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Helioseismology and the Solar Cycle: Past, Present and Future

Frank Hill
National Solar Observatory, Tucson, Arizona 85719, USA.
e-mail: fhill@noao.edu

Abstract. A major goal of helioseismology is to understand the mechanism of the solar cycle. In this paper, some results of helioseismic observations relevant to the cycle are briefly reviewed, the current state-of-the-art is discussed, and near-term future directions are sketched out. Topics covered include the internal rotation rate; activity-related parameter variations; the tachocline; far-side imaging; the torsional oscillation; and meridional flows.

Key words. Helioseismology—solar activity cycle—tachocline—far-side imaging.

1. Introduction

Helioseismology provides information about the solar interior using precise measurements of the properties of the acoustic oscillations trapped within the Sun. One of the goals of helioseismology is to understand the mechanism of the solar activity cycle. Three solar cycles have now passed since it was observationally confirmed that the solar five-minute oscillations are trapped below the photosphere (Deubner 1975) and that the modes can be used to probe the solar interior. In addition, the modern era of helioseismology, which dates from 1995 with the deployment of the Global Oscillation Network Group (GONG) instruments and the launch of the Solar and Heliospheric Observatory (SOHO) space mission, has recently completed coverage of cycle 23. It is thus timely to review the subject.

In this paper, some of the helioseismic results pertaining to the solar cycle will be briefly discussed. The current state of our knowledge will be covered, and some speculations about the future direction of the field will be presented. Due to space limitations, this is not a complete review by any means, thus the author apologizes in advance to those authors whose work is not mentioned.

2. The past

Three topics are reviewed in this section: the discovery of activity-dependent frequency shifts; the determination of the internal solar rotation and the discovery of the tachocline; and the birth of local helioseismology.

Using integrated-light irradiance measurements from the Solar Maximum Mission, Woodard and Noyes (1985) found that the low-degree oscillation frequencies were

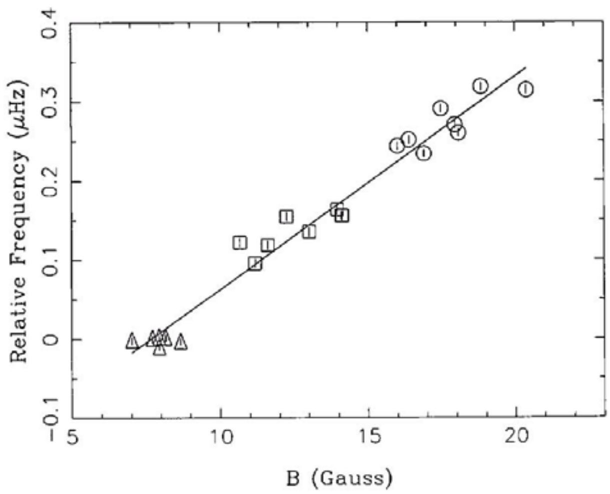

Figure 1. The linear relationship between frequency shift $\Delta\nu$ and surface magnetic field strength B as determined from Big Bear data in 1986 (triangles), 1988 (squares) and 1989 (circles). Adapted from Woodard *et al.* (1991).

0.4 μHz higher at solar maximum compared to solar minimum. This was the first evidence that oscillations varied with solar cycle. Subsequent work by Libbrecht and Woodard (1990) demonstrated that the frequency shifts were present for intermediate-degree modes, and had a strong frequency dependence. These observations were interpreted as evidence for latitude-dependent changes in solar structure associated with the activity cycle.

Woodard *et al.* (1991) studied the variations of the frequency on time scales of 22.8 days, one year and two years. They found that the frequency shift, $\Delta\nu$, is related to the surface mean magnetic field, B, by a linear relationship with a slope that is independent of the time interval between measurements (Fig. 1).

