Astron. Astrophys. 323, 231–234 (1997)

ASTRONOMY
AND
ASTROPHYSICS

Helioseismic measure of solar activity-meaning and applications

W.A. Dziembowski[1,2], Philip R. Goode[2,1], J. Schou[3], and Steve Tomczyk[4]

[1] N. Copernicus Astronomical Center, Polish Academy of Sciences, Bartycka 18, PL-00716 Warszawa, Poland
[2] Physics Department, New Jersey Institute of Technology, 323 Martin Luther King Boulevard, Newark, NJ 07102, USA
[3] Center for Space Physics and Astrophysics, HEPL Annex 201, Stanford University, CA 944305, USA
[4] High Altitude Observatory, NCAR, P.O. Box 3000, Boulder, CO 80307, USA

Received 11 June 1996 / Accepted 3 January 1997

Abstract. We analyze the antisymmetric part of the fine structure in the LOWL data, and find a remarkable agreement with the BBSO data taken during the 1986 activity minimum. For both, the $P_4(\cos\theta)$ component of the Sun's asphericity is dominant. We discuss the importance of measuring this part of the fine structure as a global probe of the Sun's varying magnetic activity.

The asphericity affects oscillation frequencies in a way that corrupts any inversion for the radial structure of the deep solar interior. The results of inversion of the original and cleansed data show that at the current minimal level of solar activity, the effect is within the errors. However, this is not true in the case of measurements taken in years of high activity. We mimic such measurements by adding in appropriate frequency shifts evaluated from 1989 BBSO data.

Key words: Sun: oscillations – Sun: interior – Sun: activity

1. Introduction

The fine structure, or m dependence, in the spectrum of solar oscillations is customarily described by the a-coefficients of Duvall, Harvey and Pomerantz (1986) as,

$$\nu_{nlm} - \nu_{nl0} = L \sum_{i=1}^{N} a_{i,nl} P_i(\tfrac{m}{L}), \quad (1)$$

where ν is the cyclic frequency of an individual (nlm)-mode, $L = \sqrt{l(l+1)}$, P is a Legendre polynomial, and N is the order of the Legendre expansion provided by the observers. The (nlm) are the radial order, angular degree and azimuthal order of the oscillation, respectively.

We consider the symmetry of the fine structure about the centroid ($m = 0$) frequency. The symmetric part (the odd-a's) arises from the linear effect of the Sun's rotation. The antisymmetric part (the even-a's), which is linked to the latitudinal variation of the solar activity, is the subject of this paper.

Send offprint requests to: W.A. Dziembowski

2. Comparison of LOWL and BBSO data on the Sun's asymmetry

The most complete set of even-a coefficients are from BBSO data, Libbrecht & Woodard (1990) and Woodard and Libbrecht (1991). These data are observations from the 1986 activity minimum, as well as the years of 1988, 1989, and 1990 during which the Sun's activity climbed to its most recent maximum. Very large changes in these coefficients were detected among the four sets. The new data discussed in this paper are the even-a coefficients from the LOWL instrument, Tomczyk et al. (1995). The data were taken between Feb. 1994 and Feb. 1995–a period of low solar activity.

Libbrecht & Woodard (1990) showed that the l-dependence of the a_{2k} coefficients is given by $(LI_{n,l})^{-1}$, where I denotes mode inertia which is evaluated assuming constant values of the radial displacement at the base of the photosphere. They noted that the inverse proportionality to the inertia implies that the perturbation giving rise to the frequency shifts described by the even-a coefficients must be located well above the lower turning point for nearly all modes in their data set, which means the outer layers of the Sun spanning at most a few percent of the radius.

Here we represent the even-a coefficients in the form

$$a_{2k,nl} = a_{2k,nl,\mathrm{rot}} + (-1)^k \frac{(2k-1)!!}{(2k)!!} \frac{\gamma_k(\nu_{nl})}{LI_{nl}} \quad (2)$$

where the $a_{2k,nl,\mathrm{rot}}$ describe the contribution of the second order effect of rotation to the fine structure and the γ_k are functions which we determine. The same form was used by Dziembowski & Goode (1996), who analysed the full set of the BBSO data, and our form differs from that used by Libbrecht & Woodard (1990) in two respects. Firstly, the effect of centrifugal distortion, which is significant only for $k = 1$, is taken into account. Secondly, a ν dependence in the γ's is allowed. If $l \gg 2k$, each γ_k-coefficient arises almost solely from the $P_{2k}(\cos\theta)$ component of the perturbation (e.g. Gough, 1988).

