GLOBAL ASYMMETRIES IN THE SOLAR INTERIOR FROM SOHO/MDI DATA AND BBSO SYNOPTIC DATA

PI: Phil Goode

Project Summary

Helioseismic frequencies change systematically through the solar cycle. They are the most accurate global measures of the cycle dependent changes in the Sun, and the SOHO/MDI frequencies are the most accurate of all. Further, the SOHO/MDI seismic data provide excellent coverage beginning with the rising phase of cycle 23. The advantages of a seismic investigation of the Sun are not only the prospect of seeing changes beneath the solar surface, but also deriving from the frequencies the surface averaged parameters which quantify the Sun. The challenge is how to connect these global, seismic measures to observed characteristics of the dynamical Sun.

It has been known for nearly ten years that a low, even order Legendre expansion of the cycle dependent changes in oscillation frequencies shows a rough correlation with the geometry of the changing active latitudes, which are the most apparent manifestation of the Sun's surface magnetic field. As a spin-off of the Princeton solar oblateness experiment, it was shown that the Sun's surface temperature varies with latitude. Further, that the latitudinal temperature structure (i.e. even order Legendre structure) varies through the solar cycle. This variation is also roughly correlated with the changes in the frequencies of the solar oscillations. However, there are also differences between the temporal variations in the active latitudes and those in the latitudinal temperature structure. It has also been clear for some time that whether the perturbation is magnetic or thermal, its proximate cause is very close to the solar surface.

Differentiation between these two scenarios requires further guidance from observations. We propose to make Legendre decompositions of 72-day long averages of various BBSO synoptic data to serve as proxies for the field and the thermal structure, respectively; our goal is to use synoptic data to determine what kind of synoptic proxy best matches the evolving oscillation frequencies−−Legendre coefficient by Legendre coefficient.

These comparisons will help us to determine whether the direct Lorentz force of the magnetic field, or its indirect effect of changing the Sun's thermal structure, is more closely associated with the cycle dependence of the solar oscillations. Knowing this will tell us how good a proxy solar oscillations are for solar irradiance and luminosity variations. Determining how solar luminosity varies over the cycle is important for comparisons with long term variability observed in solar-like stars which are not necessarily observed equator-on.

This project is timely because we are in the rising phase of the new activity cycle, and the measured SOHO/MDI oscillation spectra will be much richer without the extended gaps in time (e.g. missing years) which characterized the data from the rising phase of the last cycle.

On a different note, the SOHO/MDI f-mode data have also revealed a small, but possibly systematic variation of the Sun's seismic radius. We propose to use the coming f-mode data to track the radius and interpret any changes in it.

1 Overview

Clear evidence of the onset of the coming activity cycle is provided by the rising P_6 asymmetry (see γ_3 in Figure 1) in the fine structure as determined from the twelve 72-day long sets of SOHO/MDI oscillation data (Dziembowski, Goode, Kosovichev and Schou 1999). The twelve sets cover 5/1/96-5/31/98 and 2/3/99-4/15/99. The results for the oscillation frequencies in Figure 1 are built on our earlier work with SOHO/MDI oscillation data (Dziembowski et al. 1998 and Goode et al. 1998). Our team has also used SOHO/MDI data to determine the seismic radius of the Sun (Schou et al. 1997).

The observed frequency changes of the solar oscillation multiplets are divided into centroid changes which reflect angular averages over the whole Sun, and the changes within the individual multiplets. The changes which are not symmetric about the multiplet centroid (the so-called "even-a coefficients") show a strong cycle dependence, the direct source of which has been a matter of controversy. However, the only well established changes are dominated by effects arising in the outermost layers of the Sun. The proximate cause of both perturbations resides just beneath the photosphere, but this does not preclude a deeper lying origin.

We note that the symmetric part of the multiplet (about the centroid) arises from the differential rotation of the Sun. Many authors have noted that any cycle dependent change in this part of the fine structure is insignificant compared with that in the non-symmetric part.

