Final Report to NASA Sun-Earth Connections Guest Investigator Program for Support of

GLOBAL AND LOCAL HELIOSEISMIC STUDIES OF SOLAR CONVECTION ZONE DYNAMICS USING SOI-MDI ON SOHO

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FINAL REPORT: RECENT ADVANCES AND FINDINGS

1. Global Helioseismology

Our joint collaborative analyses of global mode data to characterize the solar differential rotation (e.g. Thompson et al. 1996, Schou et al. 1998), and most recently to detect and analyze temporal variations in angular velocity Ω profiles both within the convection zone and in the deeper radiative interior (e.g. Howe et al 2000a,b; Toomre et al. 2000), have led to a series of fascinating discoveries. These should be pursued further as the solar cycle continues. The physical deductions being made from these studies have been greatly strengthened by utilizing both SOI–MDI and GONG data in order to have two independent observational realizations of Doppler images spanning a five-year interval, using two separate procedures to determine global mode splittings, and then analyzing those splitting data sets using both RLS and SOLA inversion procedures. There are considerable subtleties in the effects of instrumental response functions and calibrations, sensitivity of peak finding algorithms and their mode leakage estimates, and stochastic variations in mode amplitudes that can all contribute to apparent changes in the Ω profiles being inferred from sequences of helioseismic data. We have come to understand the implications of many of these calibration and analysis steps, greatly aided by frequent multi-week collaborative working sessions in our Helioseismic Analysis Facility (HAF) at JILA involving many members of the SOI dynamics and inversion team, including most of our Co-Is during the summer months when we hold intensive working sessions. Considerable further focused attention is required in a collaborative setting on such global mode issues as we continue studying the changing sun.

Variations of Rotation Near the Tachocline and Deeper Interior

The tachocline of strong shear, separating the differential rotation of the convection zone from the solid body rotation of the deeper radiative interior, has been one of the most *surprising discoveries* of helioseismology. Such a tachocline was not anticipated, and current theoretical approaches to explain its presence are still only innovative sketches. A tachocline affords a promising site for the operation of the solar global dynamo: the presence of prominent rotational shear combined with a stable density stratification makes it likely that strong toroidal magnetic fields can be stretched into existence and can reside there for some time before magnetic buoyancy and other instabilities disrupt these flux concentrations and drag them upward, ultimately to emerge as loops at the surface. We have been very interested in seeking indications of possible *temporal changes* in rotation rate near the tachocline as the magnetic cycle advances. In the process of toroidal stretching, Lorentz forces will be generated to oppose the shear, causing it to weaken. These forces are relaxed when a strand of the toroidal field breaks loose and the shear returns to its earlier state. Since toroidal flux is ejected irregularly but peaks within the 11-year period of the sunspot cycle, we have little basis for expecting the time dependence to be periodic, except possibly with the time scale of the solar cycle. We have instead found a period of about 1.3 years in prominent angular velocity variations shown in Figure 1*b* that are in remarkable antiphase above and below the tachocline in the equatorial region.

Structure of Tachocline The formation of such a boundary layer of rotational shear near the base of the convection zone may involve anisotropic diffusivities and confining magnetic fields. Some theoretical discussions concerning the tachocline (Spiegel & Zahn 1992; Elliott 1997) invoke strong horizontal viscosity due to anisotropic turbulence in the stable layer to circumvent the diffusive spreading of the differential rotation radially inward. Other models invoke magnetic fields to enforce solid body rotation in the radiative interior (Gough & McIntyre 1998). In contrast, Gilman (2000) has argued that such *slow dynamical*

