THE SOI–MDI HIGH-LATITUDE JET: THE EVIDENCE FOR AND AGAINST

R. Howe[1], H.M. Antia[2], S. Basu[3],
J. Christensen-Dalsgaard[4], S.G. Korzennik[5],
J. Schou[6], M.J. Thompson[7]

[1]N.O.A.O. P.O. Box 26732, Tucson, AZ 85726-6732, USA *
[2]Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India
[3]Institute for Advanced Study, Olden Lane, Princeton, NJ 08540, USA
[4]Teoretisk Astrofysik Center, Danmarks Grundforskningsfond, Denmark, and
Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C, Denmark
[5]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
[6] Center for Space Science and Astrophysics, Stanford University, Stanford,CA 94305-4085, USA
[7] Astronomy Unit, Queen Mary and Westfield College, London E1 4NS, UK

ABSTRACT

The apparent detection of a prograde jet at latitude 75° and at a radius of about $0.95R_{\odot}$ in some inversions of rotation data from SOI–MDI (Schou et al. 1998) has excited considerable interest, but whether the jet really exists in the solar interior is certainly not yet firmly established. The detection of the feature is sensitive both to the inversion techniques used and to the methods of mode parameter estimation used to generate the input data. In particular, the feature is much more apparent in Regularized Least-Squares inversions than in inversions using an Optimally Localized Average approach, and is not detected at all in the present GONG data when analysed with the GONG peakfinding algorithm, or indeed in SOI data when analysed with the GONG algorithm. Therefore in this poster we examine critically the current evidence for the source and existence of this jet in the light of forward and inverse analyses.

Key words: Sun:Interior; Sun:Oscillations; Sun:Rotation.

1. INTRODUCTION

The recent data from the medium l observations of the MDI-SOI program on SOHO have provided information of unprecedented detail and quality on the solar interior rotation.

One of the interesting results from inversions of the data from the first 144 days of SOI-MDI medium-l data (Schou et al. 1998) was the apparent detection of a prograde jet at around $0.95R_{\odot}$ and 75° latitude. This feature was detected only in inversions using Regularized Least-Squares (RLS) methods; however, the Optimally Localized Average (OLA) methods that failed to detect it also failed to detect such a feature in a hare-and-hounds exercise where it had been deliberately introduced into the artificial rotation laws. The feature was only weakly detected in a weeded version of the dataset. It should also be pointed out that the feature is at the limit of the region where the inversion is believed to give reliable results, due to the difficulty of localizing averaging kernels at high latitudes.

The evidence presented by Schou *et al.* thus leaves it uncertain whether the apparent feature is an inversion artefact, an artefact of the peak-fitting process, or a genuine solar phenomenon. More recent data, and more detailed investigations, throw a little more light on this topic.

2. EVIDENCE FROM NEW DATA

Since the preparation of the Schou *et al.* paper, data from 360 days of medium-l observations have become available. Using two different 2DRLS techniques, that described by Antia & Chitre (1998) and that described by Schou et al. (1994), the feature has been seen in these data also, as shown in Figure 1. It should be noted that detection of the feature in the 2dRLS inversions of HMA&SB (Figure 1*a*) is somewhat sensitive to the choice of regularization tradeoff parameter. In the 2dRLS inversions using Schou's code, on the other hand, the feature cannot be suppressed without severe oversmoothing. We have therefore carried out more detailed investigations in an effort to clarify the evidence for and against the existence of the jet.

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

Proceedings of the SOHO 6/GONG 98 Workshop, 'Structure and Dynamics of the Interior of the Sun and Sun-like Stars', Boston, USA, 1-4 June 1998 (ESA SP-418, October 1998)