Since the observations show that $\Delta\nu$ depends strongly on frequency ν and only weakly on degree l, the source of the shifts must be close to the upper reflection point of the modes located immediately below the photosphere. It will be shown later that the spatial distribution of the shifts are highly correlated with the surface magnetic field, and that the slope $\partial\Delta\nu/\partial B$ depends on the time interval considered.

Prior to 1988, dynamo theories of the solar cycle (e.g., Gilman 1986) rested on the assumptions that the solar rotation rate decreased with depth from the surface, and that isorotation contours were parallel to the solar rotation axis (Fig. 2A). These assumptions were reasonable given the Taylor–Proudman theorem and the surface differential rotation. In 1988, the first 1.5-dimensional inversion of rotational splittings of global oscillation modes was published (Libbrecht 1988). The picture of the internal rotation was very different from that needed for the contemporary dynamo theories. The isorotation contours were roughly parallel to radii, not to the rotation axis (Fig. 2B).

The inversion also revealed the tachocline, the shear layer where differential rotation transitions to solid-body rotation (Fig. 2C). Located at base of convection zone, the tachocline is $\approx 0.05\,R_\odot$ in thickness. The surface rotation rate matches the sub-tachocline rate at a latitude of about 40°. This is near the latitude of sunspot

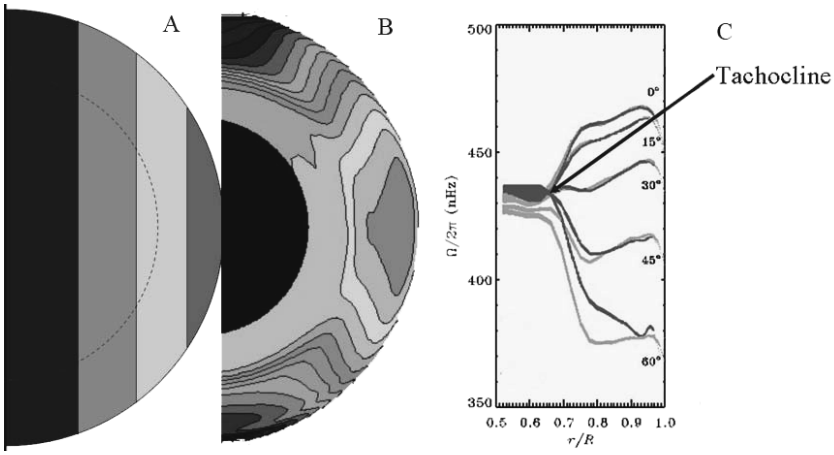

Figure 2. Panel (A): The isorotation contours assumed by pre-1988 dynamo theories. Panel (B): The isorotation contours revealed by helioseismology. Panel (C): Depth profiles of the rotational velocity at five latitudes. Dark grey lines are from MDI data, light grey lines are obtained from GONG data. The width of the lines shows the uncertainty in the measurements. The tachocline is indicated, where differential rotation in the convection zone transitions to solid-body rotation in the radiative envelope.

emergence early in the activity cycle. The existence of the tachocline was totally unexpected. It is currently thought that the dynamo operates in the tachocline, since a shear layer is an essential component of the dynamo mechanism.

The results discussed so far have been from the realm of global helioseismology, which decomposes the normal standing modes on the basis of spherical harmonics. This produces results that are averaged over the entire Sun, have no longitudinal information, and are symmetric in latitude across the equator. Since the Sun is not axisymmetric, it is of considerable interest to have helioseismic methods that can provide localized information. Such methods are known as local helioseismology. The common aspect of the techniques is the consideration of traveling waves rather than the normal modes. The analysis of the waves in localized areas can be used to obtain spatially resolved results. A comprehensive review of local helioseismology can be found in Gizon & Birch (2005).

Historically, the first local helioseismic analysis was the study of the absorption of *p* modes by sunspots. Braun *et al.* (1987) decomposed a circular area containing a sunspot into Hankel functions. They found that the amplitude of ingoing waves is higher than that of outgoing waves. This was the first indication that *p* modes can be used to sense localized conditions.

