THE HELIOSEISMIC BUTTERFLY DIAGRAM AND SOURCES OF SOLAR VARIABILITY FROM SOHO/MDI DATA

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PROPOSAL SUMMARY:

The simple, spherically-symmetric model of the sun has been strongly confirmed by helioseismic sounding. However, as small as it is, the departure from spherical symmetry is very significant and is helioseismically measurable. The departure is manifest in the centroid and multiplet structure of the oscillation spectrum that vary drastically through the eleven-year cycle. With this, solar physics obtained a new tool for studying solar activity. The tool has not been fully explored.

The oscillations provide, in fact, the most accurate measures of cycle dependent changes in the sun, and the Solar and Heliospheric Observatory/Michelson Interferometer (MDI) data are the most precise of all. Together with our formalism, the precision gives us the opportunity to address the real challenge – connecting the MDI seismic measures to observed characteristics of the dynamic sun.

We propose to (a) construct a helioseismic butterfly diagram from MDI data that utilizes the formulation of the seismic data for probing the sun's near surface as developed by Dziembowski and Goode (1991). The seismic butterfly diagram will give pole-to-equator information about the evolution of the cycle; (b) use the connection between the helioseismic near-surface perturbation and Big Bear Ca II K synoptic data to probe the solar cycle dependent variations in the solar luminosity and irradiance; (c) use the f-mode and p-mode MDI data to delineate among the magnetic field, turbulent pressure and changes in the sun's temperature structure as sources of the the evolution of the oscillation frequencies. In this, we will utilize the unique techniques we have developed over the years. Dziembowski, Goode and Schou (2001) have recently shown that the behavior of the sun's f-mode radius (near-surface) provides a new probe that makes the work we propose even more timely.

Contents

Summary of Personnel and Commitments

	1st Year		2nd Year		3rd Year	
	Time	**Cost**	**Time**	**Cost**	**Time**	**Cost**
PI: Philip Goode	2 Months	$27,000	2 Months	$27,945	2 Months	$28,923
Wojtek Dziembowski	1.25 Months	$8,000	1.25 Months	$8,000	1.25 Months	$8,000
Leonid Didkovsky:	3 Months	$10,000	3 Months	$10,350	3 Months	$10,712

A Background

The evolution of helioseismic frequencies provides the most accurate measures of cycle dependent changes in the sun. The real challenge is to connect these global, seismic measures to characteristics of the dynamic sun.

The sources of the evolution in p-mode and f-mode frequencies that reflect changes in the sun's structure, are generally considered to be some combination of changes in temperature, magnetic field and/or in the random velocity field (turbulent pressure or Reynold's stresses). Arguments can be made for each of the three – *we propose to determine the relative roles of each by interpreting MDI oscillation data to determine precisely what effect(s) of activity the evolving p-modes and f-modes are reflecting. To do this, we will exploit the unique formalism we have developed.* In the course of this investigation, we also propose to use our formalism to construct a "helioseismic" butterfly diagram and place limits on the variation of the solar radius through the cycle.

The direct source of the cycle dependent changes 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 oscillations strongly sample this region and, as detected by MDI, are ideal probes. We emphasize that MDI does *not* mask pixels covering the surface active regions (as was done in other devices in earlier years) so that MDI provides a clean probe of the field.

Dziembowski and Goode (1991) studied the asphericity in detail, and they were able to localize the site of the perturbation to be *very near the surface.* 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.

Goldreich, et al. (1991) specifically proposed that changes in the superficial, random magnetic field is 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, surface field which is significantly weaker ($< B^2 >\sim (70G)^2$). Instead, Kuhn sees a critical role for the variations of the Reynold's stresses or turbulent pressure through the solar cycle . He proposes that changes in the aspherical component of the stresses are responsible for the varying symmetric part of the spectrum of solar oscillations (the so-called even-a coefficients).