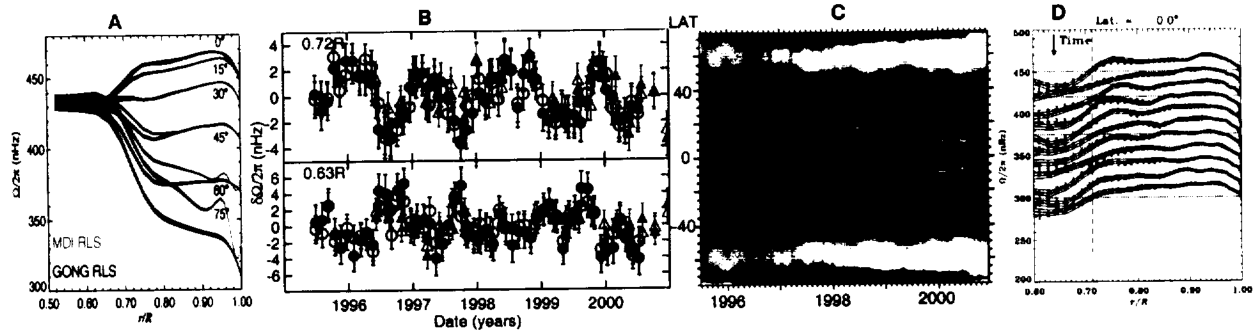

Figure 1. (*a*) Time-averaged rotation rate with radius at different latitudes for RLS inversion of global MDI data (red) and GONG data (black). (*b*) Variations with time of residuals in rotation rate at the equator at two different depths, above and below the tachocline, showing a period of about 1.3 years and antiphase behavior [Howe et al. 2000a]. (*c*) Propagating latitudinal bands of faster rotation (yellow and red tones) within the upper convection zone. A mid-latitude band forms late in 1996 and steadily migrates equatorward; the stationary high-latitude fast band strengthens as the solar cycle progresses [Howe et al. 2000b]. (*d*) Rotation rate with radius evaluated near the equator from a sequence of MDI 72-day samplings that are here displaced for clarity, showing both tachocline oscillations and substantial variations within the convection zone [Toomre et al. 2000].

processes within a tachocline (involving meridional circulations with overturning times of order one million years) may have trouble competing with *fast dynamical processes*, such as internal gravity waves triggered by combined shear and magnetic instabilities in that vicinity (e.g. Charbonneau, Dikpati & Gilman 1999). We should note that it is not yet clear from the inversions of helioseismic data whether the tachocline of shear in Ω overlaps with the base of the convection zone or not. Helioseismic estimates place the midpoint of the tachocline at radius $0.692R$, with a thickness estimated to be of order 0.02 to $0.05R$ (e.g. Kosovichev 1996; Elliott & Gough 1999), compared to the placement of the base of the convection zone at a radius of $0.713R$ from SOI and GONG data. These issues emphasize that the tachocline is likely to be the site of complex and possibly competing physical processes, with helioseismic observations having a great potential for guiding the theoretical thinking.

<u>*Approach to Assess Temporal Changes in Ω*</u> Our general procedure to detect temporal changes requires analyzing the full MDI and GONG global mode data sets in a succession of either 72-day or 108-day intervals to obtain sufficiently good frequency resolution. The resulting mode frequency splittings for each interval are inverted to determine the Ω profile with radius and latitude, and the procedure is repeated independently for the MDI and GONG data for the full duration of both experiments. The time averages of Ω determined by RLS inversion are shown in radial cuts at different latitudes in Figure 1*a*. The mean Ω profiles deduced from MDI and GONG are in close agreement up to mid latitudes of about 45°. At higher latitudes the MDI data fitting yields convoluted curves whereas the GONG profiles remain smooth. We are engaged in continuing studies to understand why there are small but systematic differences arising in the MDI and GONG peak fitting procedures to determine frequency splittings that sample the higher latitudes (e.g. Howe et al. 2001). However, at low and intermediate latitudes the deductions about Ω profiles are in good concurrence, using any combination of data sets, fitting procedures and inversion methods.

