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A NEW COMPONENT OF SOLAR DYNAMICS: NORTH-SOUTH DIVERGING FLOWS MIGRATING TOWARD THE EQUATOR WITH AN 11 YEAR PERIOD

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ABSTRACT

Time-distance helioseismology analysis of Dopplergrams provides maps of torsional oscillations and meridional flows. Meridional flow maps show a time-varying component that has a banded structure that matches the torsional oscillations with an equatorward migration over the solar cycle. The time-varying component of meridional flow consists of a flow diverging from the dominant latitude of magnetic activity. These maps are compared with other torsional oscillation maps and with magnetic flux maps, showing a strong correlation with active latitudes. These results demonstrate a strong link between the time-varying component of the meridional flow and the torsional oscillations.

Subject headings: Sun: atmospheric motions — Sun: rotation

1. INTRODUCTION

Torsional oscillations and meridional flows have been studied for over two decades (e.g., Duvall 1979; LaBonte & Howard 1982; Ulrich 1988). The meridional flow is generally agreed to have a poleward flow in both hemispheres with an amplitude of 10–20 m s^{-1}; the torsional oscillations (also termed “zonal flows”) consist of latitudinal bands of alternating faster and slower rotation that migrate toward the equator over the solar cycle and are superposed on top of the differential rotation. The time-distance helioseismology studies of meridional and torsional oscillations conducted by Giles et al. (1997) and Giles (2000) showed that meridional flows extend through the convection zone and torsional oscillations extend to at least 35 Mm below the surface.

Howard & LaBonte (1980) showed torsional oscillations as a 5–10 m s^{-1} flow pattern superposed on differential rotation that migrates toward the equator over the solar cycle similar to the “butterfly diagram” showing latitudes of magnetic activity. Recently, helioseismic techniques have been applied to probe the depth extent of torsional oscillations (e.g., Kosovichev & Schou 1997; Schou et al. 1998). The flows have been seen to extend to depths of 56 Mm (Howe et al. 2000). Furthermore, Beck & Schou (2000) have seen torsional oscillation patterns in supergranulation.

Meridional flows have been difficult to measure by direct Doppler observation owing to their small amplitude compared to the large-amplitude velocity patterns such as convective limb shift and rotation. However, Nesme-Ribes, Meunier, & Vince (1997) have studied meridional flows using sunspots as tracers and have identified a covariance of east-west and north-south motions consistent with angular momentum transport, which would sustain differential rotation. Time variations of the meridional flow were noticed by Ulrich (1988) and Hathaway (1996). Haber et al. (2002) have studied meridional flows using ring-diagram analysis. They have found indications of a second meridional cell during the years 1998–2001 in the outer 7 Mm. In addition, they found an asymmetry in the meridional flows between the northern and southern hemispheres that would have impact on angular momentum transport. Chou & Dai (2001) have studied subsurface meridional flows using time-distance helioseismology and found a time-varying component that extends down to 70 Mm. It was suggested that the varying flow could be linked to magnetic activity.

2. DESCRIPTION OF DATA AND REDUCTION TECHNIQUES

The data reduction followed the description by Giles (2000). The data spanned 1996 May through 2001 July and consist of medium-resolution Dopplergrams obtained from the Michelson Doppler Imager (MDI) instrument (Scherrer et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*) spacecraft. The gap in data from 1998 June until 1999 March corresponds to the period of broken contact with *SOHO*. Images were grouped into 72 hr periods for detrending of solar rotation and supergranulation. Regions, spanning 100° in latitude and longitude, were tracked at the solar rotation rate for the 72 hr period. These tracked regions were “stacked” into a data cube for further processing, which consisted of applying a high-pass filter (cutoff at 1.7 mHz) to remove the residual supergranule signal and applying a phase-speed filter to select acoustic modes with a range in ω/k_h, where ω is the temporal frequency and k_h is the horizontal wavenumber.

Once the data had been prepared, temporal cross-correlations were obtained using code developed by Giles (2000). Meridional flows were studied using correlations between pairs of points, separated in latitude by amounts ranging from 3° to 45°. To enhance the signal, the points were not always aligned in a strictly north-south direction. In cases when a point was displaced in longitude, a second pair, displaced in the opposite sense, was used to cancel the effect of orthogonal flows. To improve the signal-to-noise ratio, the resulting cross-correlation functions were averaged over all observed longitudes and saved to files for each nominal latitude. Subsequently, the cross-correlation function for each latitude was averaged over 3 month periods. Further averaging was done over the ranges of latitudes, keeping the midpoint constant, producing 61 latitude bins, with a width of ∼3°. This was repeated for 21 3 month epochs. This procedure was also performed in an east-west direction to measure torsional oscillations.