Clearly, we are lacking a basic understanding as to how the frequency changes arise. We need more observational information. The most crucial time period for which we need data is during the rise and through the maximum of the cycle. Fortunately, we have MDI data covering that period for the current cycle. Our efforts would be re-enforced by MDI data down the declining phase of the current activity cycle.

Covering the rising phase through the current activity maximum, we have MDI data sets containing centroid frequencies determined from measurements made between May 1, 1996 to date, with a break between June 16 and October 22, 1998, when there was no contact with SOHO. The sets are typically 72-days long, except those immediately before and after the break, which are shorter. The centroid frequencies, $\nu_{\ell,n}$, were determined by the method described by Schou (1999).

For each p-mode multiplet, the individual mode frequencies, $\nu_{\ell,n,m}$, are represented by

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

where $\mathcal{P}$ are orthogonal polynomials (see Ritzwoller & Lavely 1991 and Schou et al. 1994). This representation ensures that the $\bar{\nu}_{\ell,n}$ are a probe of the spherical structure while the a_{2k} – the even-a coefficients – are a probe of the symmetrical (about the equator) part of the asphericity described by the corresponding $P_{2k}(\cos\theta)$ Legendre polynomials. We have

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

where the geometrical coefficients, C, are

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

The even-order splitting coefficients in each of the datasets will be fit to the following formula (Dziembowski & Goode, 1991)

$$a_{2k(\ell n)} = a_{2k(\ell n)\mathrm{rot}} + C_{k\ell}\frac{\gamma_k}{I_{\ell n}}, \tag{4}$$

where $a_{2k(\ell n)\mathrm{rot}}$ represents the effect of centrifugal distortion, which we calculate from the SOHO/MDI data following the treatment of Dziembowski & Goode (1992); $I_{\ell n}$ is a measure of the modal inertia (also called the mode mass), and γ_k is the asphericity coefficient corresponding to a $P_{2k}(\cos\theta)$ shape distortion – *interpreting the γ's is key to understanding the near-surface perturbation. They are a primary quantity we propose to study to determine the source of the near-surface perturbation that causes the evolution of the p-mode frequencies. Additional help arises from the f-modes that present a powerful new probe of the near-surface (see §B.4).* Since our plan is to study the temporal variation of the γ's, we therefore eliminate the constant distortion of rotation from the γ coefficients in equation (4). The modal inertia is evaluated assuming that all modes have the same radial displacement at the base of solar photosphere. The inertia decreases with increasing ℓ or n. Equation (4) can also be used to represent changes in centroid frequencies. However, in that case we can determine only a relative γ_0. For this, we chose the first (earliest) of the MDI sets as the reference.

The $I_{\ell n}^{-1}$ factor accounts for most of the, fairly strong, ℓ and frequency dependence in the splitting coefficients. This result is due to Libbrecht & Woodard (1990). They used it as evidence that the asphericity responsible for the even-a coefficients is localized well above the lower turning point of modes in the sample – that is, close to the surface. Dziembowski & Goode (1991) were able to determine a slight, but significant ν-dependence of the γ_1 and γ_2 coefficients from the same data.

In Figure 1, we show the temporal evolution of the mean $\gamma' s$ over nearly fifteen years. The mean values of the γ coefficients are determined from equation (4) using data from

