GLOBAL ASYMMETRIES IN THE SOLAR INTERIOR FROM SOHO/MDI DATA

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PROPOSAL SUMMARY:

Clear evidence of the onset of the coming activity cycle is provided by the rising P_6 asymmetry in the fine structure of the five 72 day sets of SOHO/MDI oscillation data covering 5/1/96-4/27/97. We propose to use upcoming SOHO/MDI data to track the rising phase of solar activity in the way that has never been done before. We will track the asymmetries in the data to probe the nature of the Sun's near surface magnetic field by inverting the splitting data for the structure of the field. We will use these results to distinguish among the various models of the field. The real fields are complicated and critical clues from obsvervations are essential.

A persistent P_4 surface asymmetry on the Sun has been apparent throughout the current activity minimum when not too much happens in the Sun's outermost layers. We propose to use the SOHO/MDI splitting data to learn whether the asymmetry reflects local, near-surface properties of indirectly reflects a deeply buried toroidal magnetic field.

Further, we propose to use time-averaged synoptic maps of white light data and magnetograms from SOHO/MDI to extract the low degree Legendre dependence of the data. The time-averaging will be over the length of each SOHO/MDI splitting data. The respective degrees of correlation with the asymmetries in the splitting data will tell us to what extent the oscillation data can be used as a proxy for luminosity.

The f-mode data in the five sets 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.

PROJECT DESCRIPTION

A. Background

Beneath the photosphere, on average the Sun is almost a perfect sphere. Historically, the main photospheric asymmetry studied has been the magnetic activity cycle as reflected in the Maunder butterfly diagram. In recent years, more subtle signatures of asymmetries varying with the solar cycle have been found. As a spin-off from the Pinceton oblateness observations, large scale, small amplitude asymmetries were discovered by Kuhn (1988) in solar limb brightness observations. The asymmetries took the form of latitudinal temperature bands. Kuhn (1988) also noted that the asymmetries were dramatically changing with the solar cycle. Further, he was the first to link the systematics of these asymmetries with those in the asymmetries in the fine structure in the spectrum of solar oscillations. Specifically, he noted that the asymmetries in the fine structure in solar oscillations measured by Duvall, Harvey and Pomerantz (1986) during the activity maximum in 1981-82 although relatively small, were much larger than those measured by Brown and Morrow (1987) in 1983, and the latter were larger than those measured by Libbrecht (1988) during the 1986 solar activity minimum. He emphasized that this behavior was in one-to-one correspondence to the trends in the size of the temperature asymmetry.

This picture was strongly confirmed by Libbrecht and Woodard (1990) who compared the asymmetric parts of their 1986 and 1988 splitting data from Big Bear Solar Observatory (BBSO). They noted significant changes in centroid frequencies, $\bar{\nu}_{\ell,n}$, and the coefficients describing the asymmetric part of the fine structure, $a_{2k,\ell}$. They showed that both scale with the mode inertia (mass). This finding implied that the site of the perturbation giving rise to changes is located in the outer part of the Sun. Furthermore, they demonstrated that the angular dependence of the perturbation causing the asymmetry in the splittings is similar to the latitudinal dependence of the temperature bands.

It has been established beyond reasonable doubt that the temperature bands and the aforementioned changes in the p-mode spectrum are reflecting the changes in solar activity.

Dziembowski and Goode (1991) studied the asymmetry in more detail, in particular, they were able to localize the site of the perturbation to be *very near the surface.* We will return to this point later in Section 4.2.4.2. They considered the Lorentz force arising from the fibril fields to be the cause of the perturbation. Also, Goldreich, et al.(1991) reached a similar conclusion concerning localization of the source of the frequency perturbation varying with the solar cycle. For their argument, they analyzed the data on centroid shifts from the BBSO measurements. Overall, treating the interaction of oscillations with the fibril fields is a difficult problem and our understanding of it is far from complete (Rosenthal 1995, Rosenthal & Gough 1989 and Zweibel & Däppen 1989).

We now have appreciably more information on the fine structure from many sources—– spanning most of the last maximum and running through the current minimum. A partial list of the sources includes BBSO ('86-'90), LOWL ('94-), GONG ('95-) and SOHO ('96-). Analyses of these data revealed that in years of high solar activity, there are large values of the first three of the aforementioned even a-coefficents, which implies statistically significant distortions described by P_2, P_4 and P_6 Legendre polynomials.

We note that recent oblateness measurements reveal a P_2 distortion that may be regarded as being consistent with the centrifugal stretching of the Sun due to its rotation, Kuhn, et al. (1998).