The sources for the frequency changes are generally considered to be some combination of variations in temperature, magnetic field and changes in the random velocity field. Goldreich et al. (1991) proposed that changes in the superficial, random magnetic field are the primary cause of the centroid frequency shifts. This idea has been criticized by Kuhn (1998), who points out that Goldreich et al. require a mean, quadratic, near-surface magnetic perturbation, $< B^2 >$ of around $(250G)^2$, while the observations of Lin (1995), and Lin & Rimmele (1999) show a mean field which is significantly weaker. We emphasize that in discussing the field, one has to be careful to distinguish between the direct mechanical effect of the Lorentz force and the subsequent thermal effect arising from the annihilation of the field, and the field's influence on the thermal structure through the perturbation of the convective transport.

We propose to use upcoming SOHO/MDI data to track the rising phase of solar activity with an unprecedented accuracy. We will track the asymmetries in the data to probe the nature of the Sun's near-surface magnetic field and thermal structure by inverting the splitting data for the structure of the perturbation. We will use these results to distinguish among the various models of the magnetic field. The real fields are complicated, and critical clues from observations are essential. We have already taken the first steps by preparing codes for the needed inversions (Dziembowski and Goode 1999) and applying them to the MDI data we have in hand (Dziembowski et al. 1999). From inversions of the more recent 72-day long sets, we have preliminary evidence of magnetic and thermal structures about 30 Mm beneath the surface of the Sun. These structures may be stable and if so, the magnetic field would be dissipated *in situ*. We need more data from periods of higher activity to verify whether or not there is sub-surface magnetic reconnection occurring. Further, we need more data to determine the latitudinal structure of these asymmetries, if indeed they are real.

Clearly, we are lacking a basic understanding as to how the frequency changes arise. And so, our inversions would greatly benefit if we knew the relative roles of the direct magnetic and the thermal effects. After all, to solve an inverse problem from these data, one must first *guess* the physical form of the causal near-surface perturbation. This is the reason that we need every clue we can get about the behavior of the perturbation at the surface. To this end, we have already done a Legendre decomposition of quarterly averages of the BBSO Ca II K data from 1996 forward. From this use of K-line data as a proxy for the magnetic field, it is clear that there is a strong correlation between the $\beta's$ (Legendre coefficients of the decomposition) and the $\gamma's$ from the Legendre expansion of the changing oscillation frequencies. This correlation persists through P_{10}. A similar result is reported for the GONG data (Howe et al. 1999). These results are much more precise and significant than those a decade ago.

Not surprisingly, there are also important differences in Figure 1. In the K-line data, the P_4 (β_2 in the figure) looks as though it is beginning to change sign. No such trend is seen in the $\gamma's$. In the last cycle, the P_4 distortion in γ ultimately changed sign. This difference is an important clue. We propose to check other magnetic proxies like the MDI magnetograms. What has happened in the white light data is unknown. We propose to make a similar Legendre decomposition of BBSO intensity data to look for the comparative results for the thermal structure. We will update Figure 1, as we go along. We are concerned that our standard BBSO white light data may not be an ideal proxy for the thermal perturbation because it may be contaminated by the magnetic field and/or have signal to noise problems. So, we also plan to use as a thermal proxy Ken Libbrecht's irradiance data (see Taylor et al. 1998) which we have been gathering in BBSO since 1993. Since these data come from an improved version of the photometer used to detect thermal structure in the first place, we know they will be a good thermal proxy.