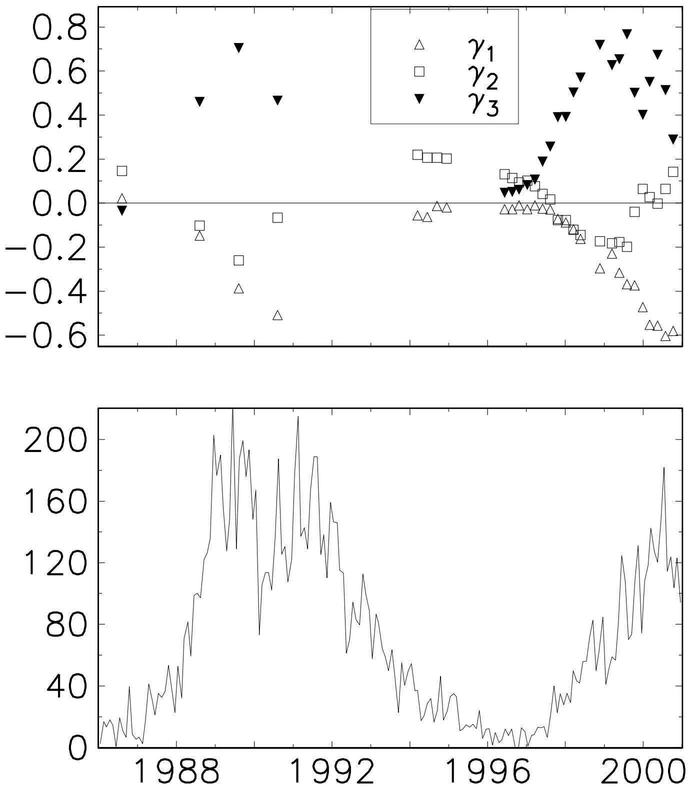

Figure 1: Lower panel shows the monthly averages of the sunspot number covering the period from 1986 through mid-2000. Upper panel shows the mean $\gamma's$ covering from 1986 through mid-2000. The first cluster of points is from BBSO data (1986-1990). The second is LOWL (1994) and the third is twenty-one MDI data sets. One aspect of the richness of the MDI spectrum is apparent in the impressive density of points.

various sources including BBSO, LOWL and SOHO/MDI. The BBSO data are from Woodard & Libbrecht (1991), and LOWL data are from Tomczyk (1996). We compare the $\gamma's$ with the monthly averages of smoothed sunspot numbers. Roughly, the BBSO data of the summer of 1989 give the largest magnitudes of the $\gamma's$, and this corresponds to the first half of the previous sunspot maximum. Unfortunately, we are missing splitting data from the rising phase (1987 or so), as well as from the declining phase of the solar cycle. Furthermore, the data are seasonal. The errors in the BBSO and LOWL $\gamma's$ are about twice as large as those in SOHO/MDI, but they are still relatively small and would not be visible in Figure 1. One interpretation of the declining P_6 asphericity beyond the middle of 1999 is that the cycle is peaking. The large P_2 distortion results from the dominance of activity at low latitudes. *For cycle 23, we have the MDI data, which are richer and more precise than earlier data. These MDI data underpin the work we propose here.*

From a brief inspection of Figure 1, it is clear that for solar cycle 23 the rapid rise through early 1999, especially of the P_6, coincides with the rise of the sunspot number. Based on a comparison with the previous maximum, it can be noted that the maximum

