Solar Cycle Changes Over 11 Years of Medium-Degree Helioseismic Observations

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Introduction

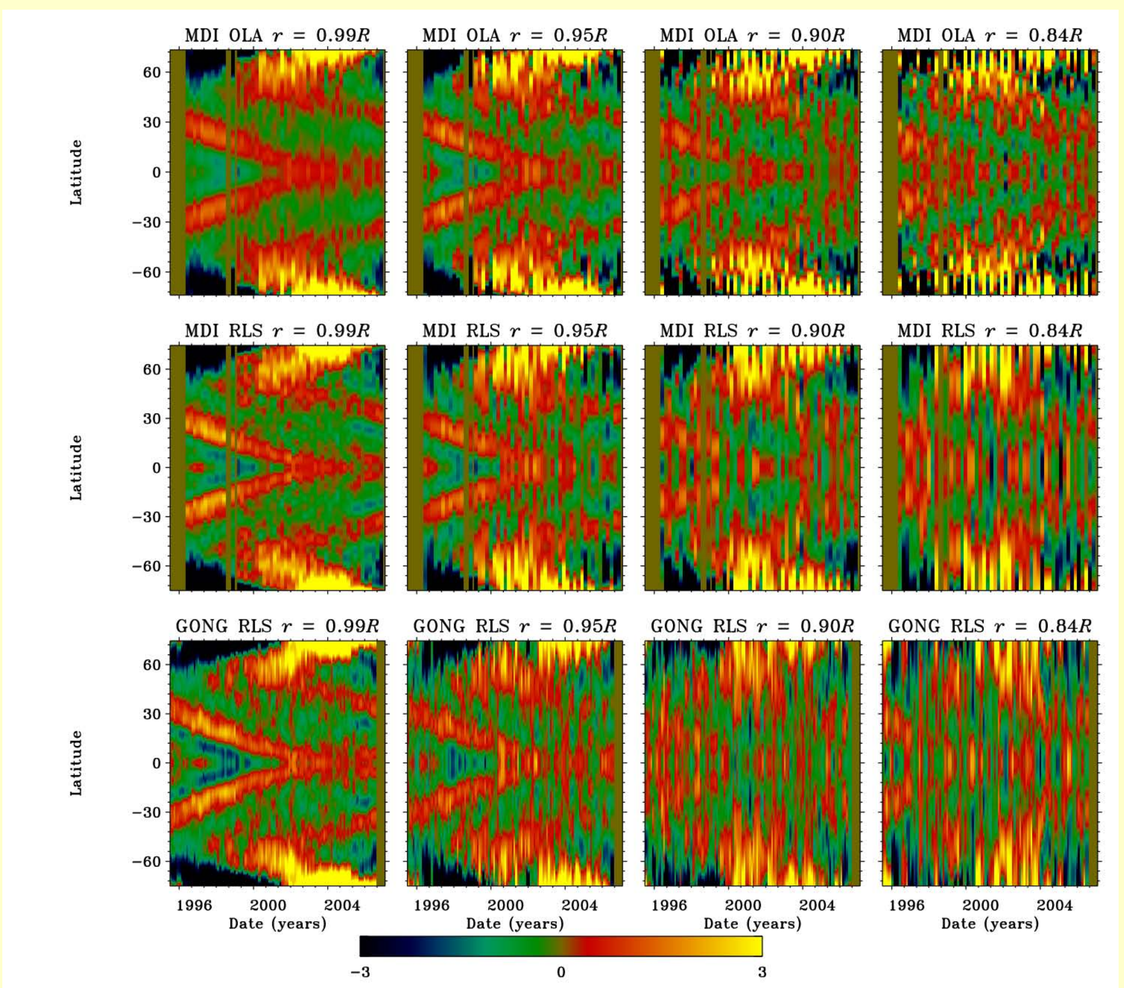
The Global Oscillations Network Group (GONG) has now completed, and the Michelson Doppler Imager (MDI) aboard SOHO will soon complete, a full eleven years of continuous observations of the medium-degree solar oscillations. This enables us to follow changes in the acoustic mode parameters and interior dynamics over a full solar cycle. We present results from the observations of convection-zone dynamics, in which the torsional oscillation pattern seen at the surface can be followed throughout most of the bulk of the convection zone, and also changes in the frequency, lifetime and amplitude of the modes which can be shown to be closely related in space and time to the migrating pattern of surface activity.

