ROTATION IN THE SOLAR CONVECTION ZONE INFERRED FROM FABRY-PEROT OBSERVATIONS OF THE 5-MIN OSCILLATIONS

Frank Hill
National Solar Observatory
National Optical Astronomy Observatories*
950 North Cherry Avenue
Tucson, Arizona 85726 USA

David M. Rust
Applied Physics Laboratory
Johns Hopkins University
Johns Hopkins Road
Laurel, Maryland 20707 USA

and

Thierry Appourchaux
Applied Physics Laboratory
Johns Hopkins University
Johns Hopkins Road
Laurel, Maryland 20707 USA

and

Service d'Aeronomie
91370 Verrieres Le Buisson, France

ABSTRACT - Full disk observations of the 5-min solar oscillations have been obtained with a lithium niobate Fabry-Perot filter. The equatorial solar rotation rate as a function of depth has been inferred from the sectoral modes of oscillation using the Backus-Gilbert optimal averaging inversion method. The results show a rotation rate that slowly decreases over the depths of 15 to 56 Mm below the photosphere. The results are in agreement with the previous Duvall-Harvey observations.

1. INTRODUCTION

Estimates from helioseismology of the equatorial rotation rate as a function of depth are now available for most of the solar interior (e.g. Duvall et al. 1984, Brown 1985, Libbrecht 1986). However, the rotation rate in the outermost layers of the convection zone has not been easily accessible to

*Operated by the Association of Universities for Research in Astronomy, Inc. under contract with the National Science Foundation.

J. Christensen-Dalsgaard and S. Frandsen (eds.), Advances in Helio- and Asteroseismology, 49–52.

https://doi.org/10.1017/S0074180900157717 Published online by Cambridge University Press

these studies which have so far been concerned with modes of spherical harmonic degree $l < 100$. Such modes sample deeper portions of the solar interior.

A measurement of the rotation rate in the outermost layers is of considerable importance to theories of convection and the dynamo generation of magnetic fields. Previous estimates of the rotation rate in the outermost layers above depths of about 15 Mm have been made by Deubner, Ulrich and Rhodes (1979), and by Hill, Gough and Toomre (1984). The data used in the latter study have recently been reanalyzed (Hill et al. 1986). This paper reports on a measurement of the rotation rate in the region immediately below these outermost layers.

2. OBSERVATIONS AND ANALYSIS

The observations were obtained with the APL/CSIRO solid lithium niobate Fabry-Perot interferometer. This instrument is described in detail in Rust, Burton and Leistner (1986); its current performance is discussed in an accompanying article in these proceedings (Rust, Appourchaux and Hill 1986), and the development of stabilization schemes are described in Rust, Kunski and Cohn (1986). The observations discussed here were obtained using the Vacuum Tower Telescope and Multiple Diode Array at NSO/Sac Peak on February 27 through March 1, 1986. Four pairs of images were obtained in the red and blue wings of the Ca I 6103 spectral line every 66 s. The detector provided 320×256 pixels across the full disk image resulting in a spatial resolution of approximately 6" × 8", with the higher resolution oriented along the solar rotation axis. Three consecutive days of data spanning 56.15 hours with a duty cycle of 47.4% have been analyzed.

Interference fringing in the detector substrate was removed using a flat field formed from an average of 90 images. Image motion was removed by registration on the limbs of the solar image and then interpolation onto a common center and size. At each time step the four red and four blue images were separately averaged and a single Doppler image was formed. The sectoral modes of oscillation were isolated by a simple spatial filter formed by averaging along straight lines over a narrow rectangular region with a length of about 1 solar radius. The spatially averaged data were interpolated onto an equally spaced longitude grid with $\Delta\phi = 0.45°$. Power spectra were computed for sectoral modes oriented North-South (polar) and East-West (equatorial). The frequency resolution of the spectra is $\Delta\nu = 4.95$ μHz, and the resolution in spherical harmonic degree is $\Delta l = 6.25$. The spectrum for the equatorial sectoral modes is shown in Figure 1.