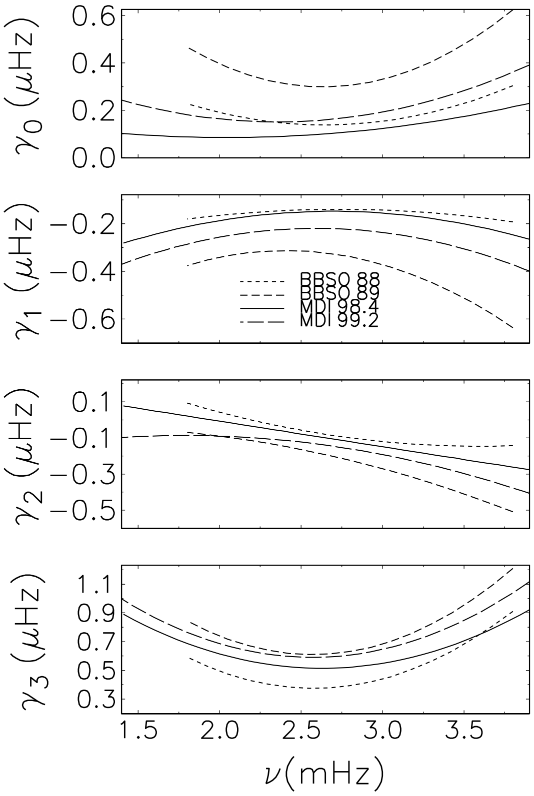

Figure 2: $\gamma(\nu)$ dependence of MDI data from 1998.4 and 1999.2 72-day sets, as determined by polynomial fits to the γ's. Also shown for comparison are the BBSO data from 1988 and 1989. Both are during the rising phase of activity, and the magnitude of each γ increases with activity. If the causal perturbation were much above or below the near-surface the γ would exhibit a much greater frequency dependence. This constraint plus the magnitude of γ's restricts choices for the cause of the aspericity.

value of γ_3 (at 1999.7) corresponds to a somewhat higher activity level than reflected in the sunspot number. The difference can only be partially explained by the difference in mode sets used to infer the γ in the BBSO and MDI sets. There is some sensitivity of the inferred γ's to the maximum ℓ in the set. The maximum ℓ in the MDI sets is between 197 and 200, while for the BBSO sets, it is 140. We find that by truncating the MDI data, we get absolute values that are a few percent lower (typically 1-3 %). Near the present time, the γ's are dominated by the negative P_2 asphericity that corresponds to activity in the equatorial region.

We propose to convert the uniquely rich p-mode spectrum of the MDI data into γ's covering the period from MDI's inception to the present. *The γ's, with their mild frequency dependence are an ideal representation from which to determine the physical origin of the near-surface solar asphericities (see Figure 2).* We further propose to use the γ's to construct a helioseismic butterfly diagram (see §B.1). This diagram will give insight to the cycle's behavior at all latitudes, not just the active latitudes of the standard butterfly diagram. Further, Dziembowski, Goode and Schou (2001) have shown the f-modes, which are near-surface waves, can provide additional constraints on the form of the near-surface perturbation. We propose to exploit that. In addition, the γ's from the p-modes are also valuable in determining how the radius of the sun varies through the solar cycle. Knowing this variation is central to understanding how the sun's luminosity varies through the solar cycle.

Over the last three years, our efforts in determining interior properties of the sun from MDI data have been financially supported, in part, by the MDI PI team. Under that support, several papers have been produced. The ones in ApJ are:

1) Schou, J.; Kosovichev, A. G.; Goode, P. R.; Dziembowski, W. A., 1997, "Determination of the Sun's Seismic Radius from the SOHO Michelson Doppler Imager", ApJ, 489L,197.
2) Dziembowski, W. A.; Goode, P. R.; di Mauro, M. P.; Kosovichev, A. G.; Schou, J., 1998, "Solar Cycle Onset Seen in SOHO Michelson Doppler Imager Seismic Data", ApJ 509, 456.
3) Dziembowski, W.A.; Goode, P.R.; Kosovichev, A.G.; Schou, J., 2000, "The Rise of Cycle 23", ApJ, 537, 1026.
4) Dziembowski, W.A.; Goode, P.R.; Schou, J., 2001, "Does the Sun Shrink with Increasing Magnetic Activity", 2001, ApJ, in press.

Also, eight conference papers were presented at SOHO, SPD and COSPAR Meetings. We now propose for GI funding for three years.

B Proposed Research

We propose to study the p-mode γ's and their evolution to determine the dynamical origin of the p-mode frequencies. The dynamics also cause changes in the f-mode frequencies, and the f-mode radius of the sun, so we will be able to use f-mode data as a probe, as well. The f-modes allow us to precisely determine an f-mode radius of the sun. The evolution of the f-mode frequencies places an additional constraint on the causal perturbation. The same dynamics are also reflected in the spectacular surface phenomena manifest through the solar cycle, the variation of solar irradiance and the source of cycle-dependent changes in the sun's radius (if any). It turns out that Ca II K data vary in lock-step with the p-mode γ's, and this gives insight to the nature of the causal perturbation. We propose to compare magnetic, temperature and turbulent pressure contributions to determine their relative roles in the variation and its evolution.