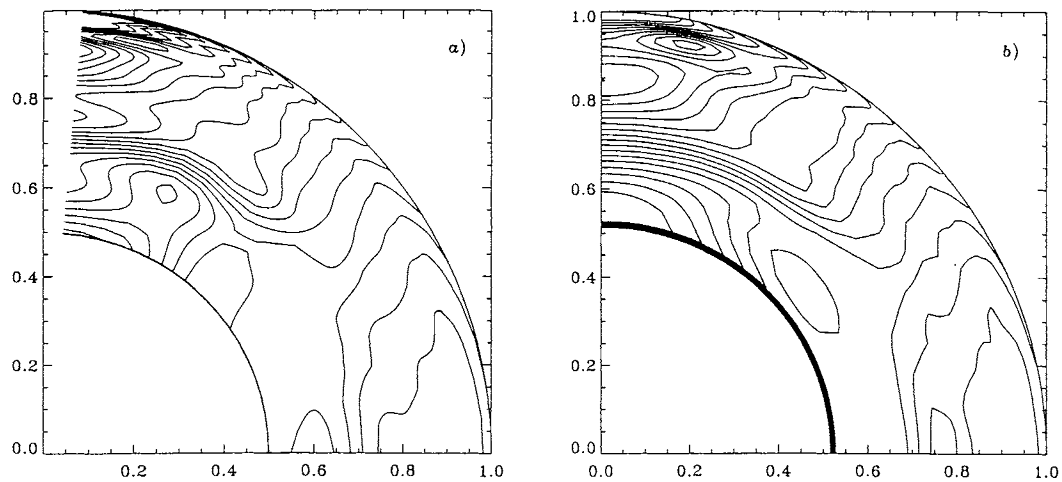

Figure 1. Sample 2dRLS inversions of MDI-SOI medium-l coefficients; (a) inversion by HMA&SB, (b) inversion by RH.

3. FURTHER INVESTIGATIONS

To clarify what follows, we first define a few terms.

In the MDI analysis, we parameterize the $2l+1$ frequencies within a given (n,l) multiplet as

$$\omega_{nlm}/2\pi = \nu_{nl} + \sum_{j=1}^{j_{\max}} a_j(n,l)\,\mathcal{P}_j^{(l)}(m) \qquad (1)$$

with generally fewer than $2l+1$ parameters ν_{nl}, a_1, a_2, ..., $a_{j_{\max}}$, and fit this expression to the peaks in the power spectra; the a_j are known as a-coefficients. The basis functions $\mathcal{P}_j^{(l)}(m)$ used in this expansion are polynomials of degree j defined by

$$\mathcal{P}_j^{(l)}(l) = l, \qquad (2)$$

and

$$\sum_{m=-l}^{l} \mathcal{P}_i^{(l)}(m)\mathcal{P}_j^{(l)}(m) = 0 \ \text{ for } \ i \neq j\ ; \qquad (3)$$

the a_j are related to Clebsch-Gordan coefficients. Only the coefficients with odd j are relevant to the rotation. In the GONG analysis (Anderson et al. 1990), the individual peak frequencies ν_{nlm} are fitted for each spectrum, and the a-coefficient expansion of Equation 1 is fitted to the frequencies after the fact.

3.1. Forward calculations

Various forward-calculation exercises have been carried out in order to determine which modes and coefficients contain the signature of the jet.

One approach is based on the correspondence between the parameterization of the splittings with m using a polynomial expansion, and the expansion of the latitude dependence in terms of analytical functions. If the splittings are expanded in terms of Clebsch-Gordan coefficients (Ritzwoller & Lavely 1991), this correspondence is a diagonal one (i.e., each additional odd term in m corresponds to an additional term for the latitudinal expansion). We can thus take a jet-like profile and expand its latitude dependence in terms of the corresponding analytical functions. Figure 2 indicates that in order to isolate the jet-like feature as seen in the inversion, the expansion must be carried at least up to a_{17}.

In another approach, we constructed an artificial rotation law from the results of an inversion showing the jet, but with the rotation rate in the jet region set to a constant value approximating the value in the surrounding region. A forward calculation was then performed, using the same modeset (a trimmed MDI modeset, as shown in Figure 3) and errors as were used for the original inversion, to obtain the splitting coefficients corresponding to this modified rotation law, and the difference between the original and final calculated splittings was investigated. The signature of the feature was visible at the appropriate value of ν/L for all coefficients, but the most significant differences were in coefficients a_3 to a_{11}. The slightly higher-order coefficients are important to localize the jet, even though its effects on these coefficients are not individually significant. Figure 3 shows the modes in the $l-\nu$ plane where the signature of the jet is strongest, and Figure 4 shows the differences in the first odd a-coefficients a_3 to a_{13}, normalized by the corresponding errors.