<u>*Detecting Periodic Tachocline Variations*</u> Using these time-averaged Ω profiles as a reference, we have been able to detect substantial variations $\delta\Omega$ in the rotation rates near the tachocline, with these being most pronounced near the equator and at high latitudes. Figure 1*b* displays the time evolution of $\delta\Omega$ both above (at radius $0.72R$) and below ($0.63R$) the tachocline near the equator, revealing vacillations with a period of about 1.3 years (Howe et al. 2000a). The temporal changes in $\delta\Omega/2\pi$ are of order 6 nHz and occur strikingly out of phase above and below the tachocline. These represent substantial variations compared to the 30 nHz drop in $\Omega/2\pi$ with radius across the tachocline at the equator (Fig. 1*a*). The variations detected at higher latitudes involve two-fold greater amplitudes for $\delta\Omega$ and have a period close to but distinguishable from 1.0 year. The differing low- and high-latitude behavior may be associated with the differing sense of the radial shear in Ω across the tachocline (Fig. 1*a*). We have no explanation for what causes these tachocline oscillations, though we suspect that magnetic fields threading across the tachocline can allow Alfven waves to communicate stresses, and these can lead to exchanges of angular momentum across the tachocline. The anticorrelation of $\delta\Omega$ between the convection zone and the upper part of the radiative interior is suggestive of back and forth exchange of momentum while conserving overall angular momentum. A radial component of the magnetic field crossing the tachocline with a strength of 500 G could yield such 1.3 year time scales (Gough 2000). We believe that these tachocline oscillations are very significant findings, for they are the first indications of detectable changes in rotation rate close to the likely site of operation of the global solar dynamo.

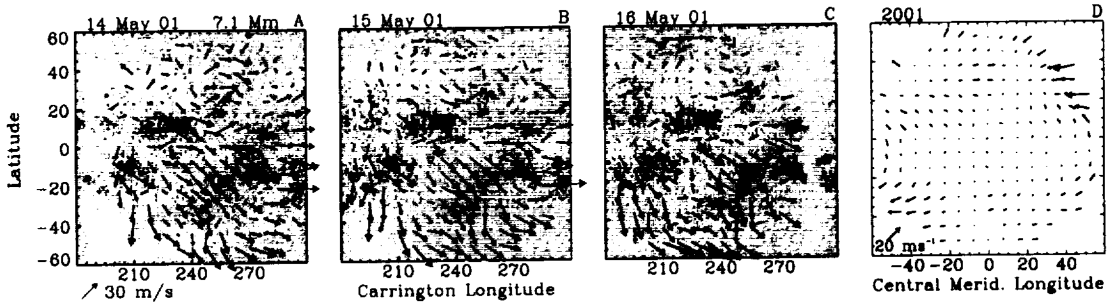

Figure 2. (*a*)–(*c*) Dense-pack maps of the horizontal flows of SSW over three consecutive days spanning 14-16 May 2001. The velocities were obtained from inversions using kernels with centroids at a depth of 7.1 Mm below the photosphere. Underlying the flow maps are magnetograms where red and green indicate opposite field polarities. The flows evolve richly from day to day with large-scale persistent patterns coexisting with more rapidly varying flows [Haber et al. 2001a]. (*d*) Estimates of systematic errors across the MDI field of view in velocities determined at a depth of 7.1 Mm in the year 2001. The largest gradients in the error estimates occur at the edges of the dense-pack matrix [Haber et al. 2002].

Jets and Fluctuations Within the Convection Zone

Propagating Fast Zonal Bands Our studies of temporal variations in Ω near the tachocline have also revealed interesting behavior both within the near-surface shearing layer and throughout the bulk of the convection zone. Our analyses and inversions of the large sets of global f and p modes over a five-year span have confirmed the presence of fast bands of zonal flow that propagate toward the equator as the cycle advances, as shown in Figure 1*c*. These bands correspond to the 'torsional oscillations' known from Doppler measurements of the surface (e.g. Howard & Labonte 1980, Ulrich 1998), and have been studied using f modes to obtain latitudinal resolution without carrying out inversions with depth since these modes are confined to the outer $0.01R$ (e.g. Kosovichev & Schou 1997, Schou 1999). Using f and p modes, we find that these flows are not just confined to the near surface, but can be detected down to radius $0.90R$ (Howe et al. 2000b), or the upper third of the convection zone. These weak banded structures, involving speedups of order a few nHz, are made visible by subtracting the dominant latitudinal variation of differential rotation. The high-latitude behavior is also most interesting, since it suggests systematic speeding up of the polar regions over this five-year interval.