The frequencies of the ridges of the equatorial modes were measured by fitting splines to the centroids of the ridges. Poorly determined centroids were rejected after comparison to the empirical relationship between ν and l derived by Harvey and Duvall (1984). The frequency splittings between 79 prograde and retrograde modes with order n of 3 to 7 and degree l of 80 to 150 were used as input to a Backus-Gilbert optimal averaging inversion scheme. The use of this technique in helioseismology has been pioneered by Gough (1985). The quality of the resulting optimal kernels was degraded by the small number of modes available for the inversion.

3. RESULTS AND DISCUSSION

The resulting rotation curve is shown in Figure 2 along with the overlapping results from the Duvall et al. (1984) study. The curve indicates that the rotation rate slowly decreases from 0.450 μHz to 0.431 μHz over the depth range of 15 to 56 Mm below the photosphere. The value of the rotation rate at a depth of about 16 Mm is close to the results of Duvall et al. and is also consistent with a reanalysis of observations covering the depths of 0.2 to 15 Mm (Hill et al. 1986), if a scale correction is allowed in those reanalyzed results for the shallower layers. The rotation rate at the deeper Duvall et al. point is somewhat different from the rate derived in this study at that depth, however, the two results agree to within the error bars.

https://doi.org/10.1017/S0074180900157717 Published online by Cambridge University Press

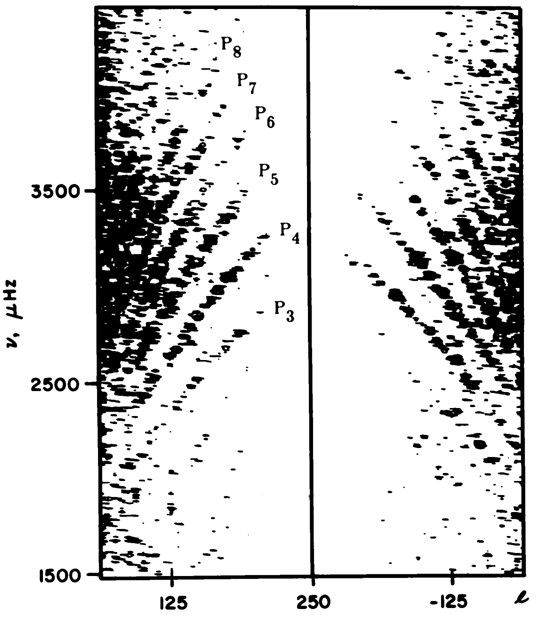

Figure 1. The l-ν diagram for sectoral modes oriented East-West on the Sun.

It should be noted that the error bars are relatively large both for the rotation rate derived in this study (due to incomplete cancellation of the kernels in the inversion) and for the Duvall et al. results (due to large measurement errors in the higher degree splittings). Thus, while the gradient $d\Omega/dR$ of the rotation rate in the region covered by our results can be formally computed to be $0.5\pm1.8 \times 10^{-3}$ μHz Mm^{-1} or $0.3\pm1.1 \times 10^{-11}$ rad s^{-1} km^{-1}, the large errors in the inferred rotation rate prevent us from reliably determining even the sign of the gradient. While the implication of our results and the full disk measurements is that $d\Omega/dR > 0$ in some region of the convection zone, the exact behavior of the rotation rate in the outer portion must still be considered to be unknown.

This situation is due to the fact that currently information about the region of the solar interior between 0.92 and 0.97 solar radii is difficult to infer from helioseismology. The modes that best probe here have values of l of about 100 to 200; such modes are at the upper limit of moderate spatial resolution full disk observations and the lower limit of high resolution observations that cover only a portion of the Sun. High resolution full disk observations are needed to adequately measure the rotation rate in this region of the Sun. Such observations may be obtained by the proposed SOHO Solar Oscillation Imager experiment.