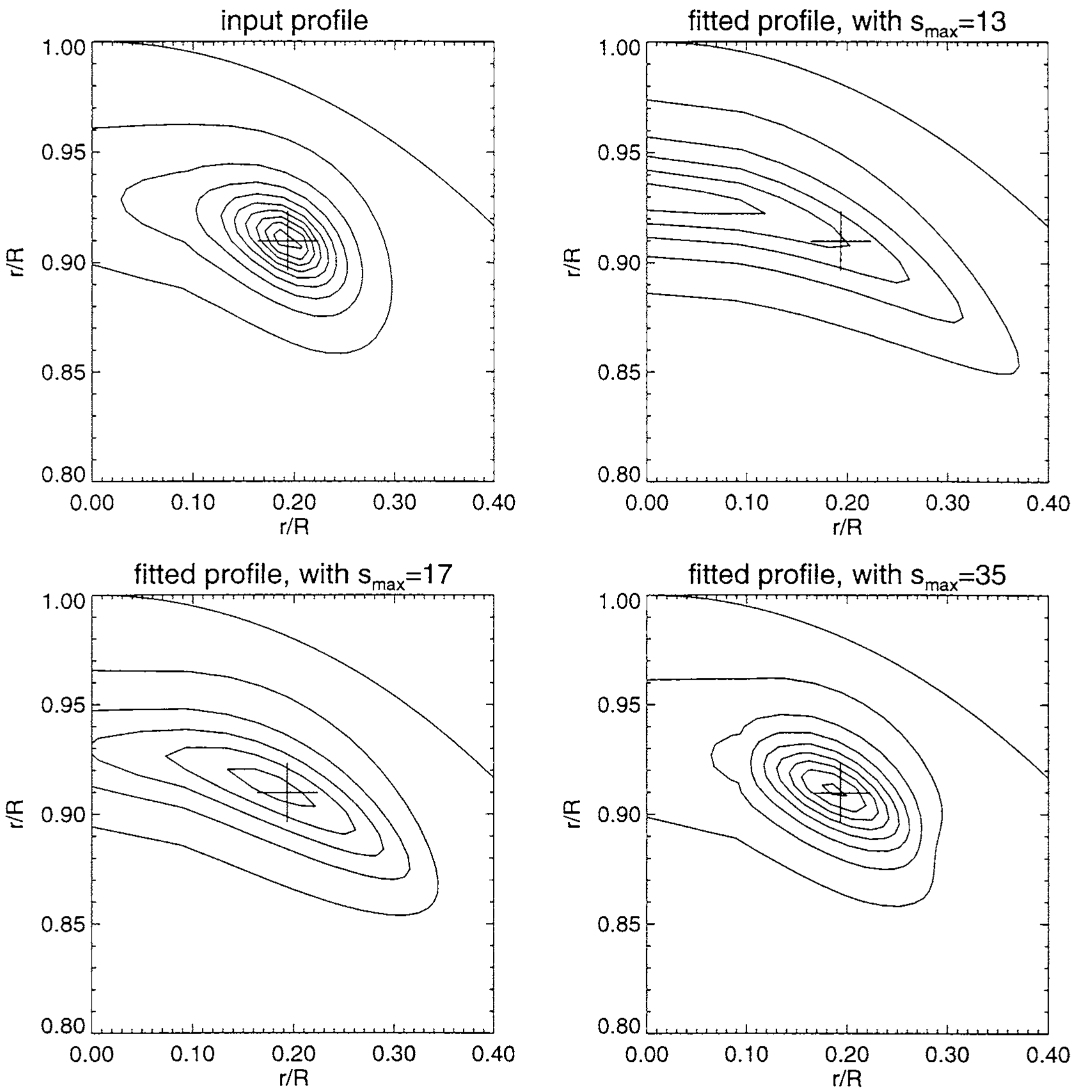

Figure 2. Contour plots showing how well a localized jet-like profile can be parameterized with a limited expansion of the splittings with m. This computation uses the correspondence between a Clebsch-Gordan expansion and its analytical latitudinal counterpart (see text). The upper left panel shows the input jet-like profile, while the other three panels illustrate how well this input profile can be approximated when limiting the expansion to 7, 9 and 18 odd terms respectively.