The centroid frequencies from the LOWL instrument were used by Basu et al. (1996) to infer the internal structure. The odd-a's were used by Tomczyk, Schou and Thompson (1995)

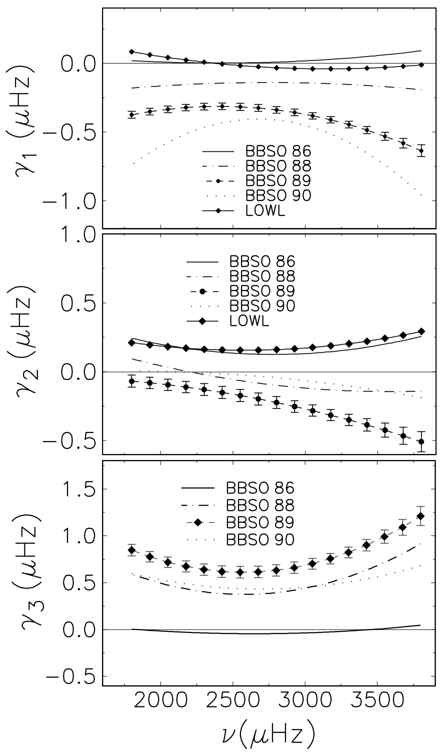

Fig. 1. From top panel to bottom γ_1, γ_2 and γ_3 are shown as a function of mode frequency for the 1986, 1988, 1989 and 1990 BBSO data. γ_1 and γ_2 for the LOWL data are shown in the top two panels. The normalization of the radial displacement amplitude at the base of the photosphere was chosen to be 3×10^4. With such a normalization, the mode inertia in Eq. (2) is of order unity for modes of frequency near 3 mHz. The least-square error bars are shown for the BBSO 89 data.

to determine the rotation in the Sun's deep interior. Here we determine the γ's for the LOWL data and compare them in Fig. 1 to those obtained from the BBSO data by Dziembowski and Goode (1996). The LOWL data contain modes ranging from l=5 to 99. while the BBSO data range from 5 to 140.

The important thing to notice in Fig. 1 is that the LOWL γ's nearly co-incide with those from the 1986 BBSO data, and that only γ_2 differs significantly from zero. These two data sets are from periods of low solar activity. We see a drastically different pattern in the γ's from years of high activity.

3. Meaning of the γ's

There is no doubt that the γ's are a measure of the Sun's magnetic activity. Kuhn (1988) first noted that the antisymmetric part of the frequency splittings in the fine structure change through the solar cycle. He found a correlation between the phase of the activity cycle and the size of the perturbation with the largest effect corresponding to activity maximum and with the perturbation nearly vanishing at activity minimum. He made this argument using splitting data from 1986 and earlier. His conclusion was strenghtened by Libbrecht and Woodard (1990) who employed observational data covering the subsequent period of high solar activity beyond the 1986 minimum. Near the last solar activity maximum, Woodard et al. (1991) found a strong correlation between oscillation frequency changes and solar magnetic variations from monthly averages of their data.

There has been much work devoted to the interaction of p-modes with magnetic fields. Nevertheless, we don't have a satisfactory theory allowing the calculation of the γ's for a specified, realistic field structure. We don't know whether they arise primarily from direct effect of the Lorentz force or through an induced sound speed perturbation. Futhermore, inertial effects from recently discovered (Duvall et al. 1996) rapid flows related to active regions may also contribute. Therefore, using the γ's as a probe of the Sun's near surface field is for the future.

Of course, a precise localization of the perturbation would be possible only after such a theory is in hand. However, the weak dependence on ν seen in Fig. 1 suggests that the perturbing agent must reside very close to the photosphere where the radial eigenfunctions were normalized. We have calculated the frequency shift induced by a localized perturbation of the sound speed. When the perturbation resided high above the photosphere, we observed a rapid increase of the magnitude of the shift with increasing mode frequency. If, instead, we located it far beneath the base of photosphere, we observed, at low frequencies, a rapid decrease of the shift, and at higher frequencies, an oscillatory behavior reflecting the nodal structure of the modes. The behavior, such as seen in the γ's shown in Fig. 1, was found only for a perturbation localized within about a megameter of the base of the photosphere. A similar localization was suggested by Dziembowski and Goode (1991). An equivalent conclusion, based on centroid shifts, was reached by Goldreich, et al.(1991).

We should stress that such a localization of the aspherical perturbation in the Sun is at variance with the recent result of Kosovichev (1996), who inverted the time-distance seismic data of Duvall, et al. (1996). In these data, the same asphericity as manifested in the γ's is seen. Kosovichev finds that it may be interpreted as a pertubation in the sound speed extending down some 30 Mm. The works of Duvall, et al. (1996) and Kosovichev (1996) clearly demonstrate the utility and potential of time-distance seismology, but advances in the theory are required for this field to reach its potential. We view the time-distance approach as being complementary to traditional helioseismology. Its greatest strength lies in probing local structure and, especially, velocity fields.