The ring-diagram analysis was developed in 1988 (Hill 1988, Morrow 1988). This analysis is based on a plane-wave representation and decomposes the waves in a localized area on the basis of sinusoids, valid for high-degree modes. In the resulting 3-D power spectrum at constant ν the ridges appear as rings, hence the name of the method. The position of the rings is a weighted average over depth of the horizontal velocity field below the analysis area. Thus, a 3-D map of the horizontal velocity field can be constructed.

Acoustic holography was developed by Lindsey and Braun (1990, 1997). In this method, a Green's function is computed that describes how an impulse originating from

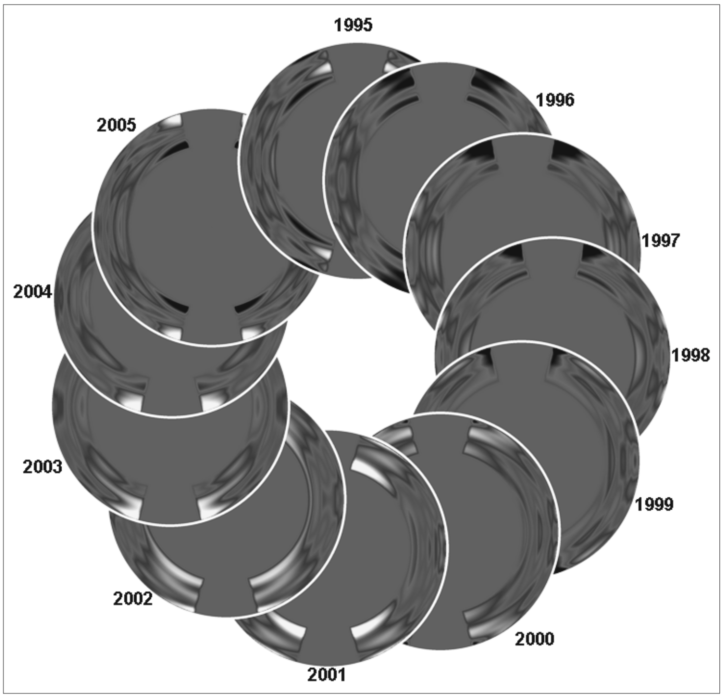

Figure 3. One solar cycle of convection zone velocity evolution as inferred from global helioseismic analysis of GONG data. Each circle is a cross-section of the solar interior for one-year intervals. Dark grey tones represent slower than average velocities, light shades are faster than average.

an arbitrary point appears at the surface. Using the Green's function, the wave field is mathematically time reversed to come to a focus at the coordinates of the original impulse. The focus can be located on the far side of the Sun as will be discussed later.

Time-distance analysis was initially developed by Duvall *et al.* (1993) and is very similar to methods used in terrestrial seismology. Acoustic waves emitted at the surface travel downward into the solar interior, are refracted upwards and reappear some time later and some distance away from the source. The time and distance is influenced by the conditions of the plasma that the wave propagates through. Time–distance diagrams are constructed by computing cross-correlation at many times T between a point and many distances D.

3. The present

We now turn to the present status of helioseismic analyses of the solar cycle. Space limitations restrict this section to only a few topics: convection zone changes; the tachocline oscillation; the torsional oscillation; surface distribution of mode parameter variations; far-side imaging; and meridional flows.

Recently, GONG and SOHO/MDI completed one solar cycle of imaging helioseismic observations covering cycle 23. Using the global modes, Howe *et al.* (2005)

have mapped the flows in the convection zone over the entire cycle. Figure 3 shows the evolution as a set of yearly averages of the velocity residuals. Several features are apparent. There are substantial fluctuations in the rotation rate in the tachocline. The torsional oscillation is clearly visible. Finally the polar regions are seen to rotate relatively slowly at solar minimum and accelerate as the cycle progresses. As the next minimum approaches, the high-latitude deep convection zone region decelerates. The deceleration region rises to the surface to complete the cycle.