Detecting Prominent Variations Within the Convection Zone Figure 1*d* indicates that there exist other significant fluctuations in rotation rate throughout the deeper convection zone, possessing changes as great as 20 nHz at many depths (Toomre et al. 2000, 2001). The amplitudes of the variations in these deep regions are considerably greater than that of banded flows in the upper convection zone. These changes in rotation rate are clear detections, with concurrence between MDI and GONG data and both types of inversion up to latitudes of at least 45°. The variations appear to be aperiodic, and we have been unable to identify any clear propagation paths for these disturbances with radius or latitude. It may be that these substantial variations are the result of averaging over many strong but localized jets or streaming zonal flows; the global modes sample the longitudinally-averaged and latitudinally-symmetric response over a several month window. On the other hand, these may be real global-scale temporal variations in the coupling of Ω to the convection for which we have not yet identified characteristic signatures. Sorting out these issues requires close interaction between the global and local helioseismic mapping of the changing flows.

2. Local Helioseismic Probing of SSW: Evolution on Various Time Scales

In the past few years the local helioseismic technique of ring-diagram analysis has led to the striking discovery of large-scale structured and evolving flows of Solar Subsurface Weather (SSW) in the near-surface shear layer. The dense-pack strategy permits the mapping of flows below the solar surface, providing the means to examine shearing flows and jets, large-scale coherent flow structures, and meridional circulations within the convection zone. Such ring-diagram probing applied to SOI–MDI data has revealed the presence of large-scale flows which are modulated by surface activity, evolving meridional cells with reversing circulations, propagating banded zonal flows, and complex evolution and meandering of flows that may be associated with the largest scales of deep convection. These SSW flows evolve on a variety of timescales, including rapid changes from day to day and more leisurely variations that occur as the solar cycle progresses.