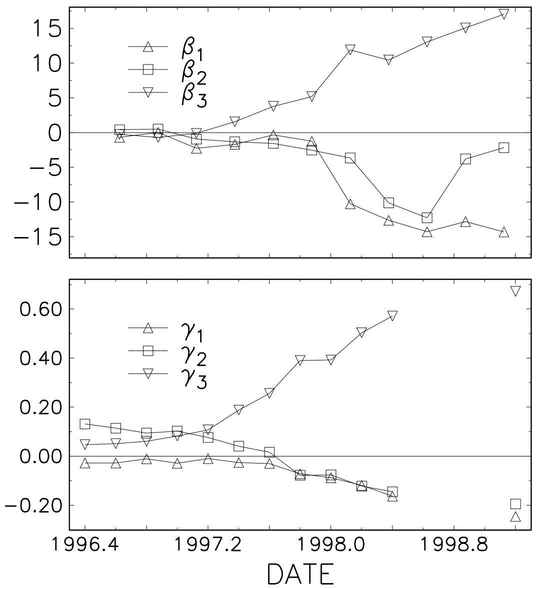

Figure 1: Top panel shows the quarterly P_2, P_4 and P_6 asymmetry in the BBSO Ca II K data. The $\beta's$ are the coefficients of an even-order Legendre fit and the ordinate is in arbitrary units, and where, for instance, β_1 is the coefficient of the P_2 distortion. This is to be compared to the bottom panel which shows the corresponding even Legendre distortions in the oscillation data arising from the near-surface perturbation as described by the $\gamma's$, Dziembowski and Goode (1992), where γ_2, in particular, arises from the P_4 distortion. The first eleven data points correspond to the first two years of SOHO observations (1996 May 1 - 1998 May 31). The twelfth covers 1999 Feb. 3 - 1999 April 15. The twelfth point is disconnected from the rest in the lower panel reflecting the SOHO time gap.

2 Work Plan and Budget

Our basic plan for this one year proposal is simple. We will make 72-day long averages of BBSO (and other) white light data and make Legendre decompositions of them. These will be compared with the results in Figure 1. Of course, Figure 1 will be extended with time. This will give us critical clues as to the relative importance of direct magnetic and thermal perturbations in the cycle's evolution. Then, in the spring of 2000, when there are five more 72-day long MDI sets available, we will use the codes we have already written to make guided inversions of these new data sets. The data reduction there is sufficiently automated that we can expect them in almost real time. For instance, the inversions done in June of 1999 already included data through mid-April.

The budget includes half-time support for Jeff Hickey, a senior observer at BBSO, who has B.S. and M.S. degrees in astronomy. Jeff now collects and reduces the daily BBSO synoptic data using new in-house software which has not been applied to synoptic data taken prior to 1999. For this project, he will reduce the old synoptic data, including the irradiance data, day-by-day, dating back to 1996, and use our existing software for doing the Legendre decomposition. The reduction of pre-1999 data is straightforward for him, but labor intensive. The budget also includes one month of summer salary for Phil Goode and $8,000 in consulting fees for Wojtek Dziembowski. Wojtek will spend April/May of 2000 in Big Bear. Finally, it includes $3,000 for travel to Stanford for Goode to work with Jesper Schou and Alexander Kosovichev on the MDI data and its interpretation, and $2,000 for publications.

References

Dziembowski, W. A. & Goode, P. R., 1992, **ApJ**, 394, 670

Dziembowski, W. A. & Goode, P. R., 1999, in preparation

Dziembowski, W. A., Goode, P. R., DiMauro, M.P., Kosovichev, A.G., & Schou, J., 1998, **ApJ**, 509, L456

Dziembowski, W. A., Goode, P. R., Kosovichev, A.G., & Schou, J., 1999, **ApJ**, submitted

Dziembowski, W. A.& Goode, P. R., Schou, J., Tomczyk, S. 1997, **A&A**, 323, 231

Goldreich, P. Murray,N.,Willette,G., & Kumar, P.,1991, **ApJ**, 370, 752

Goode, P.R., Dziemboski, W.A., DiMauro, M.P., Kosovichev, A.G. and Schou, J. 1998, in Structure and Dynamics of the Interior of the Sun and Sun-like Stars, Eds. S. Korzennik & A. Wilson, ESA, 887.