ACKNOWLEDGEMENTS - The inversion code used in this study was developed during a collaboration among one of us (F.H.), Douglas Gough and Juri Toomre. Thanks are also due to Tom Duvall, Jack Harvey, John Leibacher, Deborah Haber, and Larry November for scientific discussions, to the Sac Peak Tower support staff, and to CSIRO, where the etalon was fabricated. This work was supported partially by NASA grant NAGW-522 and by the APL Independent Research and Development Fund.

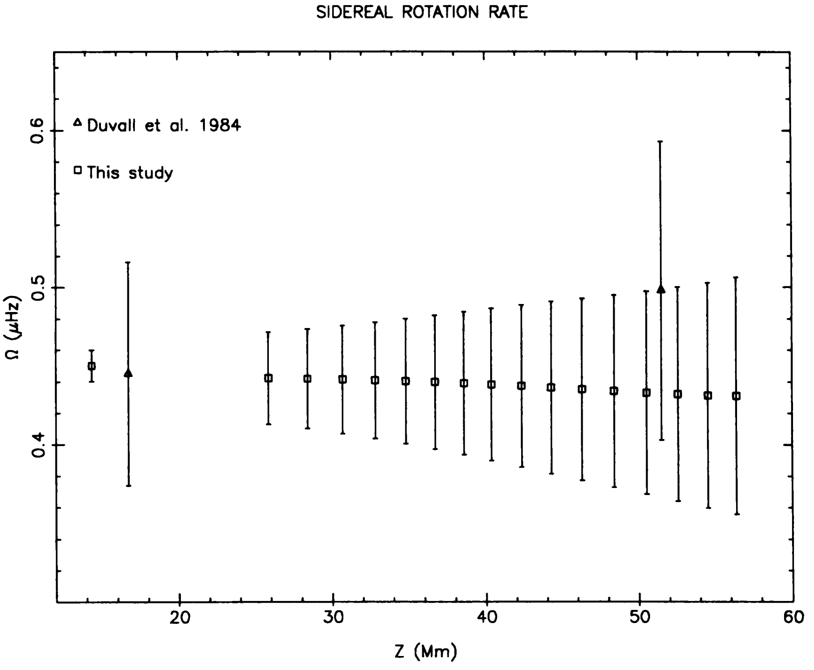

Figure 2. The equatorial rotation rate as a function of depth inferred from a Backus-Gilbert inversion of the frequency splittings of 79 modes.

REFERENCES

Brown, T.M.: 1985, *Nature* **317**, 591.

Deubner, F.-L., Ulrich, R.K., and Rhodes, E.J., Jr.: 1979, *Astron. & Astrophys.* **72**, 177.

Duvall, T.L., Jr., Dziembowski, W., Goode, P.R., Gough, D.O., Harvey, J.W., and Leibacher, J.W.: 1984, *Nature* **310**, 22.

Gough, D.O.: 1985, *Solar Phys*, **100**, 65.

Harvey, J.W., and Duvall, T.L. Jr.: 1984, in *Theoretical Problems in Stellar Stability and Oscillations*, ed. A. Noels and M. Gabriel, Liege, 209.

Hill, F., Gough, D.O., and Toomre, J.: 1984, *Mem. Soc. Astron. Ital.* **55**, 153.

Hill, F., Gough, D.O., Toomre, J., and Haber, D.A.: 1986, these proceedings.

Libbrecht, K.G.: 1986, *Nature* **319**, 753.

Rust, D.M., Appourchaux, T., and Hill, F.: 1986, these proceedings.

Rust, D.M., Burton, C.H., and Leistner, A.J.: 1986, in *Instrumentation in Astronomy IV, Proc. SPIE* **627**, in press.

Rust, D.M., Kunski, R., and Cohn, R.F.: 1986, *Johns Hopkins APL Tech. Digest* **7**, 209.

https://doi.org/10.1017/S0074180900157717 Published online by Cambridge University Press