Inside the Stars, IAU Colloquium 137
ASP Conference Series, Vol. 40, 1993
Werner W. Weiss and Annie Baglin (eds.)

SEISMIC EVIDENCE OF MODULATION OF THE STRUCTURE AND ANGULAR VELOCITY OF THE SUN ASSOCIATED WITH THE SOLAR CYCLE

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INTRODUCTION

Solar p-mode multiplet oscillation frequencies and expansion coefficients for degeneracy splitting have been measured in the summers of 1986 and 1988–1990. Temporal variations not unlike the differences between 1988 and 1986 reported by Libbrecht & Woodard (1990) continue into 1990. These differences are possibly associated with the solar cycle. We report here on our first findings about the variation of the internal angular velocity and asphericity deduced from these frequency differences.

INVERSION RESULTS

Figure ?? illustrates the angular velocity of the sun in the years 1986, 1988, 1989 and 1990 inferred from inverting the odd coefficients in the degeneracy-splitting expansion

$$\nu_{n,l,m} - \nu_{n,l,0} = l \sum_{k=1}^{5} a_k P_k(m/l)$$

of data acquired at Big Bear Observatory and analysed by the procedure described by Libbrecht (1989). The angular velocity is plotted as a function of radius for three values of colatitude θ.

Because the differences are small, we have inverted the data both as optimally localized averages and by a regularized least-squares procedure.

A contour plot for 1989 is shown in Figure ??*a*. Notice that Ω is approximately constant on cylinders in the very equatorial regions. The averaging kernels are insufficiently localized at high latitudes for us to be certain that that behaviour does not persist further than suggested by the figure.

Although the differences from year to year are comparable with the differences between these methods of inversion, those methods yield comparable

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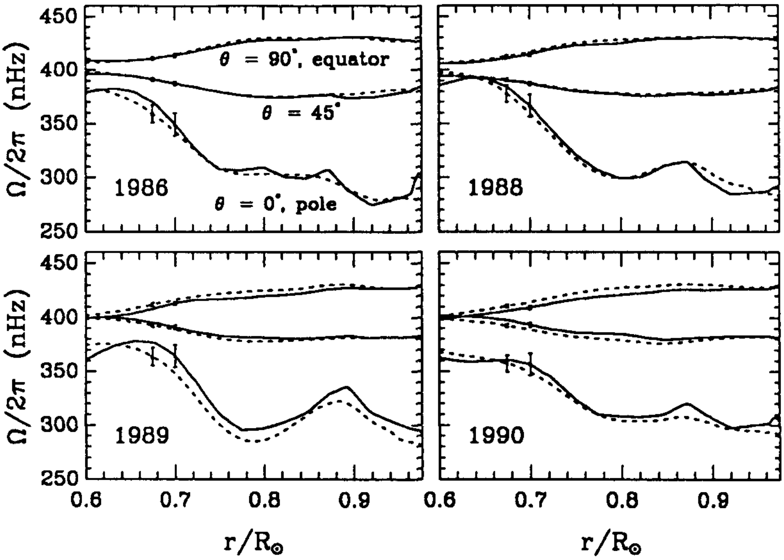

FIGURE I The solar angular velocity $\Omega/2\pi$ against r for $\theta = 0, \pi/4$ and $\pi/2$. The continuous lines are optimally localized averages, the dashed lines are regularized fits by least-squares.

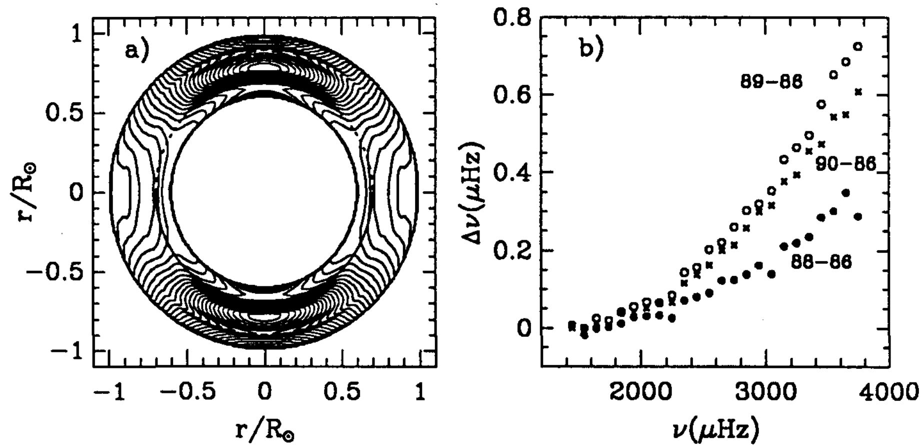

FIGURE II a) Contours of constant $\Omega/2\pi$ in 1989. Adjacent contours are separated by 5 nHz. The dashed circle shows the bottom of the convection zone. b) Multiplet cyclic frequency deviations from the corresponding values in 1986.