Analysis of the residual rotation rate around the depth of the tachocline by Howe *et al.* (2000a) showed an apparent oscillation with a period of 1.3 yr visible in both GONG and MDI data. However, Antia and Basu (2000) were unable to confirm the result with an independent analysis. A more recent analysis by Howe *et al.* (2007) shows that the character of the oscillation may change during the cycle. Figure 4 shows the tachocline rotation rate as a function of time, and power spectra of the rotation rate for various epochs. From these spectra, it appears that there may be a coherent 1.3-yr oscillation in the rising phase that evolves into a more chaotic pattern in the declining phase.

The torsional oscillation was discovered by Howard and Labonte (1980) and appears as zonal flow on the surface with a velocity about 5 m/s greater than the local rotation rate. Active regions tend to emerge at the equatorward boundary of the flow. Work by Howe *et al.* (2000b, 2006) and Vorontsov *et al.* (2002) has demonstrated that the torsional oscillation pattern extends much deeper than the surface. The pattern is visible down to at least 40% of the depth of the convection zone, and there are indications that it may well exist throughout the entire CZ.

As discussed earlier, the frequency shifts associated with the solar cycle are mainly a surface effect. This is further demonstrated when the global frequency shifts are reprojected onto the solar surface. As shown in Fig. 5(A), the location of the shift regions is highly correlated with the activity bands (Howe *et al.* 2002). Studies of frequency shifts using ring diagrams also show large shifts, as much as 40 μHz, associated with specific active regions (Hindman *et al.* 2000). Finally, the lifetime and energy of the modes also vary with the activity level and are tightly correlated with the surface activity (Komm *et al.* 2002) as seen in Figs. 5(B) and 5(C).

Acoustic holography can produce maps of the phase shift arising from sound speed perturbations caused by surface activity on the far side of the Sun (Lindsey and Braun 2000). These far-side images can thus provide a prediction of the existence of large active regions as much as two weeks before solar rotation carries them to the front side where flares can influence terrestrial technology. Both GONG and MDI are currently providing continual near-real-time far-side maps on the web (González Hernández *et al.* 2006a). Figure 6 shows an example of a sequence of far-side maps showing AR10808 which subsequently produced a large X-class flare when it appeared on the east limb.

As discussed earlier, dynamo theories had to be revised after helioseismology revealed the true nature of the internal rotation rate. Modern flux-transport kinematic dynamo theories require a deep meridional return flow to transport flux from the poles back towards lower latitudes (e.g., Dikpati and Gilman 2006). So far, helioseismology has only been able to approximately measure the magnitude and depth of the return flow, the best current values from time-distance are 3 m/s at a depth of 0.8 $R_\odot$ (Giles *et al.* 1997).