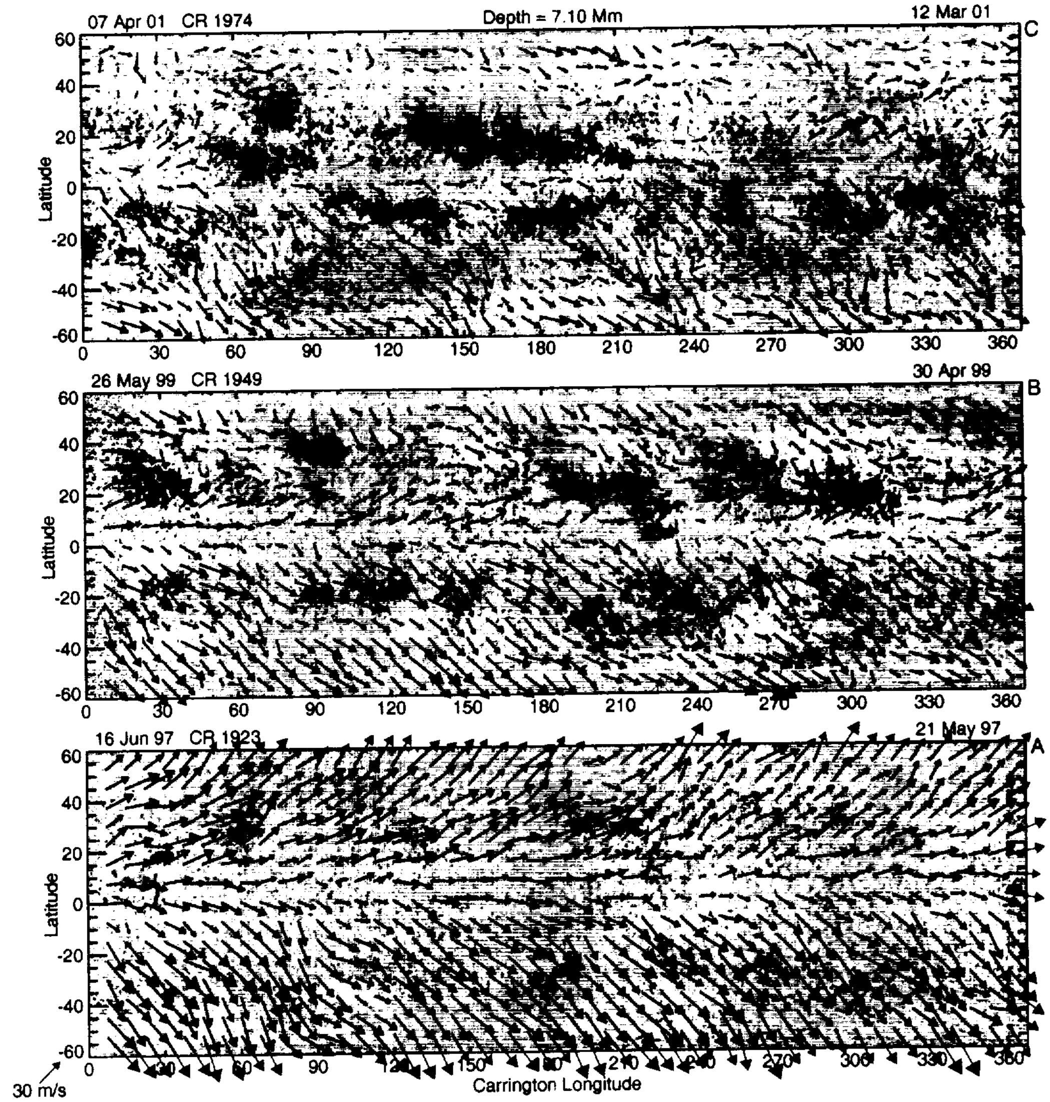

Figure 3. Changes in global-scale flows with advancing solar cycle. Synoptic maps of horizontal flows deduced from ring-diagram probing at a depth of 7.1 Mm for Carrington rotations (*a*) 1923 (from the year 1997), (*b*) 1949 (year 1999) and (*c*) 1974 (year 2001). The large-scale patterns possess strikingly different character from year to year as magnetic activity intensifies. In particular, active regions appear as zones of convergence and possible subduction. For latitudes higher than 40° in the northern hemisphere, there exists a band or cell of reversed meridional circulation with equatorward flow in 1999 and 2001. In the southern hemisphere meridional flows are consistently poleward [Haber et al. 2002].

Rapid Day-to-Day Variability in SSW

Ring-diagram probing is showing great promise in revealing the spatial and temporal variations in the large-scale flows near the top of the convection zone. Figures 2*a*–*c* present dense-pack mosaics of flow fields for three successive days in May 2001, with the velocities extracted from the inversions at a depth of 7.1 Mm below the photosphere. All such velocities are shown relative to the surface differential rotation rate (Snodgrass 1984; Haber et al. 2000). The horizontal flows revealed by these analyses exhibit rich spatial and temporal behavior. The flows near active region complexes can be especially intricate, and it appears that magnetic activity and the ordering of SSW flows in their vicinity are closely linked. Some of the flow structures are ephemeral and are seen to emerge, develop and propagate over several days, and then disappear. There are longer-lived structures which arise and vanish on a time scale between a week and a month, and there are very long-lived structures which persist longer than a month and may evolve as the solar cycle progresses (Haber et al. 2000).

Monthly Synoptic Global Mappings of SSW

The meridional and zonal flows of SSW possess intriguing and complex meanderings on global scales. These large-scale flow properties are revealed by averaging velocities from the dense-pack mosaics at fixed longitude and latitude over the seven days that a given location remains within the observing matrix,