3.2. Coefficient combinations

Some insight into the solar rotation can be gained by forming certain linear combinations of the a-coefficients that correspond to given radii, as discussed for example by Wilson & Burtonclay (1995). Figure 5 shows the result of such a combination for latitude 75 degrees, for MDI data and for artificial data with and without the jet. Taken together with the forward calculations that locate the signature of the jet in modes that we would expect to be reliably fitted, this tends to suggest that the jet is not an artefact of the inversions.

3.3. Truncating the a-coefficient expansion

Inversions were carried out with several different levels of truncation for the a-coefficient series describing the splittings, and the results are shown in Figure 6. In data with only $a_1 - a_5$ the jet is completely obscured, but it is clearly visible with coefficients $a_1 - a_{17}$.

3.4. Data analysed using the GONG pipeline

A 3-month time series of MDI data has been analysed using the GONG pipeline, in an effort to discriminate

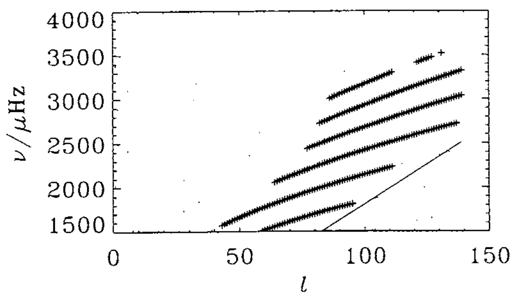

Figure 3. The $l - \nu$ diagram for the modeset used in the forward calculation. Multiplets where at least one coefficient derived from the modified rotation law has a $\geq 1\sigma$ difference from the value found in the original inversion are indicated by crosses. The slanting solid line shows the boundary to the left of which lie modes having their lower turning points below $0.95R_\odot$.

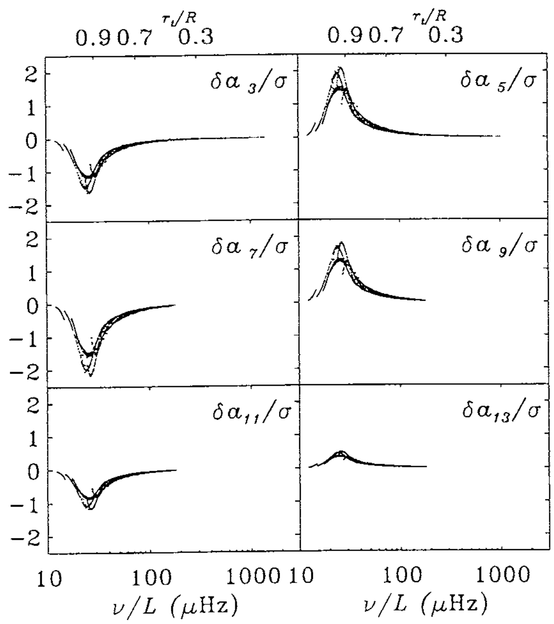

Figure 4. Differences between the forward-calculated splitting coefficients for the original inversion result and for the profile with the jet artificially suppressed, divided by the corresponding errors, for a_3, a_5, a_7, a_9, a_{11} and a_{13}.

between peak-finding effects and effects inherent in the raw data. These results are compared with those from an MDI-pipeline analysis of the same data, and from a GONG analysis of GONG data for the same period.