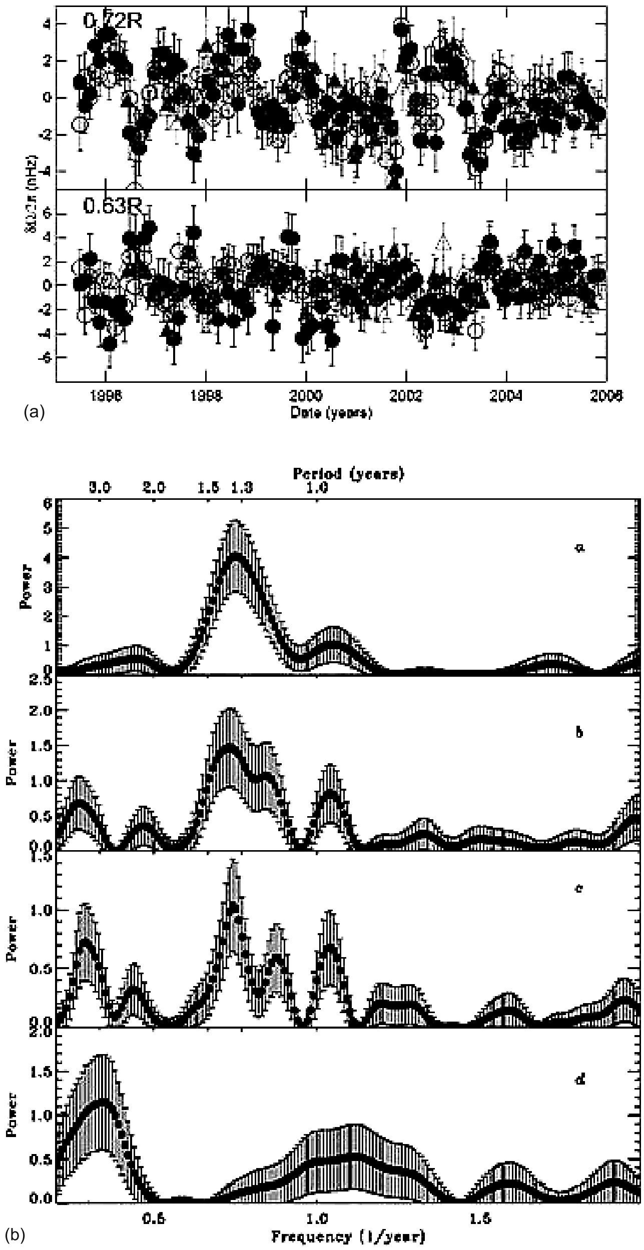

Figure 4. Variations in the rotation rate at the tachocline. **(a)** Residuals at the equator at 0.72 (top) and 0.63 (bottom) $R_\odot$, for RLS (filled) and OLA (open) inversions of GONG (triangles) and MDI (circles) data. **(b)** Power spectra of the rotation residual at depth 0.72 $R_\odot$ and latitude 0° from GONG RLS inversion. Four time periods are shown: (a) 1995–2000, (b) 1995–2003, (c) 1995–2005, and (d) 2000–2005.

In addition, some numerical models of solar convection exhibit a two-cell meridional flow with a counter-cell at high latitudes (e.g., Brun and Toomre 2002). Analysis of

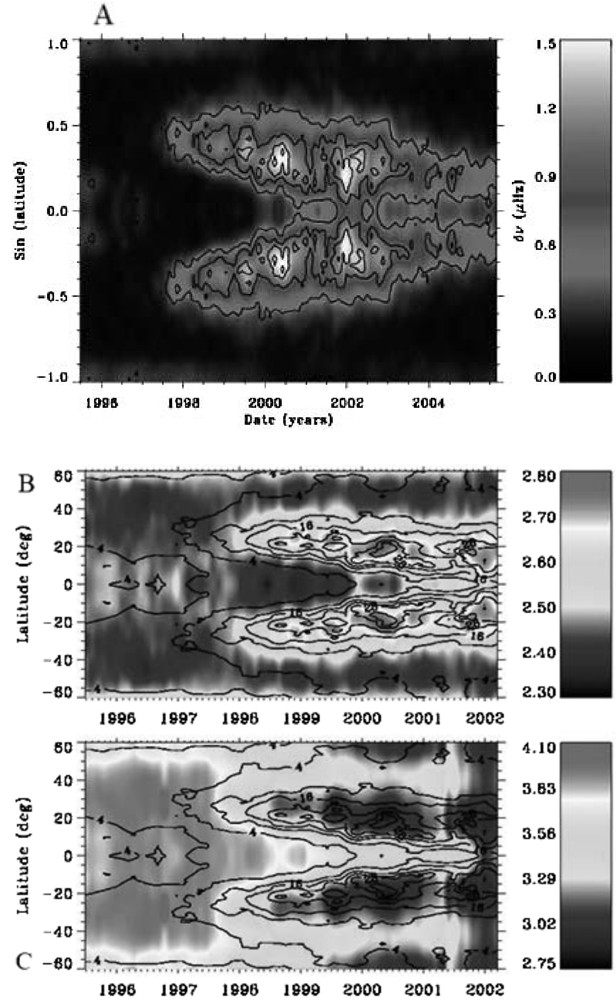

Figure 5. Global mode parameter shifts reprojected onto the surface show a very high correlation with surface magnetic activity. Panel (A): Frequency shifts. Panel (B): Mode width. Panel (C): Mode energy.