To illustrate that the p-mode γ's are a powerful probe of the near- surface dynamics, we assume that the γ's arise purely from an asphericity in the temperature (or "thermal") structure of the outermost layers. To do this, we assume a temperature perturbation of arbitrary Legendre rank, and we try three different depths (and spreads or radial widths) for the perturbed layer – 20 Mm (with a 10 Mm spread), 1.0 Mm (with a 2.0 Mm spread) and -0.25 Mm (with a 0.5 Mm spread). In Figure 3, we see a wide variation in the behavior of the calculated $\gamma(\nu)$'s. In particular, only the long dashed line – perturbation centered at a depth of 1 Mm – has the functional form one sees in Figure 2. If the assumed perturbation is too deep (solid line), one samples beneath the outer turning point of the modes and is sensitive to the detailed modal oscillatory behavior. If the perturbation is

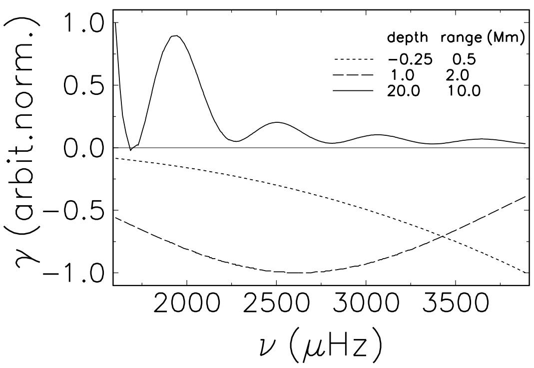

Figure 3: Polynomial fits to the shape of the $\gamma(\nu)$ function resulting from the three assumed shapes of the relative temperature (squared sound speed) perturbation. In each of the cases the functional form of the perturbation is given by cubic spline function centered at the indicated depth below the base of photosphere and 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 photosphere (long dash).

placed too high (dotted line), then the γ's show a strong frequency dependence, which results from the lower frequency modes having their outer turning points largely beneath the perturbing layer. 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.

The butterfly diagram for sunspots has long been used to compare one activity cycle to another. The diagram provides a powerful view of the cycle. However, such diagrams do not provide insight to the higher latitudes. We propose to use the MDI data to construct a *seismic butterfly diagram*. This diagram would contain information about all latitudes – even the polar latitudes, and will be a powerful, new diagnostic.

B.1 The Helioseismic Butterfly Diagram

We propose to construct a *helioseismic butterfly diagram* using the MDI p-mode data, after their conversion to the p-mode γ's. Since the γ's are a weak function of frequency, we plan to use a mean γ for each k (see Figure 4). The angular dependence of γ_k is given by $P_k(\cos\theta)$, where the argument of the Legendre polynomial is the co-latitude of the γ_k asphericity. Thus, the contribution of the k^{th} rank Legendre at angle $\theta_\circ$ arises from $\gamma_k P_{2k}(\cos\theta_\circ)$. It is easy to calculate the value at the poles – it is simply the sum of all the γ_k's. This sum is large and noisy, but statistically significant at activity minimum (1996), and goes to zero by mid-2000 (the most recent MDI data we have). Near the equator, it is also easy to determine the result, and we find essentially a null near activity minimum that rises to a large value by mid-2000. The latitudes in between require integration over bands of, say, $\sim 5°$ width. We will optimize between narrow (noisy) bands of high resolution and broad (much less noisy) bands of lower resolution. As initially envisioned, the seismic butterfly diagram would consist of a series of panels (one for each latitude band) with each

