Recent Insights into the Physics of the Sun and Heliosphere:
Highlights from SOHO and Other Space Missions
IAU Symposium, Vol. 203, 2001
P. Brekke, B. Fleck, and J. B. Gurman eds.

New Inferences on the Sun from High-degree Modes: The External Layers and the Equation of State

M. P. Di Mauro

Teoretisk Astrofysik Center, Danmarks Grundforskningsfond,
Bygn. 520, Ny Munkegade, DK 8000 Aarhus C, Denmark

J. Christensen-Dalsgaard

Teoretisk Astrofysik Center, and Institut for Fysik og Astronomi,
Aarhus Universitet, DK 8000 Aarhus C, Denmark

Abstract. We investigate the structure of the Sun by helioseismic inversion of a set of p-mode frequencies which include new precise observations of modes with high degree obtained from the MDI instrument on the SOHO satellite. Such data have the potential to improve the resolution of the solar structure in the near-surface region, to test the equation of state and constrain the envelope helium abundance.

1. Introduction

Helioseismic inversion of acoustic frequencies of oscillation observed on the solar surface is an extremely powerful tool for the investigation of the internal structure and dynamics of the Sun. In particular, the study of high-degree acoustic modes (Di Mauro 2000) allows us to resolve the near-surface region of the Sun, where the effects of the equation of state and of the convective motion are felt strongly.

2. Helioseismic inversion

The current analyses have been carried out by inversion of preliminary helioseismic data (Rhodes et al. 1998), which include high-degree modes ($l < 1000$), obtained in 1996 by the MDI instrument on board the SOHO satellite. For comparison, we have also inverted another set obtained by the same instrument, which includes only modes with harmonic degree $l \leq 100$ (Schou 1998). The method is based on the inversion of integral equations to determine the corrections to a reference model required to match the observed oscillation frequencies. We have used Model S of Christensen-Dalsgaard et al. (1996) as reference model; it uses the OPAL equation of state (Rogers, Swenson & Iglesias 1996). In addition, a modified Model S has been considered, differing from the previous one only in that it uses the MHD equation of state (Mihalas, Däppen & Hummer 1988). Non-adiabatic effects and other errors in modeling the surface layers have been taken into account by including an arbitrary function of frequency, known as surface term, in the integral equations.

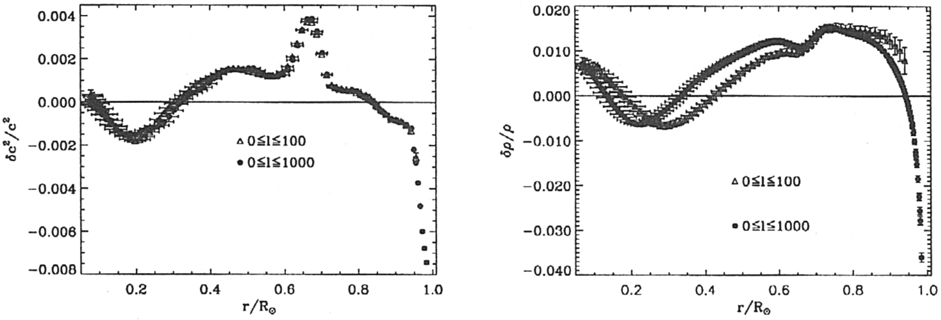

Figure 1. The relative squared sound-speed (left panel) and density (right panel) differences between the Sun and the reference model by using two different sets of data with high-degree modes (filled circle) and with no high-degree modes (open triangle). The vertical error bars are the standard deviations of the errors in the data, whereas the horizontal bars give a measure of the localization of the solution.

3. The near-surface region: the results

The relative differences in the squared sound speed and density between the Sun and the reference model are shown in Fig. 1 as functions of the fractional radius. High-degree modes are able to determine variations very near the solar surface, through the He II ionization zone and also part of the He I ionisation zone, while by using only low- and intermediate-degree modes, we cannot determine solutions further than $r \simeq 0.96 R_\odot$. The results for the sound speed indicate that high-degree modes do not affect the helioseismic inferences in the deeper interior when all observed modes of oscillation are considered. On the other hand, the density profile in the radiative zone is somewhat influenced by the use of higher-degree modes.

The difference between the equation of state of the Sun and those of the reference models can be studied through the resulting intrinsic differences in the first adiabatic exponent Γ_1 (Fig. 2). The precise high-degree modes allow us to affirm that, as noticed by Basu, et al. (1999), the OPAL equation of state seems to describe better the plasma conditions below 0.97 $R_\odot$, while we have found no evidence that MHD is better than OPAL above $0.97 R_\odot$.

The solar helium abundance, inferred from inversion, is sensitive to the equation of state. By using the MHD equation of state we have obtained a value of 0.2426 ± 0.0005, consistent with the results obtained by Kosovichev (1997) and Richard et al. (1998) by employing a similar variational technique. By considering the OPAL equation of state we have obtained a value of 0.2648 ± 0.0004, which is strikingly higher than previous values quoted in the literature.

We conclude that the structure of the near-surface region is still quite uncertain, since there remains substantial difficulties in modeling convective effects and the thermodynamic properties of this region, as well as in the treatment of

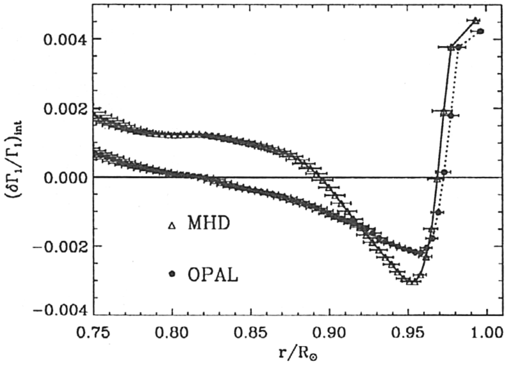

Figure 2. The intrinsic difference in the adiabatic exponent Γ_1 between the Sun and the OPAL model (filled circle) and the Sun and the MHD model (open triangles) in the upper parts of the Sun.

non-adiabatic effects on the oscillations. We note that the expression for the surface term used here may not be completely valid, particularly for high-degree modes. Finally, the determination of observational frequencies for high-degree modes still suffers from substantial difficulties, related to the merging of power into ridges and the proper treatment of the leakage matrix (e.g. Schou 1998); this could cause systematic errors in the frequencies which may, for example, be responsible for the rather high value of the helium abundance inferred with the OPAL model.

Acknowledgments. This work was supported by the Danish National Research Foundation through the establishment of the Theoretical Astrophysics Center.

References

Basu, S., Däppen, W., & Nayfonov, A. 1999, ApJ, 518, 895

Christensen-Dalsgaard, J., et al. 1996, Science, 272, 1286

Di Mauro, M. P. 2000, Mem. S.A.It., in press

Kosovichev A. G., 1997, Bull. Astron. Soc. India, 24, 355

Mihalas, D., Däppen, W., & Hummer, D. G. 1988, ApJ, 456, 902

Richard, O., et al. 1996, A&A, 312, 1000

Rhodes, E. J. et al. 1998, in ESA SP-418, Structure and Dynamics of the Interior of the Sun and Sun-like Stars, eds S.G. Korzennik & A. Wilson, (Noordwijk: ESA Publications Division), 73

Rogers, F. J., Swenson, F. J., & Iglesias, C. A. 1996, ApJ, 331, 815

Schou, J. 1998, in ESA SP-418, Structure and Dynamics of the Interior of the Sun and Sun-like Stars, eds S. G. Korzennik & A. Wilson, (Noordwijk: ESA Publications Division), 47