In the GONG analysis, (discussed for example by Hill et al. 1996), each (l, m) spectrum is fitted independently, yielding up to l individual splitting measurements for each (l, n) multiplet. In the MDI analysis, on the other hand, the a-coefficients are fitted di-

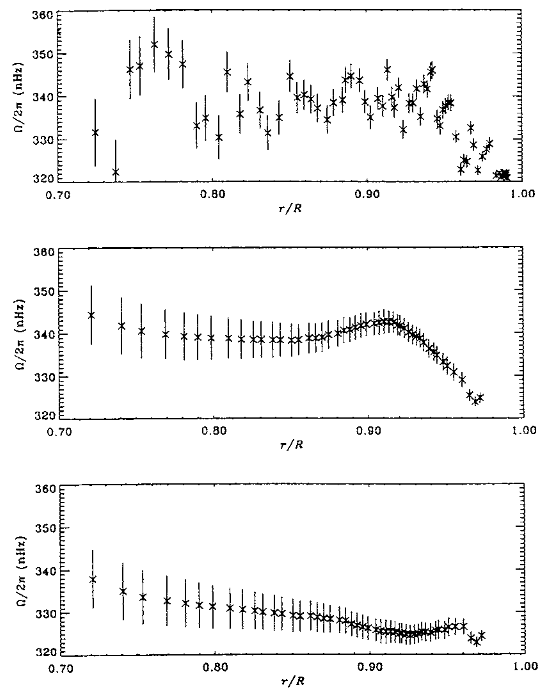

Figure 5. The splitting coefficients for MDI data (top) and artificial data with (centre) and without (bottom) the jet, combined to represent the rotational velocity at 75 degrees latitude. The points represent the combinations binned in groups of 15 modes.

rectly to the spectra. The other significant difference between the two approaches is that in the GONG analysis the 'm-leakage' between spectra with the same l and different m is ignored (or implicitly assumed to be zero), whereas in the MDI analysis the form of the leakage matrix, including the m-leakage, is explicitly included in the fit. One might expect that a dataset of independent splittings would contain more information than one analysed entirely in terms of a limited number of coefficients. However, in practice this appears not to be the case; when we take the independent splittings obtained using the GONG fitting and model them as an a-coefficient series, the coefficients cease to be significant at around a_9. Inversions with the derived coefficients show almost as much detail as those using the full set of splittings; Figure 8 shows the results of such an inversion for the same original dataset (MDI data with GONG fitting) as that used in Figure 7*b*.

No evidence for the jet is seen in the inversion of the splittings derived from the MDI data using the GONG pipeline, whereas it is quite evident in an inversion of the same data using the splitting coefficients calculated via the MDI pipeline. On the other hand, if the MDI-calculated coefficients are cut down to the same number of coefficients as was produced by the GONG processing, no jet is seen. In the light of the experiments described above, this is not too surprising; the higher-order coefficients are needed to resolve the jet, and the GONG fitting, for some