3. ANALYSIS AND RESULTS

Wave travel times were measured by fitting to the cross-correlation function. A positive time delay corresponds to a flow to the north in the case of meridional flows or a flow to the west for east-west flows. The measurement of the travel-time shifts due to flows follows closely the method discussed by Gizon & Birch (2002). At each distance, a mean reference cross-correlation symmetric for the two senses of time lag was derived. This reference function was cross-correlated with an individual cross-correlation to yield an approximately zero-centered result except for the shift away from zero due to the flow. A weighted average over distances was derived with the contribution peaked near a distance of 17° with a width of 4°. A ray connecting points separated by 17° extends to a depth of 65 Mm. The time shift was measured as twice the shift of the maximum of this correlation away from zero lag by forcing a parabola through the three closest points to the peak. The factor of 2 is necessary to match earlier definitions of time shift, which involved measuring the shift of positive time lags and negative time lags separately and taking the difference, effectively doubling the signal.

The meridional flow is strongly antisymmetric as a function of latitude (shown in Fig. 1), with positive values indicating flows in the northward direction. The peak velocity is about 15 m s^{-1} toward the pole at midlatitudes, going to zero near the equator.

Small errors in the pointing of the MDI telescope (*P*-angle) can cause solar rotation to contaminate meridional velocity measurements. Taking the antisymmetric component removes this error. The time-varying component of the meridional flow was obtained by subtracting a smooth fit to the 5 yr average of the measurement at each epoch. Figure 2*a* shows the resulting time-varying residuals after applying a three-point (0.25, 0.5, 0.25) smoothing in both latitude and longitude. To better compare with east-west motions, the sign of the signal in the southern hemisphere is reversed, with red indicating poleward motion in both hemispheres.

The east-west flow was similarly analyzed, with the exception that the north-south symmetric component of rotation was subtracted from the signal to produce the torsional oscillation pattern shown in Figure 2*b*. Torsional oscillations obtained from *f*-modes by Schou (1999) are shown for comparison.

A map of magnetic field strength is included in Figure 2*d* to indicate the active latitudes over the period of interest. To compare with the flow maps, a mean latitude of magnetic activity was derived corresponding to the calendar quarters of the velocity analysis by averaging the absolute value of MDI magnetic synoptic charts for the appropriate Carrington rotations, rebinning in latitude and longitude to again match the velocity analysis, symmetrizing in latitude, squaring and fitting a Gaussian function in latitude at each longitude. The location of the peak of the Gaussian is then the mean latitude of activity. The fit was done to the square of the field strength so that the

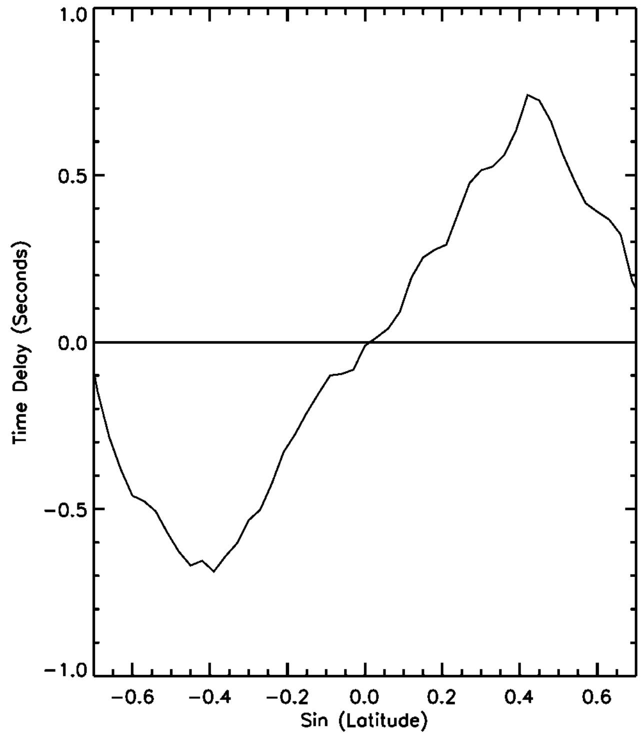

FIG. 1.—Mean meridional flow. The mean signal of meridional flows is shown here for the interval from 1996 May to 2001 July. A northward flow corresponds to a positive travel-time shift. From a simple meridional flow model (Giles 2000), we estimate that a 1 s time shift corresponds to ∼20 m s^{-1} .

background function would be inconsequential. The curve of mean latitude of activity is plotted on top of the velocity images in Figure 2 to indicate the strong connection between the activity and the equatorward propagating flow pattern.

The flows are organized about the mean latitude of activity. The north-south flow is away from this latitude, implying an upflow to conserve mass. Whether this upflow causes the magnetic activity to emerge at this latitude or is a result of rising magnetic flux is unknown. The torsional oscillation is faster equatorward of the mean activity latitude and slower poleward, as noted previously by LaBonte & Howard (1982). From the *p*-mode studies, we know that the torsional oscillation persists at depths of at least 56 Mm. In the present work, we have not derived the depth dependence of the north-south component explicitly, but we might expect it to persist over a similar depth.

4. DISCUSSION

The time-varying component of the meridional flow correlates very well with the torsional oscillations, with a more strongly poleward flow corresponding to a slower rotation. The lanes between bands of stronger or weaker flow match for both the meridional and torsional oscillations, and these lanes align with the mean latitude of magnetic activity.