MDI data showed such a counter-cell near the north solar pole (Haber *et al.* 2002), but this is now thought to be a consequence of the annual variation of the solar B_0 angle (González Hernández *et al.* 2006b).

4. The future

What will be learned during cycle 24 from helioseismology? While predicting the future is always at best an approximation, there are some foreseeable developments. Since cycle 24 is the second half of a Hale cycle which began with cycle 23, there is considerable interest in continuing many of the current analyses to compare the internal solar dynamics between the two cycles. Will any difference be seen that can be related to the global polarity reversal?

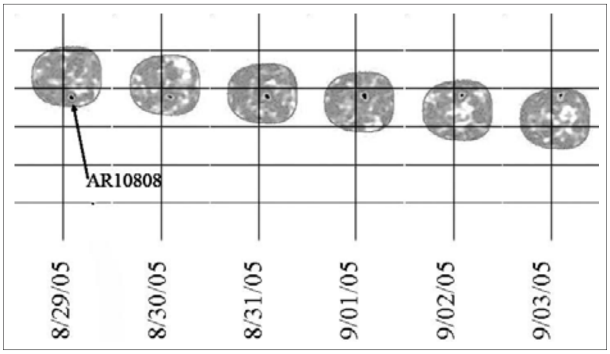

Figure 6. A sequence of far-side maps from 29 August 2005 to 3 September 2005 showing the signature of AR10808 as it rotated across the far side of the Sun. This active region produced a large X-class flare as it appeared on the east limb.

Of particular interest will be the behavior of the tachocline oscillation, if it exists. Will the 1.3-yr oscillation return with the ascending cycle? Another major question for cycle 24 is the existence of spatial structure in the tachocline. Can we see any signal of a structure in the tachocline that then evolves into an emerging active region? This will be a challenging observation for helioseismology – global analyses cannot provide spatial resolution, and the depth of the tachocline makes it difficult to observe with local methods.

Estimates of the characteristics of the deep meridional return flow are important to test modern dynamo theories. While some information will be gained by comparing the kinematic flux-transport dynamo predictions for the amplitude and timing of cycle 24 with what actually happens, it would be better to have helioseismic estimates. Current theories imply that the return flow has a magnitude of 1–2 m/s at the base of the convection zone, just beyond the capabilities of current helioseismic methods.

While the far-side images are already useful for predicting the appearance of active regions, they will be even more valuable if they can be calibrated in terms of active region properties. Recent work (González Hernández *et al.* 2007) has produced the first such calibration between the far-side signal, magnetic field strength, and area of active regions, but this initial work needs to be tested and improved.

The variation of the mode parameters over the solar cycle was the first indication that the oscillations can provide information about surface activity. It may thus be surprising if there is anything new to learn in this area, but recent work using very short nine-day time series has revealed a more complex relationship between the mode frequencies and the surface field. Tripathy *et al.* (2007) have shown that the slope of the linear relationship between $\Delta\nu$ and various activity indices varies with time and the phase of the solar cycle, as seen in Fig. 7. This suggests that there are two activity components that contribute to the variability of the slopes. The major contribution comes from the overall weak magnetic field, and hence during the ascending and descending phase of the cycle there is a strong correlation with activity. But during the maximum phase of the cycle, when the field is dominated by the strong field, due to the increase in the number and strength of the active regions, the slopes do not follow the activity measurements. Additional support for this scenario is provided by