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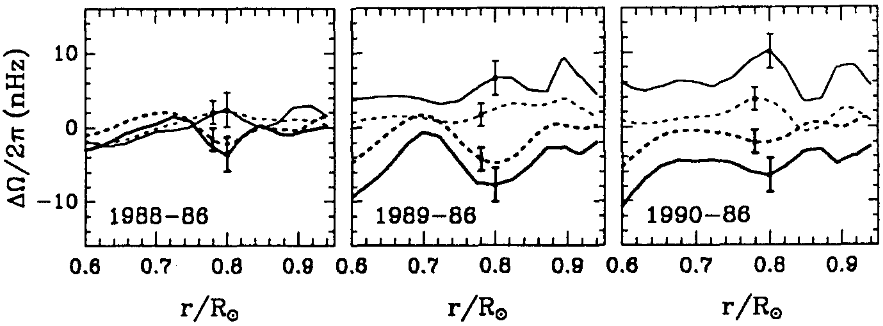

FIGURE III Deviations of $\Omega/2\pi$ from its value in 1986 for $\theta = \pi/4$ (thin lines) and $\theta = \pi/2$ (thick lines). Continuous lines are optimal averages and dashed lines are least-squares fits.

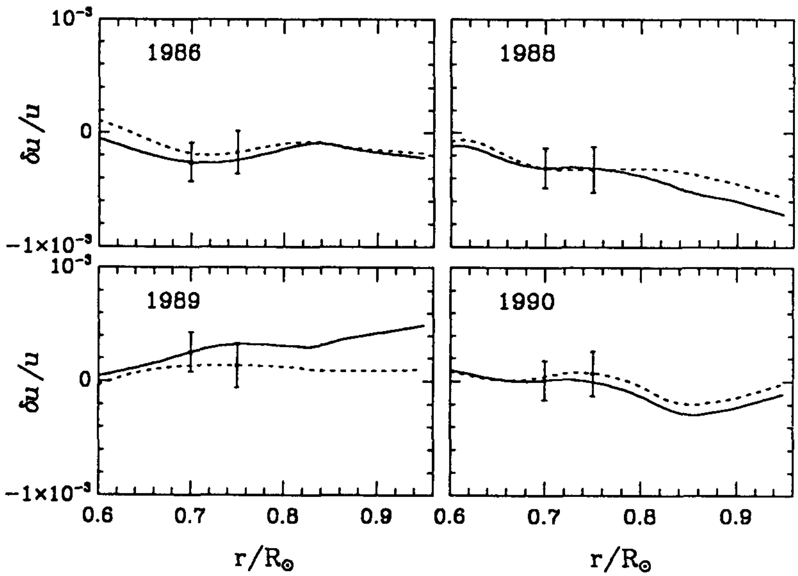

FIGURE IV Relative difference $\delta u/u$ between the value of u in the sun and that of a standard reference model for $\theta = \pi/4$ (dashed lines) and $\theta = \pi/2$ (solid lines)

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temporal trends, as shown in Figure III, suggesting, in agreement with the statistical analysis of 1986 and 1988 data by Gough & Stark (1992), that the sun's angular velocity does change with the solar cycle.

The multiplet frequency variations are plotted in Figure II*b*. As was previously reported by Libbrecht & Woodard (1990), most of the variation is inversely proportional to the modal inertia, suggesting that most of the temporal variation in the sun is in the very outer layers. The same is true of the even splitting coefficients. After removing that dominant trend, inversions for δu, the difference between $u = p/\rho$ in the sun and u in a standard reference model, are shown in Figure IV. Although it has been assumed that the acoustic propagation speed c is given by $c^2 = \gamma u$, the apparent variation in u could result from a modification to c by, for example, a magnetic field.

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