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Facility: MtW:46m solar tower

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Polar Upwelling at Three Sunspot Minima

ROGER K. ULRICH ¹, THAM TRAN,¹ AND JOHN E. BOYDEN¹

¹ *Dept. of Phys. and Astro.,*

University of Calif. at Los Angeles

475 Portola Plaza, Los Angeles, CA 90095-1547

ABSTRACT

We summarize the analysis methods used to derive differential rotation leading to the Torsional Oscillations (TO) and a new method for determining Meridional Circulation (MC). The new MC results show a reversal of the flow direction at near-polar latitudes with the time of reversal corresponding closely to the time of Sunspot Minima.

1. HISTORY

In order to regularize the reduction methods, we have carried out a re-analysis of the Doppler shift velocities and line-of-sight magnetic fields measured with the Babcock magnetograph at the 150-foot solar tower telescope on Mt. Wilson. The digital records begin in 1967 but the implementation of a revised calibration procedure in late 1982 produced a much improved record so we have concentrated on the period 1983 to the end of 2012 when the observations ceased due to the failure of the control computer and the loss of funds.

2. OBSERVATIONS

Several large-scale solar velocity structures need to be subtracted before the patterns known as Torsional Oscillations and Meridional Circulation can be revealed. The two structures we remove

are the limb shift and the differential rotation. The limb shift is a consequence of vertical convective motions for which hot, rising matter is overweighted so that there is an apparent, position dependent blue shift. For the limb shift we follow the approach described by [Ulrich et al. \(1988\)](#). That publication gives an extensive discussion of the issues involved with the limb shift and defines the zone parallel to the equator used for the fit. This zone, defined in heliographic coordinates, is $\pm 4/17 \times R_{\odot}$ wide. We excluded pixels with a magnetic field in excess of 20 Gauss and the fit yields an equatorially binned limb shift function.

The overall observing process is described in [Ulrich et al. \(2002\)](#). During the observing scan of the solar image the spectrophotometric parameters along with the control guider positions and the time are recorded at regular intervals. Each scan line goes off the edge of the solar disk and the parameters are recorded for those pixels to allow determination of the limb position and scattered light. Because the pixel positions are irregular relative to heliographic coordinates, the reduction finds the limb position and interpolates the observed quantities into a regular grid and makes an adjustment of position using differential rotation to bring all pixels to a common time. Reduced data we use here has been binned into 34×34 arrays for which the pixels are at regular intervals of $\sin(\phi)$ and $\sin(L)$ where ϕ and L are heliographic latitude and central meridian distance.

The effect of scattered light is removed after the completed reduction through a correlation between the measured scattered light values and the parameters from the whole observation and the adopted parameter value is found by extrapolation to zero scattered light.

3. DIFFERENTIAL ROTATION

The solar differential rotation is typically described by a polynomial of the form:

$$\omega = A + B \sin^2(\phi) + C \sin^4(\phi) \quad (1)$$

where ω is the sidereal rotation rate and ϕ is the latitude. This formula was used by [Howard & Harvey \(1970\)](#) and has been discussed subsequently ([Howard 1976](#); [Labonte & Howard 1982](#); [Snodgrass 1985](#)).

We do not attribute physical significance to the coefficients and carry out the differential rotation fitting with B and C fixed so that the variation shows up in the latitude dependent coefficients. The A

coefficient is fitted and subtracted from each observation. It shows large variations from day to day, probably due to supergranulation, and also has year-long trends which do not correspond to solar phenomena we have been able to identify. We obtain a good Torsional Oscillation map by binning daily averages into three Carrington Rotation intervals then subtracting the average over the 1983 to 2012 time period to yield a rotation rate deviation $\delta\omega$.

4. MERIDIONAL CIRCULATION

We have used a new method to study the meridional circulation pattern. After subtraction of the equatorially binned limb shift function, we determine line-of-sight difference velocities δV within each of the 34 latitude bands as a function of $\sin(L)$. We fit δV to a quadratic function of $\sin(L)$ for pixels with $|\sin(L)| < 0.75$ and then evaluate this function at $L = 0$. This gives an offset velocity difference along the central meridian. We average these values of δV over each year.

5. DISCUSSION

The figure shows the two functions $\delta\omega$ and δV along with the times of sunspot minima. The polar regions show approaching (negative) velocity for each of the minima while the rotation rate slows down in the polar regions at the same time. Matter approaching in the polar regions must originate from mass upwellings at the poles. Because this matter has little angular momentum as it flows outward, it retards the rotation rate of the matter it joins at lower latitudes. This deviation in rotation rate could trigger the start of the Torsional Oscillations and the deviation is well aligned with the lower latitude slowdown wave.