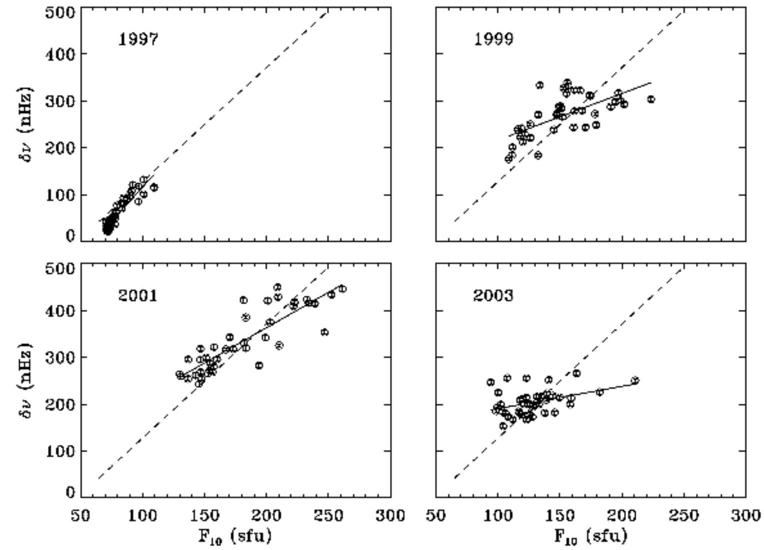

Figure 7. Mean frequency shifts plotted as a function of activity for four separate years. The solid line in each panel is the linear fit for that year. The dashed line is the linear fit for all datasets covering cycle 23.

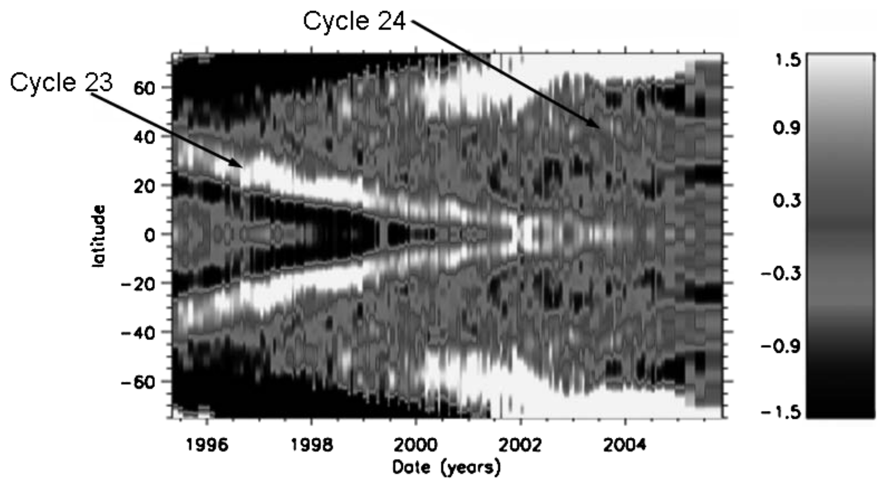

Figure 8. The torsional oscillation at a depth of 1000 km as function of latitude and time. The grey-scale bar indicates the rotation rate residual in nHz; 1 nHz $\approx$ 5 m/s. The flow associated with cycle 24 appeared in mid 2002, and seems to be substantially weaker than the flow for cycle 23. Does this predict a low amplitude for cycle 24?

similar results when the data are separated on the basis of latitude. Recent work by R. Howe (private communication) suggests that $\partial\nu/\partial B$ is different above and below 60° in latitude. Since no active regions are present at high latitudes, this may indicate that the interaction between the modes and the surface magnetic field is sensitive to the type of field.

Finally, every paper about the solar cycle should contain an audacious prediction about the next cycle. Figure 8 shows the temporal evolution of the torsional oscillation pattern at a depth of 1000 km below the photosphere. The flows associated with cycles 23 and 24 are indicated by arrows. The cycle 24 torsional oscillation appeared in mid 2002, and so far it seems that it is substantially weaker than the flow for cycle 23. Does this mean that cycle 24 will have a lower amplitude than cycle 23? Only time will tell.

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