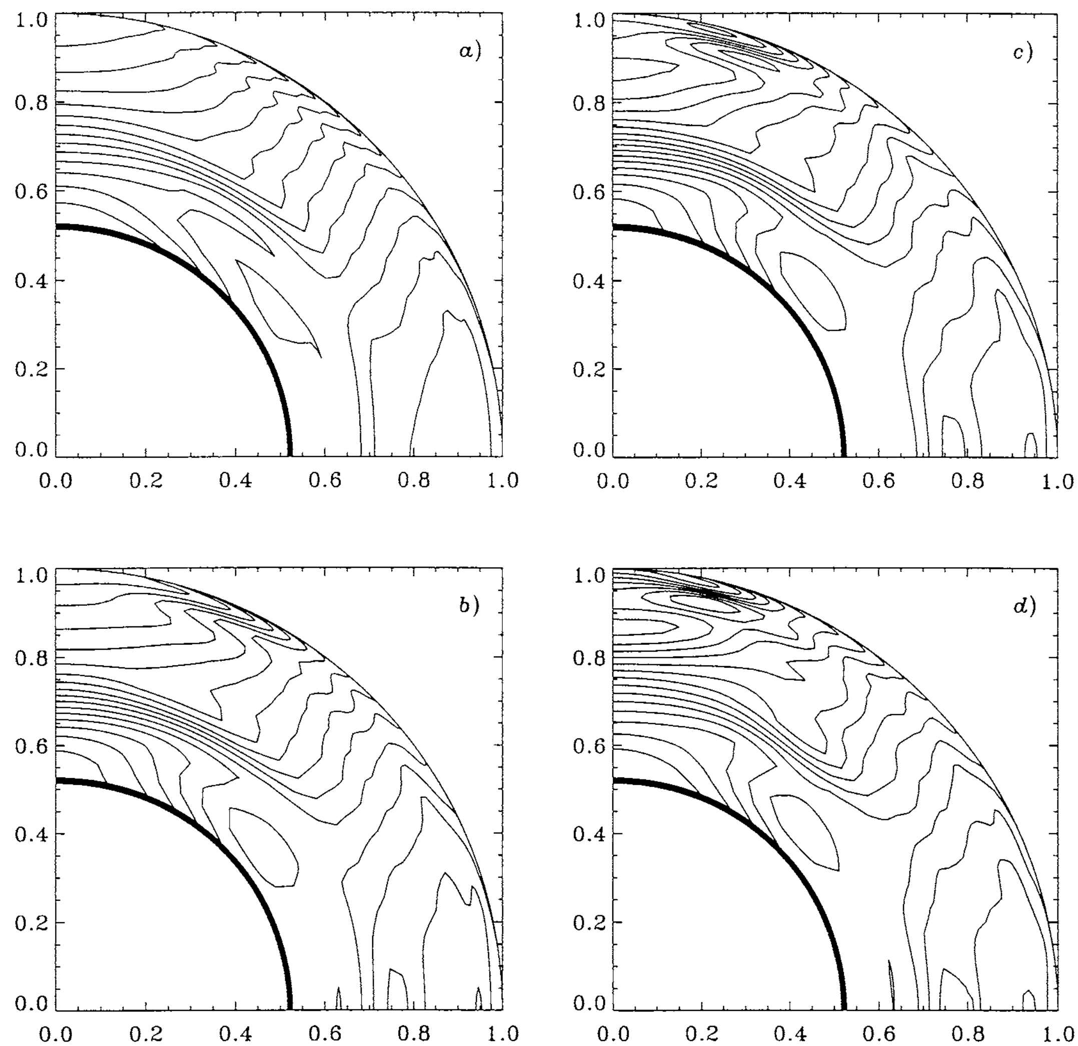

Figure 6. Sample 2dRLS inversions for SOI-MDI data, illustrating the effect of truncating the a-coefficient sequence at various points: a) $a_1 - a_5$*, b)* $a_1 - a_9$*, c)* $a_1 - a_{13}$*, d)* $a_1 - a_{17}$

reason not as yet understood, does not produce significant values for these coefficients.

4. DISCUSSION

The tentative conclusion from the above investigations is that the apparent feature is present in the fitted coefficients from the MDI data, rather than being an inversion artefact, but that its detection depends on the method used to fit the peaks. If the results from the planned fitting of the GONG data with the SOI pipeline were to show the jet, this conclusion would be strengthened. What is not yet evident is which peakfitting approach (if either) is more correct – whether the MDI approach introduces systematic features due to the imposition of a leakage matrix, or whether the GONG approach loses detail by not using leakage information, or whether some other difference in the peakfinding procedures is more important. It is therefore not yet clear whether the jet is a real solar feature or a peakfitting artefact. Further investigation of this issue will be of interest.

ACKNOWLEDGMENTS

The authors acknowledge many years of effort by the engineering and support staff of the SOI-MDI development team at the Lockheed Palo Alto Research Laboratory (now Lockheed-Martin) and the SOI-MDI development team at Stanford University.