The Data

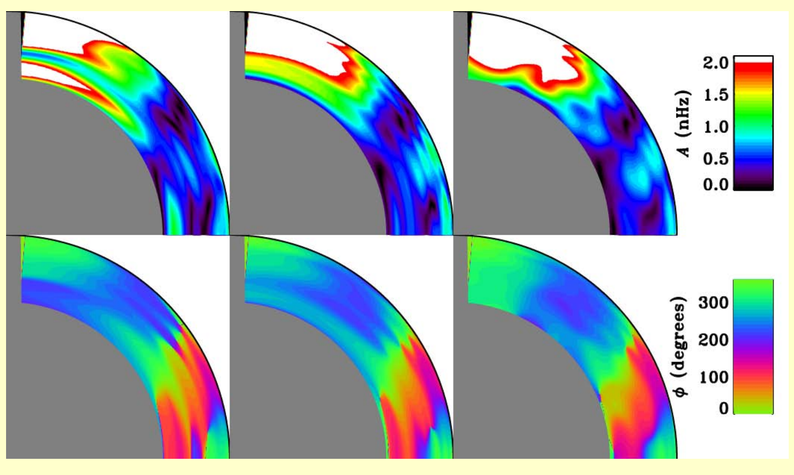
The GONG data consist of 112 sets of medium-degree mode parameters, each derived from 108 days of observations with start dates at 36 day intervals. Observations start in 1995 May and have been analyzed through 2006 July. The analysis includes modes up to l=150; because the spectrum for each azimuthal order is analyzed independently, we can obtain information on the variation of the mode widths and amplitudes, as well as frequencies, as a function of the azimuthal order m and hence as a function of latitude. The MDI data cover the period from 1996 May to 2006 December in non-overlapping 72 day periods, with brief interruptions in 1998 and 1999. The analysis used for these data fits all azimuthal orders for a given degree together, expressing the frequencies as a 36-term polynomial expansion; this method allows the fitting of modes up to l=300, but does not take account of latitudinal variations affecting the mode width and amplitude.

Convection-Zone Dynamics

The pattern of migrating zonal flow bands known as the torsional oscillation can be seen through much of the bulk of the convection zone using global inversion techniques (Howe et al. 2000, 2005, Vorontsov et al. 2002). Here we show the residual inferred rotation rates after subtracting the mean rotation profile, as a function of date and latitude at different depths. We show results for both GONG and MDI; for MDI we show the results using two different inversion techniques.



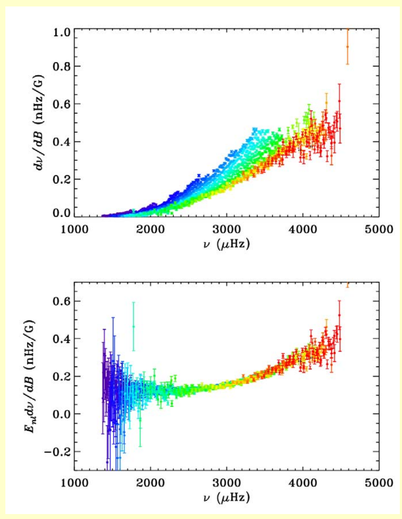
The branches propagating from mid-latitudes towards the poles and equator can clearly be seen in this figure; notice that the a new equatorward branch is visible from about 2002. There is evidence of a phase shift with depth, at least for the lower-latitude part of the pattern.



The plots at left show the amplitude (top) and phase (left) of 11-year sinusoids fitted to the rotation-rate variation, for GONG RLS (left), MDI RLS (middle) and MDI OLA (right) inversions. Like the contours of constant rotation, the lines of constant phase lie at an angle of about 25° to the axis.