Investigating the global asymmetries of the Sun is of primary importance in formulating a phenomenology of the temporal and angular dependences of the solar cycle. It is striking that during the years of this solar minimum and the last one, the only significant distortion is the one proportional to P_4. This angular dependence is what we would expect as a result of the effect of a quadrupole toroidal field. In dynamo theory, such a field is expected to be present mostly in deeper layers. However, we certainly are not directly seeing the buried field. Further, in fairness, we must point out that there could be a completely different cause of the distortion, e.g. the inertia of the solar velocity field.

We propose to use the latest seismic data from SOHO/MDI and SOHO white light and magnetogram data to track and determine the origin and nature of the asymmetry. From the seismic data we will determine the asymmetries as seen by modes of different frequency. This information will be used for radial localization (determining the depth or site of the perturbation). We further note that the seismic data on the asymmetry allows for a straightforward determination of the Sun's near surface magnetic perturbation due to activity, Dziembowski and Goode (1996), which can be used to purge other low degree data from other SOHO instruments of this corruption which effects both centroid frequencies and relative frequencies within individual multiplets. (see Section B.5.).

The novel aspect of what we propose is seaching for correspondences with time-averaged synoptic images. We believe that the correlation between the global asymmetries in the oscillation data and those in contemporaneous synoptic data will provide valuable insights, like how good a proxy the frequency changes in the seismic data are for intensity variations (from which we can determine irradiance and luminosity changes), see Section B.3. The direct effect of the field on the oscillation frequencies would have one synoptic manifestation. The indirect or structural modifications of the Sun by the field would have another. In particular, we would like to know whether the γ's correlate better with the average field strength or the temperature (as determined by intensity measurements). That is, we propose to use synoptic data to search for global asymmetries. Worthy of special note here is the persistent P_4 asymmetry at activity minimum. We expect that correlations will shed light on the origin of the asymmetries. It is, in particular, important to establish the relation between the average surface magnetic field and the splitting coefficients. The connection between temperature and splitting coefficents can be used to convert solar constant variations to total luminosity variations (see Section B.3.).

B. Proposed Research

1. Solar Near Surface Asphericity from SOHO/MDI Seismic Data

Splitting data from ongoing seismic resolved disk observations are typically presented in the following form (Ritzwoller & Lavely 1991 and Schou, et al. 1994),

$$\nu_{\ell,n,m} - \bar{\nu}_{\ell,n} = \sum_{k=1} a_{k,\ell n}\mathcal{P}_k^\ell(m), \tag{1}$$

where $\bar{\nu}_{\ell,n}$ is centroid frequency in the absence of asymmetries and the $\mathcal{P}_k^\ell(m)$'s are orthogonal polynomials in m of degree ℓ. They are defined for $k \leq 2l$ through the following formulae

$$\mathcal{P}_k^\ell(\ell) = \ell$$

$$\sum_{m=-\ell}^{m=\ell} \mathcal{P}_j^\ell(m)\mathcal{P}_k^\ell(m) = \delta_{k,j}$$

For $\ell \gg k$ we have $\mathcal{P}_k^\ell(m) \approx lP_k(m/l)$. A primary advantage of this formulation over earlier ones is that the $\mathcal{P}$ representation has a the one-to-one correspondence of a_{2k} coefficients to P_{2k} polynomials. In the earlier formations, this correspondence applied only in the asymptotic limit of $l >> 2k$. The early data were for higher l and contained $2k$ up to six, therefore, this distinction was not often important. However, with the latest data, the distinction is important because, for instance, these data have a value of 36 for $2k$ in the latest release of the SOHO data. In using data from SOHO, and other sources, to follow the asymmetries as presented in the formalism developed by Dziembowski and Goode (1991, 1997), we will represent the observed a_{2k} in the following form,

$$a_{2k,\ell n} = (a_{2k,\ell n})_{\mathrm{rot}} + C_{k,\ell}\frac{\gamma_k(\nu)}{I_{\ell n}}, \tag{2}$$

where the first term on the r.h.s. represents the effect of centrifugal distortion which we calculate following the treatment of Dziembowski and Goode (1992) in which the full second order problem of rotation was solved for the first time. Since our plan is to study temporal variations in the asymmetry, we eliminate the constant distortion of rotation from the γ's in eqn. (2). The coefficient of the second term on the r.h.s. is

$$C_{k,\ell} = (-1)^k \frac{(2k-1)!!}{k!}\frac{(2\ell+1)!!}{(2\ell+2k+1)!!}\frac{(\ell-1)!}{(\ell-k)!}. \tag{3}$$

The $\gamma_k(\nu)$ are the functions we determine by inversion, and the $I_{\ell n}$ are calculated mode inertia, which is evaluated assuming all modes have the same value for the radial displacement at the base of solar photosphere. Adopting a value of 10^4 for the displacement, we have $I_{20,9} \approx 1$. The inertia decreases with increasing ℓ or n. For $\ell \gg 2k$ we have

$$C_{k,\ell} \approx (-1)^k \frac{(2k-1)!!}{(2k)!!}$$

and this approximation was used before by Dziembowski and Goode (1991, 1997), it is not used in the figures shown here.