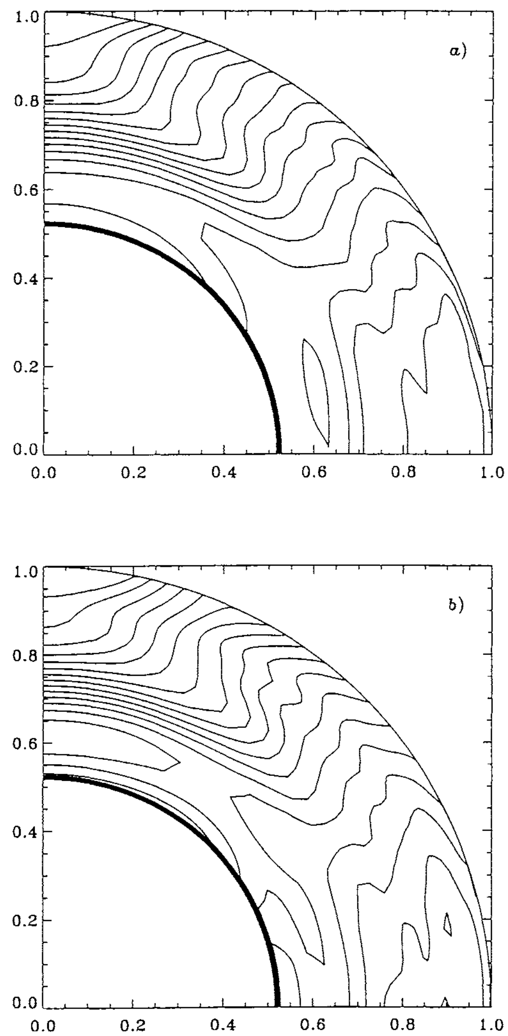

Figure 7. Sample 2dRLS inversions for data of GONG months 21-23: (a) GONG data analysed with GONG pipeline; (b) MDI-SOI data analysed with GONG pipeline.

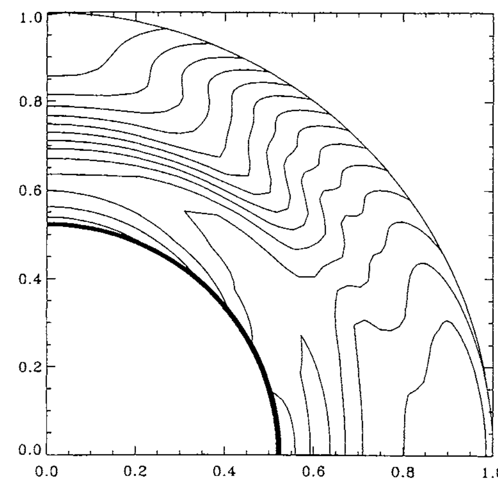

Figure 8. Inversion result for MDI-SOI data for GONG months 21-23 analysed via the GONG pipeline, using derived a-coefficients (based on fitting a Legendre polynomial series to the frequencies) rather than individual splittings.

The SOI–MDI project is supported by NASA grant NAG5-3077 to Stanford University, with subcontracts to Lockheed Martin, to University of Colorado, and to Harvard University. SOHO is a mission of international cooperation between ESA and NASA.

This work also utilizes data obtained by the Global Oscillation Network Group (GONG) project, managed by the National Solar Observatory, a Division of the National Optical Astronomy Observatories, 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 Astrofisico de Canarias, and Cerro Tololo Interamerican Observatory.

This work was supported by the Danish National Research Foundation through its establishment of the Theoretical Astrophysics Center. S.B. was supported by an AMIAS fellowship.

REFERENCES

Anderson, E.R., Duvall, Jr., T.L., Jefferies, S.M. 1990, ApJ, 364, 699

Antia, H.M., Basu, S., Chitre, S.M. 1998, MNRAS, in press (astro-ph9709083)

Hill, F., Stark, P.B., Stebbins, R.T., Anderson, E.R, Brown, T.M. et al. 1996, Science, 272, 1292

Ritzwoller, M. H., Lavely, E. M. 1991, ApJ, 369, 557

Schou, J., Christensen-Dalsgaard, J., Thompson, M.J. 1994, ApJ, 433, 389

Schou, J., Antia, H.M., Basu, S. et al. 1998, ApJ, In Press

Wilson, P.R., Burtonclay, D. 1995, ApJ, 438, 445