measurements reliably it is imperative that we devise further diagnostics to characterise it better. In this regard, it has been suggested [Rajaguru & Antia(2017), Chen & Zhao(2018)] that the dependence of CLS on wave frequencies is examined: filter acoustic waves forming resonant p modes in frequency domain over several narrow frequency bands, and measure travel times against these frequency bands. Here, we implement the above by fitting frequency filtered cross-correlations: a total of 15 different frequencies spaced every 0.2 mHz interval starting from 2.0 mHz with a FWHM of 1 mHz. Both the N-S and W-E (CLS) cross-correlations are frequency filtered, and the meridional flow travel times at each frequency are estimated by subtracting the CLS from the N-S travel times. We have used seven years (2010 - 2017) of SDO/HMI data in this study. Figure 2 displays the CLS as estimated from W-E travel times and the meridional flow signals, which are obtained after subtracting the CLS from the N-S travel times, for two representative frequencies, 3.0 and 4.0 mHz. The CLS has a strong frequency dependence with rapid increase up to about 4 mHz before levelling off and decreasing slightly at higher frequencies. A detailed look at the frequency dependence of CLS and travel times is deferred to a separate publication, except showing the main impact of this on flow inferences (see next Section). We note that [Chen & Zhao(2018)] have also performed a detailed analysis of frequency dependence of CLS via a direct Fourier phase analysis of cross-correlations. Since the magnitudes of CLS is several times that of signals due to meridional flows, any slight inaccuracies in the estimation of CLS would cause significant errors in the signals due to flows. Comparison of signals and CLS in Figure 2 already indicates a correlation between them, viz. a larger depth gradient
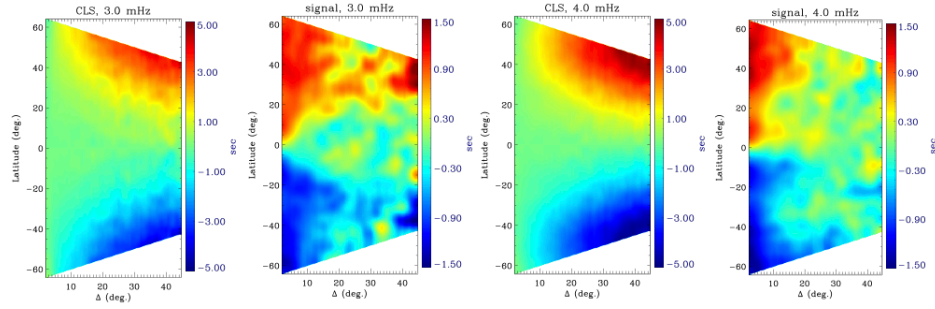
Fig. 2 Estimates of CLS and meridional flow signals at two representative frequencies, 3.0 and 4.0 mHz. Flow signals are obtained after subtracting the CLS from the N-S travel times at the same frequencies.

of signals correlate with the increased CLS against frequency. It is unclear as to at which frequency the estimation of CLS is robust and hence the signals too.

4 Differing Meridional Flow Solutions Over Wave-Frequency

The travel times at different frequency bands estimated as above are inverted in ray theory approximation using the same method as in [Rajaguru & Antia(2015)] with proper accounting of the frequency dependent ray paths, and the results are shown in Figure 3. Surprisingly, the solutions differ, with the lower frequency (3.0 mHz) travel times yielding a single-cell profile while those from the higher frequency (4.0 mHz), where the CLS is maximum, yielding a double-cell profile. This property of solutions obtained clearly implicate the impact of the strong frequency dependence of CLS and hence points to the role of any residual CLS, depending on the accuracy of the procedure to estimate and remove it, in introducing artefacts in the inverted solutions. On the other hand if we assume that the frequency dependence of travel times seen in Figure 2 is due to the finite wavelength effects and not due to leakage of CLS, then it cannot be modeled by ray-theory approximation and require wave modeling such as first Born approximation. We defer a detailed analysis of the nature of solutions against frequency, comparisons with Born approximation treatments of wave-propagation, including the temporal evolution of MC solutions, to a forthcoming publication.

5 Conclusions

The difficult proposition of measuring the deep MC, down to the base of the convection zone, is further compounded by the large systematics, CLS, described and
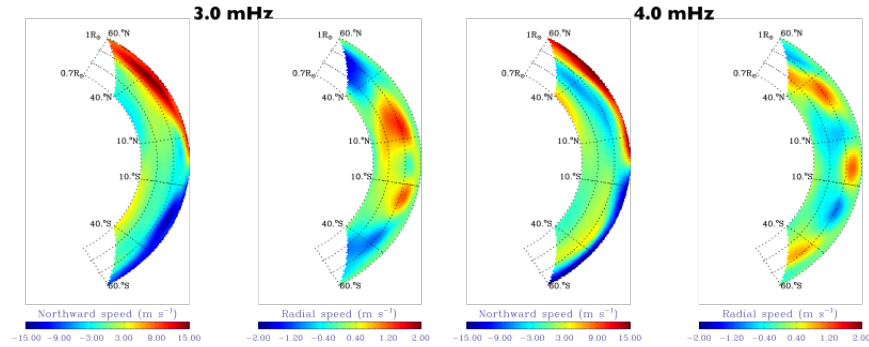
Fig. 3 Meridional circulation profiles obtained from ray-theory inversion of travel time signals shown in Figure 2. While travel times measured around 3.0 mHz give a single-cell profile while those around 4.0 mHz, where the CLS is maximum, yield a double-cell profile.

analysed in this work. We have shown that the very different inferences drawn by different studies in the field are attributable to the CLS: travel time signals estimated at frequency bands ($\approx$ 4 mHz and above) where the CLS is large yield double-cell MC, while those at lower frequency bands it is smaller yield single-cell MC. We however point out that we have not established the robustness of our estimates of CLS and that it is unclear as to at which frequency the estimation of CLS and the signals are robust and hence which of the obtained solutions for deep MC are closer to reality. We therefore caution that more detailed analyses are necessary to draw firmer conclusions on the above.

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