Each of the γ_k coefficients, which we determine from the data corresponds separately to a single $P_{2k}(\cos\theta)$ distortion, and we have

$$\int_0^{2\pi} \int_{-1}^{1} |Y_\ell^m|^2 P_{2s} d(\cos\theta) d\phi = C_{k,\ell} \mathcal{P}_{2k}^{\ell}(m). \tag{4}$$

The $I_{\ell,n}^{-1}$ factor accounts for most of the ℓ and frequency dependence in the splitting coefficients. This was given by Libbrecht and Woodard (1990) as evidence that the asphericity responsible for the even-a coefficients is localized well above the lower turning point of modes in the sample i.e. close to surface. Dziembowski and Goode (1991) were able to determine a significant ν dependence of the γ_1 and γ_2 coefficients from the same data, and showed that it helps to determine the depth of the relevant asphericity. In general, we should also expect an ℓ-dependence in the $\gamma' s$. We shall return to this problem later. First, we motivate the work we propose by showing the results of fitting constant γ's to each of the five sets of the even-a coefficients from the SOHO/MDI instrument, Dziembowski, et al. (1998). The MDI/SOHO splitting data treated there and shown here are five 72-day sets covering (1) 5/1/96-7/11/96, (2) 7/12/96-9/21/96, (3) 9/22/96-12/2/96, (4) 12/3/96-2/12/97, and (5) 2/13/97-4/25/97.

Each set contains data for 18 even order coefficients for over 1300 p-modes with ℓ ranging from 2 to 184. We did not include f-modes in our determinations of the γ's because p- and f- modes have vastly different properties even in the outermost layers of the Sun. In Figure 1, we show the first 12 γ's. We see that the errors rapidly increase with the order, k. We will focus on the first four coefficients in the expansion. The changes found in some higher order γ's are formally significant, but we are reluctant to interpret them. We do not see a significant trend in either γ_0 or γ_1. There is no absolute measure of γ_0. We arbitrarily assume it is zero for SET 1. The plotted value is, thus, the difference from the centroid frequency divided by mode inertia. The frequency differences have already been presented by Kosovichev, et al (1998) in a different form. Further, they showed that the frequencies in the SET 1 are lower than in the remaining sets. However, they reported no apparent solar cycle variation.

The absolute values of γ_2 and γ_3 are much larger than those for $\Delta\gamma_0$ (defined to be zero at activity minimum, as in Fig. 1) and γ_1 at activity minimum, as in Fig. 1. We note, however, that $\Delta\gamma_0$ and γ_1 are comparable to γ_2 and γ_3 at times of high activity. The γ_2 term describes the P_4 distortion was dominant in 1996.

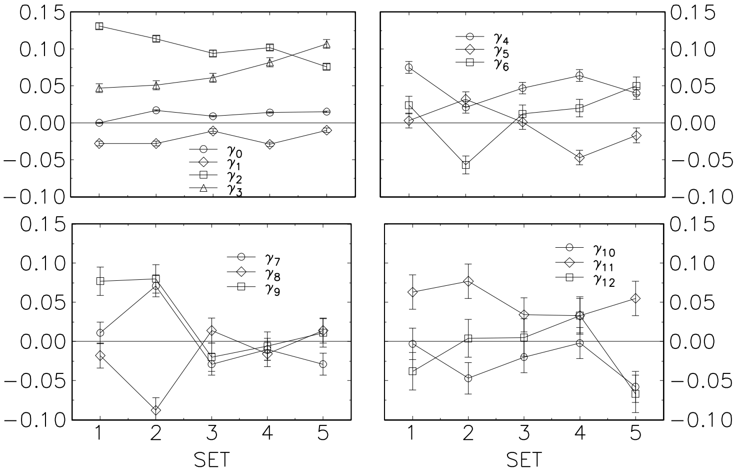

Fig. 1. Mean γ's (in μHz from from five SOHO/MDI sets.