This correlation between these flows and magnetic activity may be interpreted as a result of rising material, accompanied by rising flux tubes, diverging in the upper convection zone. Whether the diverging north-south flow is a cause or an effect of the rising flux tubes is unknown.

However, it should be noted that the covariation of the torsional oscillations and the time-varying meridional flows is not

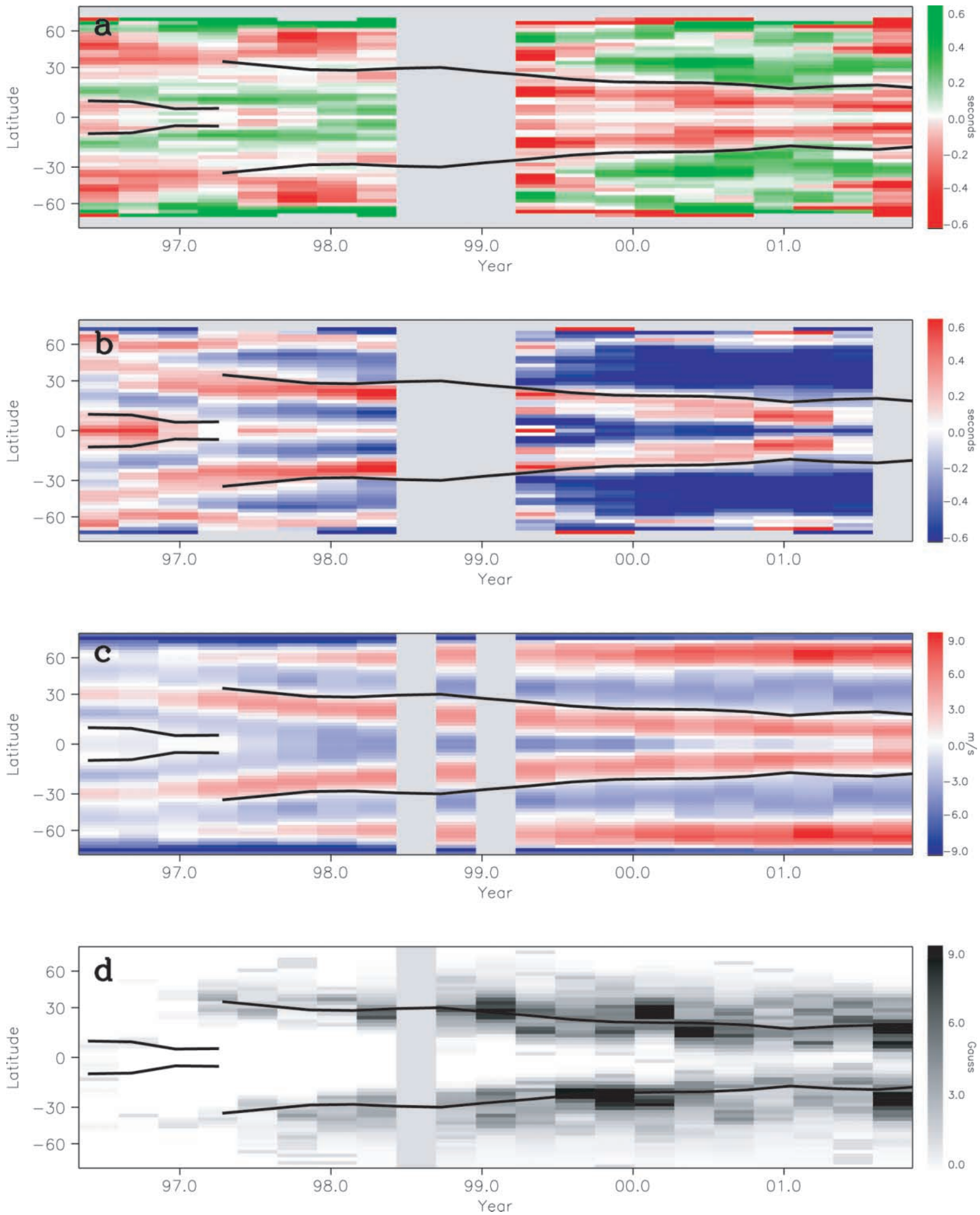

FIG. 2.—Residual meridional flow and torsional oscillation maps from time-distance helioseismology compared with a torsional oscillation map from *f*-modes and a butterfly diagram of magnetic fields. The thick black line overplotted is the mean latitude of activity. (*a*) Poleward flow, obtained from subtracting a fit to the mean meridional flow and symmetrizing the residuals. A positive time delay indicates a poleward flow in both hemispheres. (*b*) Torsional oscillations obtained from time-distance helioseismology. (*c*) Torsional oscillations obtained from *f*-mode frequency splittings (Schou 1999). (*d*) Mean magnetic field derived from MDI synoptic charts.

consistent with the Coriolis effect acting upon rising material. Rather, the covariance is consistent with angular momentum transport toward the equator.

Another interpretation could be that these time-varying flows are long-term averages of outflows from active regions.

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