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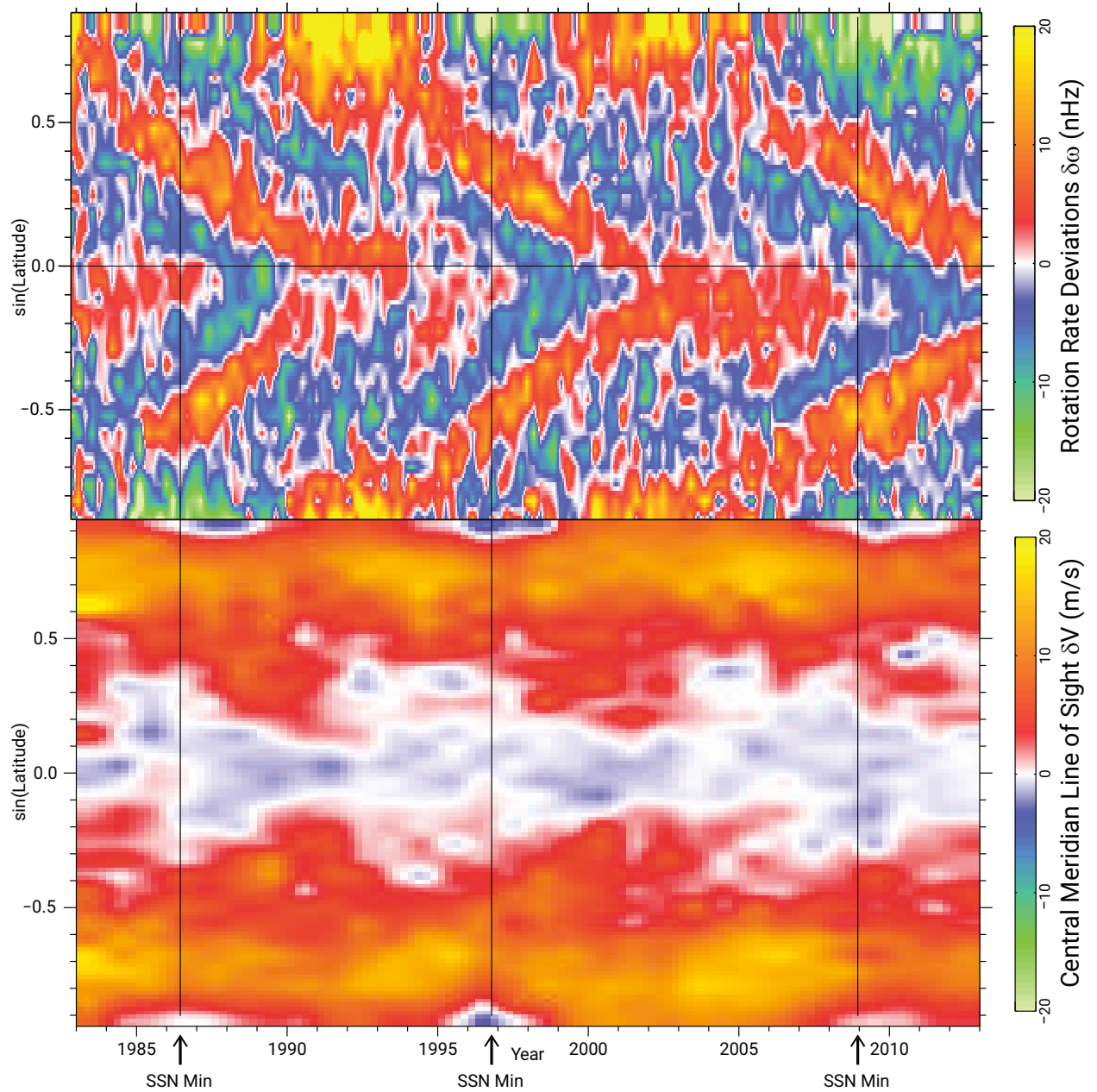


Figure 1. Comparison of the latitude and time dependence of the rotation rate deviation $\delta\omega$ (Top plot) to the line-of-sight velocity offset δV (Bottom plot). For δV poleward flow is positive in both hemispheres. Times of sunspot minima are shown by the arrows below the figure and by the vertical lines through the figure.

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