The corresponding distortion has been found by Kuhn, et al. (1998) in their intensity measurement with the SOHO/MDI instrument. P_2 is the dominant distortion in their measurement, and is consistent with centrifugal stretching. In particular, if we represent their result for the asymmetry in terms of the fractional radius change in the Sun, we have

$$\frac{\delta R}{R_{\odot\, A}} = [(-5.41 \pm 0.46)P_2 + (1.43 \pm 0.56)P_4] \times 10^{-6}.$$

Roughly, the differential rotation implies a value of

$$\frac{\delta R}{R_{\odot\, DR}} = [-6.0P_2 + 0.6P_4] \times 10^{-6}.$$

Thus, after removing the part of the asymmetry due to rotation, only the P_4 distortion is significant at the 1σ level. We stress that we removed the effect of centrifugal distortion from our γ's. The effect is 0.037 μHz for γ_1 and about ten times smaller for γ_2 and is completely negligible for γ_3 and higher order terms. Note that the size of centrifugal stretching removed from γ_1 is smaller than γ_2 or γ_3. In detail, we find that the P_6 term is dominant in SET 5. This set was obtained contemporaneously with theirs, but they did not report for a P_6 distortion. This might be due to the relatively larger noise level in the intensity data. The relative accuracy in dtermining the asymmetry serves to emphasize the broad utility of the seismic data, especially in the uses for we propose here.

The trend seen in γ_2 and γ_3 is the same as at the beginning of the rising phase of the previous activity cycle. We note that the data from the previous rising phase covered a similar frequency range, but they were restricted to lower ℓ values. The maximum value of ℓ in the BBSO data (Libbrecht and Woodard,

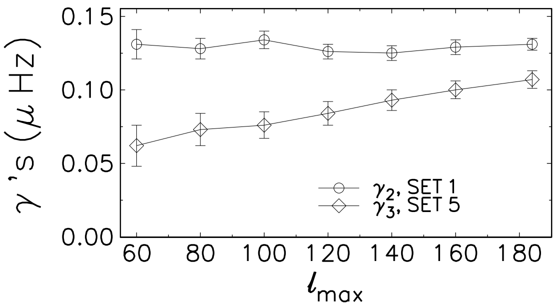

Fig. 2. Values of γ_2 and γ_3 inferred from data sets truncated at specified values of ℓ. Effect of truncation is similar for the other three sets.

unpublished) is 140, while in LOWL data (Tomczyk,) it is 100. Thus, to make a meaningful comparison we have to examine the behavior of the γ's with changes in the ℓ composition of the data−−in particular, the maximum value of ℓ in the truncated sets. Fig. 2 shows an example. We show there the effect of truncation of selected data sets on the inferred values of γ_2 and γ_3. The values are the largest in the two sets selected, but the patterns are the same for the other original sets. We see that there is a difference in the behaviors−−the value of γ_2 is insensitive to $\ell_{\max}$, whereas the value of γ_3 montonically increases with it. The behavior of γ_1 is similar to that of γ_3, but the values are much smaller. These facts must be taken into account when comparing γ's obtained from various data sets. They may be also important for understanding the origin of the asphericity reflected in p-mode frequencies, and we propose to carefully consider the treatment of the outermost layers in the models to investigate this.

In Fig. 3, we present mean values of the γ's from various sources which includes BBSO (Libbrecht and Woodard, private communication), LOWL (Tomczyk, private communication) and SOHO/MDI (SOHO team, private communication). We compare them with the monthly averages of smoothed sunspot numbers (NSO website). Clearly, the BBSO of 1988 and 1989 give the largest magnitudes of the γ's and this corresponds to the first half of the sunspot maximum. Unfortunately, we are missing splitting data from the rising phase (1987 or so), as well as from the declining phase.

The errors in the BBSO and LOWL γ's are about twice as large as those in SOHO/MDI, but they are still relatively small and the errorw would not be visible in Fig. 3. The relatively small errors in the low-order γ's encourages a search for the ν dependence. As we have pointed out, this dependence yields information about the localization of the underlying asphericity. The $\gamma_k(\nu)$ functions were determined by means of a least-square fit to the data assuming a three-term Legendre polynomial dependence.