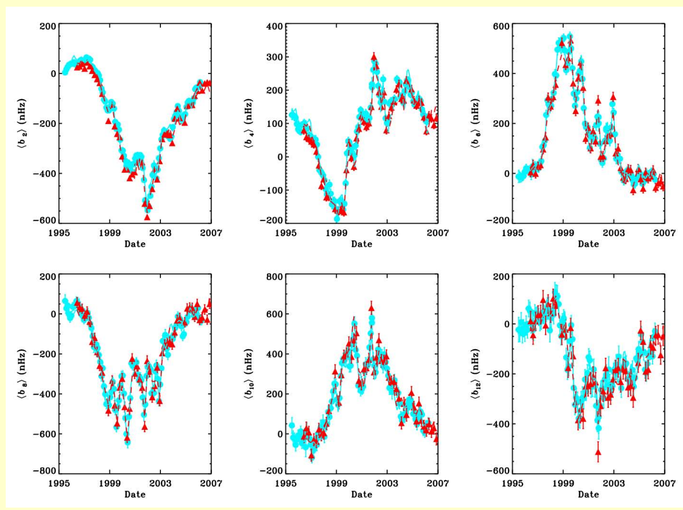
Mode Frequency Shifts

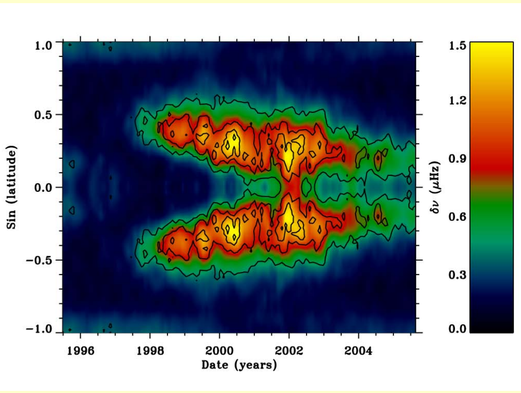
Magnetic activity variations bring about small shifts in the frequencies of the normal modes. These changes have been shown to follow not only the overall variation of the gross magnetic field strength, but changes in its latitudinal variation, which are detectable because modes of different m sample different latitude ranges (Howe, Komm & Hill 2002 and references therein).



For medium-degree modes, the variation of the central frequency of the multiplet is well described by a linear trend with the global magnetic field index, but the slope of this trend varies with the frequency and radial order of the modes. The plots at left show the sensitivity to magnetic index, color-coded by radial order n, in unweighted form in the top panel and weighted by the inverse mode inertia in the lower panel. The mode inertia weighting (first used by Libbrecht and Woodard 1990), collapses the sensitivity points onto a single curve, suggesting that the effect is concentrated close to the surface.

The plots at right show the variation of the first six even-order coefficients of the polynomial expansion of the m-dependence of the frequencies within a multiplet, averaged over the modes that are common to all the data sets, for GONG (blue) and MDI (red.) The dashed curves show the best fit to the variation of the corresponding terms of the Legendre decomposition of the latitudinal magnetic field distribution.

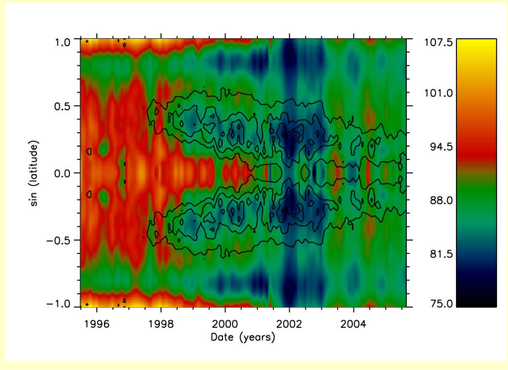


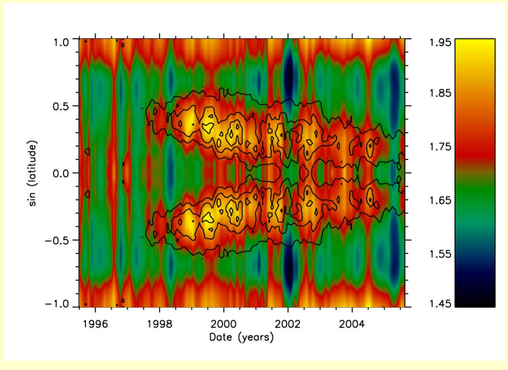


Using the GONG data with frequencies for each m, we can carry out a latitudinal 1-dimensional inversion to relate the frequency changes to the activity distribution in time and latitude. The results of such an inversion, averaged over modes with $40 \le l \le 80$ and $8 \le n \le 10$, are shown in the figure at left, where the color scale is in μHz and the contours show the gross magnetic field strength at 10 G intervals. The frequency shifts are well correlated with the activity levels in space and time; the higher latitudes show less sensitivity.

Width and Amplitude Variations

In a similar way, we can invert the changes in width and amplitude of the modes of different m to show their relation to the surface magnetic activity (Komm, Howe and Hill 2002), as shown below for amplitude (left, in 10^{30} erg) and width (right, in μHz). The upgrade in 2001 to the higher-resolution "GONG+" cameras changed the detected mode amplitudes slightly, so the data have been roughly corrected for this effect by adding a 10-unit offset. As is also seen in local and unresolved analyses in the 5-minute frequency band, the mode amplitude is suppressed and the width (inversely proportional to lifetime) enhanced in the presence of activity.





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Acknowledgements

This work utilizes data obtained by the Global Oscillation Network Group (GONG) program, managed by the National Solar Observatory, which is operated by AURA, Inc. under a cooperative agreement with the National Science Foundation. The data were acquired by instruments operated by the Big Bear Solar Observatory, High Altitude Observatory, Learmonth Solar Observatory, Udaipur Solar Observatory, Instituto de Astrofisica de Canarias, and Cerro Tololo Interamerican Observatory. The Solar Oscillations Investigation (SOI) involving MDI is supported by NASA grant NAG 5-13261 to Stanford University. *SOHO* is a mission of international cooperation between ESA and NASA. RK, and RH in part, were supported by NASA contracts S-92698-F, NAG 5-11703, and NNG 05HL41I.