Howe, R., Komm,R., & Hill, F., 1999, **ApJ**, submitted

Kuhn, J. R., 1998, in Structure and Dynamics of the Interior of the Sun and Sun-like Stars, Eds. S. Korzennik & A. Wilson, ESA, 871

Lin, H., 1995, **ApJ**, 446, 421

Lin, H. & Rimmele,T.R., 1999, **ApJ**, 514, L448

Schou, J., Kosovichev, A. G., Goode, P. R., & Dziembowski, W. A., 1997, **ApJ**, 489, L197

Taylor, S.F., Varsik, J., Woodard, M.F., Libbrecht, K.G., 1998, **Solar Phys.**, 178, 439

CURRICULUM VITAE

PHILIP R. GOODE

Address:

Big Bear Solar Observatory
40386 N. Shore Lane
Big Bear City, California 92314
(909)-866-5791 ext. 20
(909)-866-4240 fax
pgoode@bbso.njit.edu

Education:

Rutgers, The State University
New Brunswick, New Jersey
Ph.D. (Physics), February 1969

University of California
Berkeley, California
A.B. (Physics), June 1964

Positions Held:

1997-present: Director, Big Bear Solar Observatory

1996-present: Visiting Associate, California Institute of Technology

1994-present: Distinguished Professor of Physics and Mathematics, NJIT

1984-1994: Professor of Physics, NJIT

1990-1991: SERC Visiting Fellow, Institute of Astronomy, University of Cambridge

1984-1990: Chairperson, Department of Physics, New Jersey Institute of Technology

1980-1984: Associate Research Professor, University of Arizona

1977-1980: Member of Technical Staff, Bell Telephone Laboratories

1971-1977: Assistant Professor of Physics, Rutgers University

1969-1971: Postdoctoral Research Associate, University of Rochester

1969: Postdoctoral Research Associate, Rutgers University

Ten Selected Publications

Measuring Seeing from Solar Scintillometry and the Spectral Ratio Technique, P.R. Goode, H. Wang, W.H. Marquette, C. Denker, 1999, in preparation.

The Excitation of Solar Oscillations, P.R. Goode, L.H. Strous, T.R. Rimmele, R. F. Stein, Å. Nordlund, 1999, Sac Peak Workshop, in press.

New Vectormagnetographs at the Big Bear Solar Observatory, T.J. Spirock, C. Denker, H. Wang, P.R. Goode, 1999, AAS Meeting 194.7607.

Local Helioseismology of the Sun's Seismic Events, P.R. Goode, L.H. Strous, T.R. Rimmele, 1998, in IAU Symp. 185. New Eyes to See Inside the Sun, eds. F.L. Deubner, J. Christensen-Dalsgaard and D. Kurtz, p. 183.

Synoptic Halpha Full-Disk Observations of the Sun from Big Bear Solar Observatory - I. Instrumentation, Image Processing, Data Products, and First Results, C. Denker, A. Johannesson, W. Marquette, P.R. Goode, H. Wang, H.Zirin, 1998, Solar Phys., 184, 87.

New Digital Magnetograph At Big Bear Solar Observatory, H. Wang, C. Denker, T. Spirock, P.R. Goode, S. Yang, W. Marquette, J. Varsik, R.J. Fear, J. Nenow, D.D. Dingley, 1998, Solar Phys. 183, 1.

On the Origin of Solar Oscillations, P.R. Goode, L.H. Strous, T.R. Rimmele, R.T. Stebbins, 1998, ApJLett, 495, L27.

Solar Asymmetries from SOHO/MDI Splitting Data, P.R. Goode, W.A. Dziemboski, M.P. DiMauro, A.G. Kosovichev and J. Schou, 1998, in IAU Symp. 185. New Eyes to See Inside the Sun, eds. F.L. Deubner, J. Christensen-Dalsgaard and D. Kurtz, p. 196.

Contrast of Faculae at 1.6 Microns, H. Wang, T. Spirock, P.R. Goode, C. Lee, H. Zirin and W. Kosonocky, 1998, ApJ, 495, 957.

IR Magnetograph System at BBSO, T.J. Spirock, P.R. Goode, H.F. Wang, H.Wang, 1998, AGU Spring Meeting.