In Fig. 4, we compare the $\gamma_k(\nu)$ inferred from SETs 1,3, and 5 of SOHO/MDI data with those inferred by Dziembowski and Goode (1996) from the BBSO data of Libbrecht and Woodard and by Dziembowski et al. (1997) from LOWL data

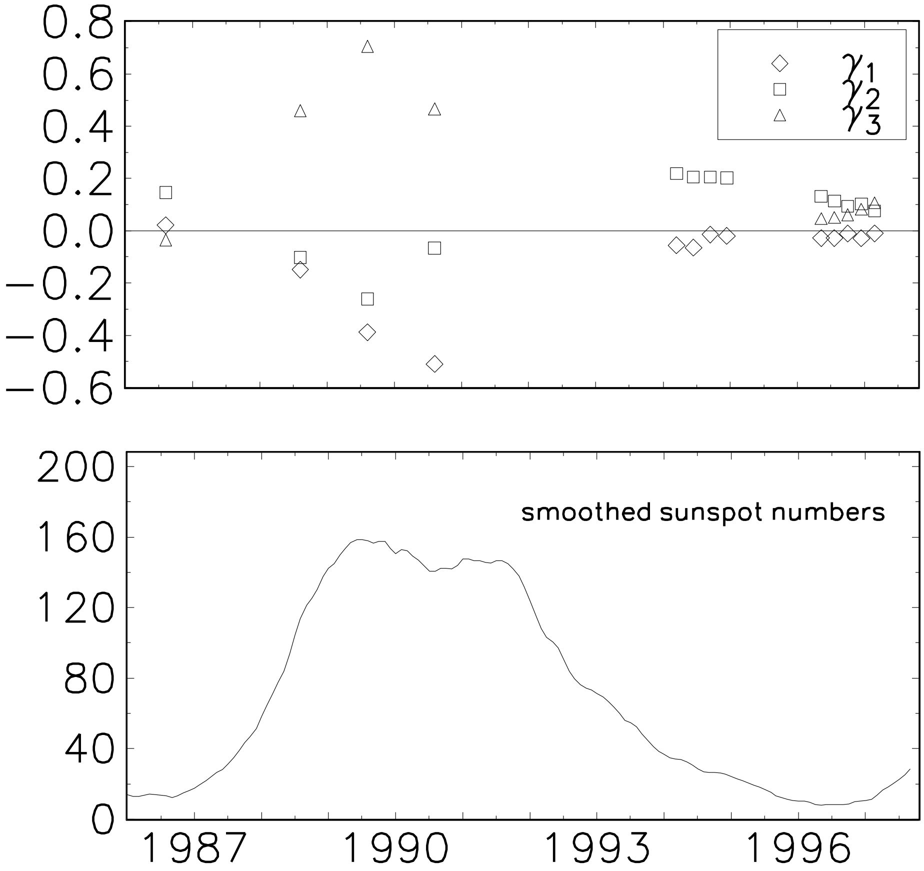

Fig. 3. The lower panel is a smoothed monthly average of the sunspot number covering the time since the 1986 activity minimum. The upper panel is a combination of γ's derived from BBSO (1986-1990), LOWL (1994) and SOHO/MDI (1996-) data. The errors in the γ's are smaller than the symbols used to represent their values.

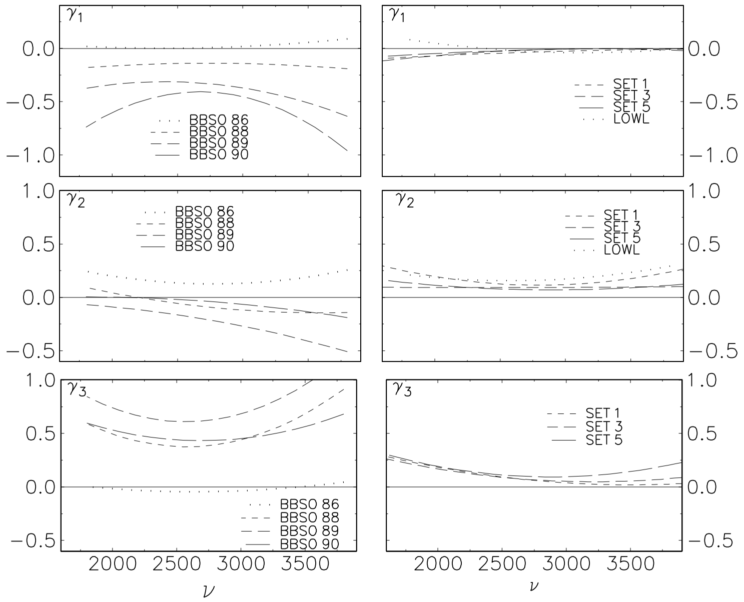

Fig. 4. The $\gamma_k(\nu)$ dependence from various data sets. The BBSO observations were made in summers of the indicated years. The LOWL data were taken from February '94 to February '95. Measurements for SET 1, SET 3 and SET 5 were done in the intervals 05/01/96 – 07/11/96, 09/22/96–12/02/96, and 02/13/97–04/25/97, respectively.

of Tomczyk. The similarities in γ_1 and γ_2 between BBSO86 and LOWL data has already been observed. We note that the sets are from successive activity minima. The mean values of γ_2 derived from LOWL data were divided into four quarters and showed a barely significant decreasing trend from the value of 0.22 to 0.20 mHz. The mean value from SET 1 measurements taken about one year and a half later was 0.13 mHz. It decreased during next three-quarters of a year to 0.08 mHz, as seen in Figs. 1 and 3.