In spite of the fact that we don't have detailed theoretical knowledge of the origin of the γ's, measurements of them are important and interesting. The angular structure of the non-axisymmetric perturbation, as given through the γ coefficients, reflects the underlying global structure of the magnetic field. In this context, the observation that in the years of minimum solar activity, the fact that γ_2 is the only significant component seems particularly interesting. We take this as evidence that the Sun's asphericity is dominated by its P_4 component at activity minimum. Here we assume that asphericity of high polynomial order, of which we have no direct information yet, does not contribute significantly to low order γ's. If such components

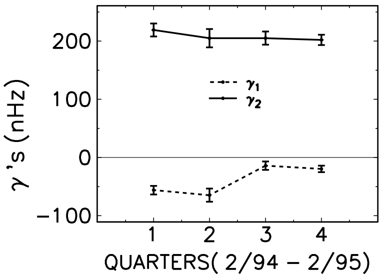

Fig. 2. γ_1 and γ_2, averaged over frequency, are shown for each of the four quarters of the LOWL data .

are present, then the $l \gg 2k$ condition may not be satisfied for bulk of the modes in the data set used to determine the γ's. This is the condition for a one-to-one correspondence between the γ_{2k} and the P_{2k}-asphericity. The successful fit of the data to Eq. (2) suggests that high-k are not significant because they should affect the l-dependence of the a_{2k} coefficents.

The P_4 geometry corresponds to the quadrupole toroidal magnetic field generated by an ω-dynamo action operating at the base of the convection zone where there exists a large radial gradient in rotation. The perturbation that we see in the γ's is localized in the outer layers, and we can only speculate as to how a buried toroidal field may affect these layers. Following changes in the γ's through the whole activity cycle may yield essential clues to understanding the physics of solar activity.

The BBSO data used in Fig. 1 are too spread out in time to allow one to follow the transition of the γ from low activity years to high activity years. However, with the LOWL, GONG and SOHO instruments, we will have the chance to follow that transition. In Fig. 2, we may observe the behavior of γ_1 and γ_2 for the four quarters between Feb '94 and Feb '95. This was a period of low activity. The γ's are the weighted averages over the frequency range. We see no significant change in γ_2 over the four quarters. The determination of γ_1 in the first two quarters appears significant, and its sign is the same as in years of high activity, but it is about an order of magnitude smaller.

We remark that the use of frequency-averaged $\gamma's$ to follow cycle-dependent changes is justified if one compares averages from sets of modes covering the same frequency ranges. Otherwise, the calculated changes may reflect difference in frequency range rather than a genuine temporal evolution of γ.

4. Effect on structural inversions

Regardless of the interpretation of the γ's, they may be used to cleanse centroid frequency data for use in structural inversions. Dziembowski and Goode (1996) showed that the latitudinal dependence of the near surface perturbation due to activity (NSPA) causes corruption in the helioseismic determination of the structure of the solar core. The corruption is significant only for the lowest l modes. Thus, an inversion for the structure in layers above $r \approx 0.2R$, which relies mostly on higher l modes, is not affected by this problem. Once the $\gamma(\nu)$'s are determined, they may be used purify the frequency data for inversion. The assumption is being made that γ's adequately describe the whole Sun's asphericity. Current data are consistent with such an assumption. Dziembowski and Goode (1996) also showed that the centroid frequency shifts relative to 1986 for $l = 0, 1$ and 2 modes, as determined from direct measurements within admittedly large errors, agree with the shifts evaluated from the γ's.

Basu et al. (1996) have already inverted the LOWL data to determine the internal structure of the Sun. Their structural inversion of the LOWL data agrees very well with that from the combined BBSO&BISON results– if the latter are from a period of low activity. We confirm their result, but do not report our calculations here, except to add one point that they did not discuss – the inferred surface He abundances, which we determine simultaneously with structure parameters, are in agreement for the two data sets. The inferred values are Y=0.253 and 0.251 from LOWL and BBSO&BISON, respectively. Here, we focus on quantifying the corruption caused by the NSPA.

Like Basu et al. (1996), we use the SOLA method of inversion (Pijpers and Thompson 1992). Our reference model was constructed by Sienkiewicz and Pamyatnykh, and has no recent refinements like the inclusion of elemental diffusion. These omissions are inconsequential for the present application. The model very closely describes the Sun and this justifies the linearizations implicit in our inversions.