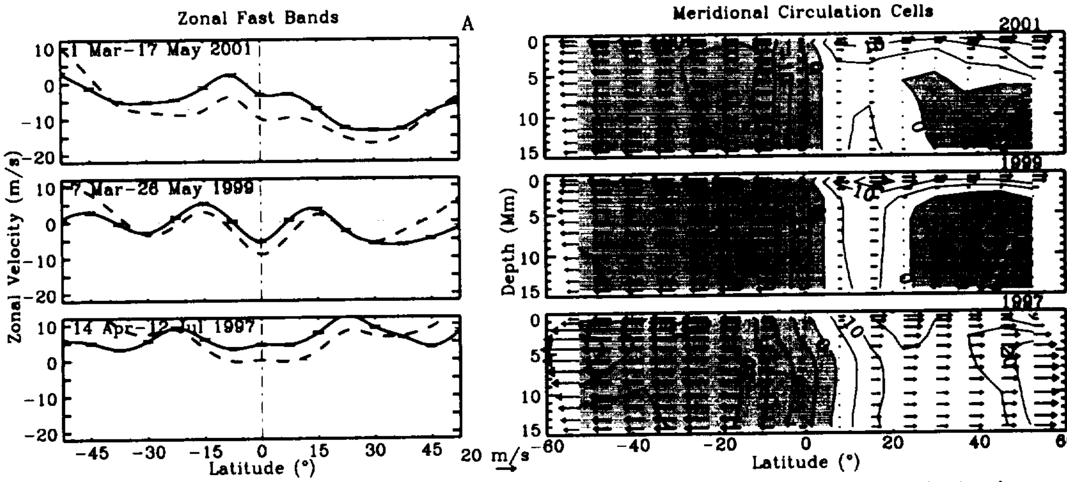

Figure 4. (*a*) Variation of the longitudinally and temporally averaged zonal flows with latitude at depths of 0.9 Mm (dashed) and 7.1 Mm (solid) as sampled in several month intervals in the years 1997, 1999, and 2001. The zonal flow is measured relative to the surface rotation rate and for clarity is offset by a constant that varies with depth. (*b*) The meridional flow as a function of latitude and depth, with gray regions being southerly flow and white regions northerly. The mean meridional flow is consistently poleward (southerly) in the southern hemisphere (negative latitudes). It is likewise poleward near the surface in the northern hemisphere, but at greater depths in the later years the circulations are reversed within a submerged midlatitude cell [Haber et al. 2002].

yielding synoptic maps for a range of depths for each Carrington rotation. Figure 3*a* is such a synoptic map at a depth of 7.1 Mm for one rotation in 1997 when the magnetic activity was relatively weak, showing meandering jets and wavy flow structures. There exists a poleward meridional circulation in both hemispheres, and a net prograde zonal flow (here to the right) due to the increasing rotation rate with depth that occurs within the near-surface shear layer. Coexisting with these flows is a low-order undulation in longitude, somewhat reminiscent of the jet stream flow present in the earth's atmosphere; it is possibly an inertial wave response (e.g., Ulrich 2001). This undulatory pattern changes from one rotation to the next, as do the convective structures that are seen in the numerical simulations, which distort and propagate and thus are unidentifiable from one rotation to the next (Brun & Toomre 2001, 2002). Figures 3*b* and 3*c* present synoptic maps for rotations in 1999 and 2001 when the sun was magnetically active. Many of the large-scale flow patterns are clearly correlated with the presence of magnetic active regions, which appear as zones of convergent flow.

Year-to-Year Evolving Global Circulations

There are also pronounced changes with solar cycle in the mean zonal and meridional flows (obtained by averaging over all longitudes), as shown in Figure 4 for the three years 1997, 1999, and 2001. Figure 4*a* shows the mean zonal flow with latitude at two depths, confirming the presence of fast bands of zonal flow that propagate toward the equator as the cycle advances (Haber et al. 2001b,c; Haber et al. 2002). The gradual migration of these zones of slightly faster rotation are clearly evident once one has subtracted out the dominant latitudinal variation of differential rotation. These bands correspond to the 'torsional oscillations' known from Doppler measurements of the surface (e.g., Howard & LaBonte 1980; Hathaway et al. 1996; Ulrich 1998). They are also seen in global *f* and *p*-mode studies (e.g., Kosovichev & Schou 1997; Schou 1999; Howe et al. 2000). Our ring-diagram studies reveal that the zonal fast bands in the northern and southern hemispheres are increasingly less symmetric in recent years. We find that the main sites of sunspot emergence tend to lie about 10° poleward of the evolving latitudinal position of the faster zonal bands, suggesting that the dynamics are related, though it is unclear how this is accomplished. Turning to the mean meridional flows shown in Figure 4*b*, we note the emergence of reversed meridional circulations in the northern hemisphere as the sun has become more magnetically active. During 1996 and 1997 the meridional circulation is primarily poleward in both hemispheres. The flow speeds are typically 20 m s^{-1} and are remarkably constant with depth. In the years 1998 through 2002, there is a striking change of behavior in the northern hemisphere, where at midlatitudes and at greater depths, a flow cell with reversed meridional circulation appears (see also Figs. 3*b*,*c*). The flow just below the surface remains poleward. The depths and latitudes over which this submerged cell spans varies from year to year. Such a submerged cell with reversed circulation is a fascinating finding, and its presence serves to emphasize that the flow responses contributing to SSW in the near-surface shear layer can possess prominent differences (or symmetry breaking) in the two hemispheres.

3. References

(Detailed citations to our recent work with partial support from this grant)

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