2. SOHO/MDI data and the rise of the coming cycle

The most clear evidence of the onset of the rising phase of activity during this three quarter of a year period is the systematic increase of γ_3 from SOHO/MDI seen in Figs. 1 and 3. In the lowest boxes of Fig. 3, we see that the values in the data fill the gap in γ_3 between BBSO86 and BBSO88. Still, even SET5 is closer to BBSO86 than to BBSO88 but the increase in γ_3 is evident. Presumably, this reflects growing fields at higher latitudes. *We propose to use the SOHO/MDI data to track the rising phase of the new cycle in a way it has never been done before.*

In γ_1, we also observe an evolution toward the values it has in the Sun's more active state. This evolution presents the weakest case. One should note, however, that temporal changes in γ_1 were also lagging behind those in the higher order γ's in the last cycle, see Figs. 3 and 4.

As we already mentioned, Libbrecht and Woodard (1990) showed that the mean γ's are related to amplitudes of the latitudinal temperature bands. The shape of the $\gamma_k(\nu)$ functions yields information about the site of the perturbation giving rise to a_{2k}.

We propose to use time-averaged synoptic maps of white light data and magnetograms from SOHO/MDI to extract the low degree Legendre dependence of the data. The time-averaging will precisely correspond to that in the SOHO/MDI splitting data. The degree of correlation between these Legendre coefficients varying through the solar cycle with the temporally corresponding low degree Legendre coefficents from splitting data will enable us to ascertain, from a completely different perspective, the role of the magnetic field in the Sun's cycle dependent asphericity. That they are related is illustrated in Fig. 3.

The key to this part of the proposed work follows from correlating the γ's with the changes in the mean magnetic field and surface temperature variations. Unfortunately, a full theory linking changes in frequency to changes in magnetic field is not available for fibril fields, because it is indeed quite difficult. However, simplified models, such as those of Zweibel and Dappen (1989) and Rosenthal (1995) will be tested.

The effects of magnetic fields on oscillations are twofold. Magnetic fields perturb the mean temperature structure which alters the frequencies. Second, the Lorentz force has a direct effect on oscillation frequencies. Thus, it is not a great surprise that the asymmetries in the oscillation spectrum are related both to temperature and local field structures, but which part is more important? For a specified field geometry, both effects can be, in principle, calculated. In practice, however, it is quite difficult, and , as mentioned above, we are far from satisfactory models of the interaction. From a comparison of the asymmetries as expressed in terms of γ coefficents, we plan to correlate the various temporal averages of synoptic maps which should provide a valuable constraint on the relative importance of temperature and the direct role of the field.

Asphericities as expressed in the γ's imply that there is a non-radial perturbation of the Sun's mechanical equilibrium. The connection to magnetic fields is obvious in times of high activity, and we have discussed in some detail the direct and indirect roles of the magnetic field, but we should also consider the posssible role of inertia. Inertia can arise from rotation, meridional circulation and convective velocities. The rotational shape distortion is essentially time-independent, and so we quantify and remove it. The effect of meridional circulation is negligible (see Section B.4). However, the convective flows can be both non-symmetric and time dependent. For instance, the "thermal shadow" of a deeply buried magnetic field could be reflected in global asymmetries in the near-surface velocity field, Kuhn and Stein (1996).

If the γ's primarily reflect temperature asymmetries, then the precise local-

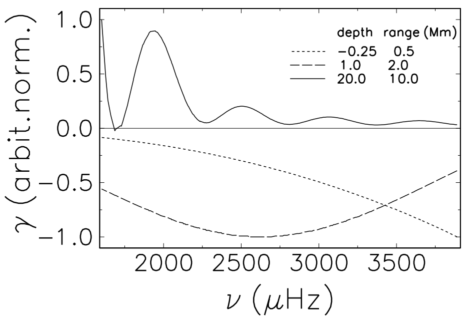

Fig. 5 The shape of the $\gamma(\nu)$ function resulting from the three assumed shapes of the relative temperature (squared sound speed) perturbation. In each of the cases the functional form of the perturbation is given by cubic spline function centered at the indicated depth below the base of photosphere an spanning the indicated range. The shapes of the measured γ_k functions (see Fig 4) is most similar to that resulting to the perturbation localized just beneath the photsphere (long dash).

ization of the temperature fluctuation may be inferred from $\gamma(\nu)$ dependences. If the direct role of the field dominates, the localization is not quite so precise. In Figure 5, we show how various localizations of the temperature perturbation are reflected in the form of the $\gamma(\nu)$ dependence. The wide variation in the function $\gamma(\nu)$ demonstrates the strong sensitivity of it to the location of the perturbation. Clearly, there is also a good prospect of probing changing subphotospheric asymmetries by using the $\gamma_k(\nu)$ functions.