Inversion of the LOWL data, as provided, was followed by inversions which included various treatments of the NSPA effect. First, we removed the magnetic perturbation as implied by the γ's from the LOWL data. The perturbations for l = 0–3 were of the order of 10^{-2} μHz and comparable with errors for only a few modes. At higher l's, the perturbations were negligable. The effect of removing the magnetic perturbation on the inverted sound speed shown in Fig. 3 is noticeable only in two innermost points, but it is within the 1 σ errors. Then, to assess the effect of the NSPA in years of high activity, we separately added to the LOWL data the effects implied by the γ's from 1989 and 1990 BBSO data–years of high activity. The frequency perturbations were one order higher than for the low activity data. In Fig. 3, the only results we show for high activity are those computed from the 1989 data because the results from the 1990 data are very similar. The figure clearly shows the size of the corruption –5 $\times$ 10^{-3} at the innermost point, which is similar to the whole difference between the seismic and current standard models of the Sun. We emphasize that this innermost core is the part of the Sun which is critical for testing stellar evolution theory.

The effect of the Sun's activity on structural inversions has also been discussed by Basu et al. (1996). They point out that it is important to use contemporaneous data in the inversions. We stress here that it is not enough to use data from the same phase of solar activity to eliminate its effect, but it is also necessary to remove the NSPA effect as determined from the fine structure in solar oscillation spectrum. We emphasize that all inversions for the structure of the core done previous to those in shown Fig. 2, have presumed that the near surface perturbation has no latitudinal dependence.

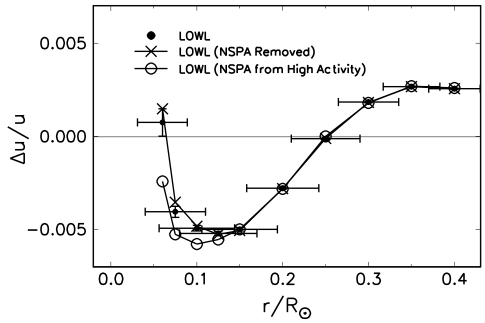

Fig. 3. Relative seismic corrections to $u = p/\rho$, the square of the isothermal speed of sound, as inferred from the original LOWL data and with two modified sets. The error bars reflect measurement uncertainties. The horizontal ones are the full width at half maximum of SOLA kernels, and the vertical ones are those on $\Delta u/u$. Removal of NSPA as determined from LOWL data results marginally significant changes in the deep core. The effect is so small because the data are from the activity minium. Adding the NSPA corrections implied by BBSO γ's from 1989, which was a year of high activity, causes a large change in Δu in the inner core.

We conclude by noting that measuring even-a coefficients is important as a clue to the physics of solar activity, and for providing purifying information which enables more reliable probing the inner part of the solar core.

Acknowledgements. We are grateful to Ken Libbrecht and Martin Woodard for providing us their fine data over the years and to Yvonne Elsworth for her constructive remarks that helped us to improve the paper. This work was supported by AFOSR-95-0070, NSF-AST-93-14820, NSF-INT-93-14820, and by KBN-2P304-013-07.

References

Basu, S., Christensen-Dalsgaard, J., Schou, J., Thompson, M.J., Tomczyk, S., 1996, ApJ, 460, 1064
Duvall, T.L., Jr., Harvey, J.W., Pomerantz, M.A., 1986, Nat, 321, 400
Duvall, T.L.Jr., D'Silva, S.,Jefferies, S.M., Harvey, J.W., & Schou, J., 1996, Nat, 379, 235
Dziembowski, W.A. & Goode, P.R. 1991, ApJ. 376, 782
Dziembowski, W.A., Goode, P.R., 1997, A&A, 317, 919
Goldreich, P., Murray, N., Willette, G. & Kumar, P. 1991, ApJ, 370, 752
Gough, D.O. 1988 in *Proc.Symp.Seismology of the Sun and Sun-like Stars*, ed. E.J. Rolfe, (Noordwijk:ESA), p. 679
Kosovichev, A.G., 1996, ApJ, 461, L55
Kuhn, J.R., 1988, ApJ, 331,L131
Libbrecht, K.G., Woodard, M.F., 1990, Nat, 345, 779
Pijpers, F.P., Thompson, M.J., 1992, A&A, 262, L33
Tomczyk, S., Schou, J., Thompson, M.J., 1995, ApJ, 488, L57
Tomczyk, S., Streander, K., Card, G., Elmore, D., Hull, H., Cacciani, A., 1995, Sol.Phys., 159, 1
Woodard, M.F., Libbrecht, K.G., 1991, ApJ, 374, L61
Woodard, M.F., Kuhn, J.R., Murray, N., Libbrecht, K.G., 1991, ApJ, 373, L81

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.