3. Variations in solar luminosity

It would be of great interest to know what are the solar luminosity variations over the 11 year cycle. We know how intensity varies equator-on (irradiance is 0.1% greater at activity maximum), but converting it to a relative luminosity requires knowledge of the variation of the angular structure of the intensity variations. From our comparisons of the intensities, primarily from the SOHO/MDI white light data the coresponding γ's from splitting data, we will determine whether it is possible to use γ's as proxys for intensity. We can write the intensity as

$$I(\cos\theta) = I_0 + \Delta I_0 + \sum_{k=1} I_{2k} P_{2k}(\cos\theta)$$

where I_0 is the intensity at some chosen epoch (e.g. a 72 day average around activity minimum) and ΔI is the “present” intensity with respect to the chosen epoch and the I_{2k} are the various higher multipolarities of the intensity. One of the aims in comparing the γ's with the synoptic data is to determine whether or not

$$I_{2k} = \text{constant} \times \gamma_k.$$

If so, then it seems reasonable to assume that we also have

$$\Delta I_0 = \text{constant} \times \Delta\gamma_0.$$

The relations between the γ's and the I's is true to the extent that the γ's reflect the latitudinal and temporal temperature changes. because both arise from the same local physics. Once we know ΔI_0 and I_{2k}, we can easily convert the intensity variations into irradiance and luminosity variations with respect to the activity minimum. We emphasize that $\Delta\gamma_0$ is much easier to determine than ΔI_0.

Determining how solar luminosity varies over the cycle is important for comparing with long term variability observed in solar like stars which are not necessarily observed equation-on.

4. Cause of the $P_4(\cos\theta)$-distortion at activity minimum

The main quesion here is whether this distortion is reflecting local properties of the outermost layers, or it indirectly reflects the deeply buried toroidal field. One way of examining this problem is by following the behavior of γ_2 during the activity minimum when not much happens in the outermost layers. We have a hint of that from the behavior of the values of the γ's derived from the LOWL data of 1994, Dziembowski, et al. (1997) and MDI data in Figure 4. From which we learned that the value of γ_2 from the LOWL data is about twice the size of γ_2 from the MDI data which were taken later in the same minimum. Does this slow variation reflect a steady change in the leakage from the quadrupole tordoidal field buried buried near the base of the convection zone? If so, then it tells us about the dynamo field. Or perhaps the leakage is nearly constant and arises from the global structure of the inertia of the flows (sometimes called "thermal shadowing", but this would be a misnomer for this case). Another way of getting at this is comparing the degree of correlation through analyzing correlations of γ's with various polynomial distortions inferred from the synoptic maps. In this comparison, we recognize the special role of γ_2 and will consider both γ_2 and $\gamma_2 - \gamma_{2,min}$ in the comparisons, where $\gamma_{2,min}$ is the value at activity minimum. If the latter is a better match, then it points toward a steady P_4 perturbation through the cycle. Such a result leads us back to a possible role for inertia.

As discussed in Section B.2., one potential alternative source of a constant P_4 distortion is the inertia of the velocity field. However, it cannot be due to meridional circulation−−the velocity of which was recently determined from SOHO data by Giles, et al. (1997) to be 10-20 m/s which is roughly three

Relative corrections to model S0 (JCD) from SOHO/MDI f-mode frequencies

SET	$\Delta R/R_\odot$
1	$(-4.48 \pm 0.01) \times 10^{-4}$
2	$(-4.51 \pm 0.01) \times 10^{-4}$
3	$(-4.53 \pm 0.01) \times 10^{-4}$
4	$(-4.49 \pm 0.01) \times 10^{-4}$
5	$(-4.46 \pm 0.01) \times 10^{-4}$

to five times too low to account for the effect. One could imagine a thermal shadowing of the turbulent velocities, however, which could be large enough. In this case, we might expect a cycle independent P_4-distortion. That possibility can be separately tested with forthcoming measurements of the flows from time-distance seismology analyses of MDI data.

5. Purging low ℓ-mode Data

A straightforward, but useful application of the γ's derived from the even a-coefficients is to purge the low-ℓ mode frequencies of the near surface perturbation due to activity (NSPA). The best information about these modes is from unresolved disk observations such GOLF on SOHO or the ground-based BiSON network. Dziembowski and Goode (1996) have shown that in the years of high solar activity, the NSPA effects both the centroid frequencies and fine structure, thereby impairing the extraction of information about core structure and rotation. In the same paper, the method of purging these effects was developed. We will apply this methodology to the forthcoming seismic data, like those from non-imaging instruments like SOHO/GOLF VIRGO and the ground-based BiSON network.

6. Variation of the solar radius from SOHO/MDI f-modes

Schou, et al. (1997) showed that the f-mode ridge in the SOHO/MDI data k-ω diagram is so precisely determined that a constant offset between the true frequencies and their model counterparts was apparent. They noted that since the asymptotic f-mode frequency is $\sqrt{g\mathrm{k}}$, the only source of the offset could be an incorrect model radius. They determined that the seismic radius is about 300 km small than the model radius. They also pointed out that the f-mode data open the possibility of determining the cycle dependence of the solar radius. We propose to track the Sun's seismic radius.

We have already seen small variations in the seismic radius with the five SOHO/MDI data sets we have. Each of the sets contains data for 33 f-modes. We only made use of their centroid frequencies. Separately, for each set we determined corrections to the standard solar model solar radius. The corrections were evaluated from

$$\frac{\Delta R}{R_\odot} = -1.5 < \frac{\Delta\nu_{\ell,0}}{\nu_{\ell,0}} >, \tag{6}$$

where $<>$ denotes the average weighted by the inverse square of the measurement errors. The results are given in the table. The differences among the sets are bigger than the formal errors (which are very small indeed), but there is no clear trend unless one imagines a peak in the difference at activity minimum.

C. Plan of Operation

The proposal is to support a half-time effort for Martin Woodard from Big Bear Solar Observatory for the three years of the proposal. In addition, there is a request of $6000 per year to partially support the work of Wojtek Dziembowski. NJIT will provide an annual match of $2000 for Dziembowski . Goode and Kosovichev will donate time to the project.

Woodard is based in Big Bear and Goode and Dziembowski will work with him there. Goode will spend a significant part of each year in residence in Big Bear. Dziembowski will do part of his in Big Bear and part of it in Warsaw. He will spend at least one month a year in Big Bear. There is also a small amount of money to support Woodard visiting Stanford to work with Kosovichev.

The remainder of the budget is for Woodard to travel to one meeting each year and for publication charges.

The SOHO/MDI team will provide the splitting data. Woodard will utilize the data analysis routines of Goode and Dziembowski. The interpretation of the results will be done by all four collaborators together.

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Summary of Personnel Commitments and Costs

The direct labor in the proposal is a half-time effort of Dr. Martin Woodard who is employed by the Big Bear Solar Observatory. Dr. Woodard's salary during the first year is $43,000. It is assumed to inflate at 3% per year. The fringe benefits on his salary are 24% and the overhead rate on the sum of the two is 45.5% during the first year and 46% during the second and third years. Goode and Kosovichev will be donating time to the project.

The travel budget is for Dr. Woodard to travel from Big Bear to Stanford to work with Dr. A.G. Kosovichev. He would take one trip per year and stay for two weeks ($1500). The remainder of the travel budget is for Dr. Woodard to attend one professional meeting per year ($1500).

The consultant is Prof. W.A. Dziembowski. He will spend five weeks in Big Bear each year working on this project with Woodard and Goode. His consulting fee, including travel and per diem is $6000 for the five weeks. In addition, NJIT will match with $2000 for other work he does on the project while he is in Poland.

There is also a $1000 request to cover page charges.

The resumes of all of the principles appear after the body of the scientific proposal.

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Ten Selected Publications

Determination of the Sun's Seismic Radius from the SOHO Michelson Imager, 1997, Schou, J., Kosovichev, A.G., Goode, P.R., and Dziembowski, W.A., ApJLett, 489, L197.

Helioseismic Measure of Solar Activity–Meaning and Applications, Dziembowski, W.A. and Goode, P.R., Schou, J. and Tomczyk, S., 1997, A&A, 323, 231.

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Determination of the Sun's Seismic Radius from the SOHO Michelson Imager, 1997, Schou, J., Kosovichev, A.G., Goode, P.R., and Dziembowski, W.A., ApJLett, 489, L197.

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List of Principal Collaborators in the Last Four Years W.A.

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L.H. Strous
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H. Wang My Ph.D. and postdoctoral expe-

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