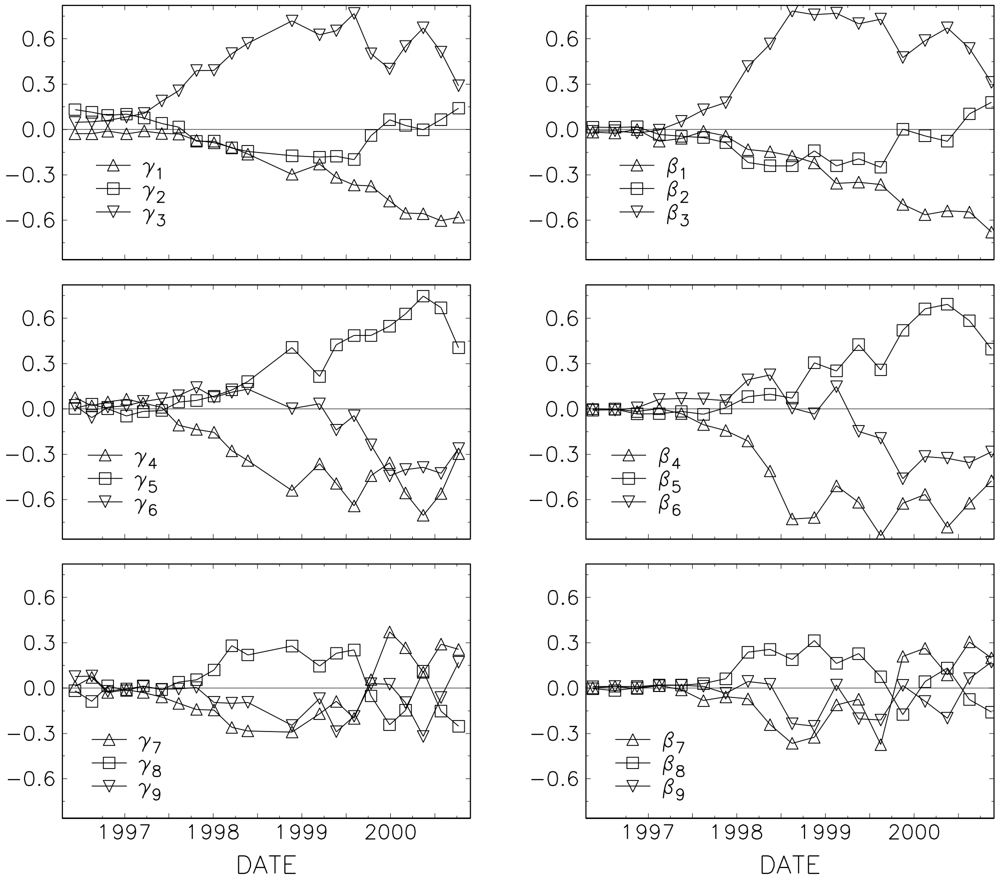

Figure 4: Left panels show the quarterly P_2, P_4, ... P_{18} distortions reflected in the γ_1, γ_2, ...γ_9 of the MDI p-mode data. Right panels show the corresponding β_1, β_2, ...β_9 coefficients from the the BBSO Ca II K data. The $\beta's$ are from a Legendre fit and the ordinate is in arbitrary units. The error bars are within the symbols.

panel illustrating the amplitude of the summed and integrated $\gamma_k P_{2k}(\cos\theta)$'s vs. time.

The helioseismic butterfly diagram will enable one to see the pole to equator evolution of the solar activity cycle from the MDI data. We can calibrate the seismic butterfly diagram with the standard butterfly diagram for latitudes below 35°. Also, the seismic diagram should make it easy to see the evolution of old cycle and extended cycle activity.

In part, we are confident that this diagram will be a useful representation of activity because of the close correlation between the γ's from the p-modes and synoptic measures, like Ca II K that tell us primarily about the active latitudes.

B.2 The γ's and the Ca II K Synoptic Data

Another clue to the origin comes from comparing the p-mode γ's to a decomposition of BBSO Ca II K data. In Figure 4, we show a series of Legendre decompositions of successive quarterly averages of daily BBSO Ca II K images using one image per day. This result is consistent with that of Howe et al. (1999). To compute the average, each day's data were projected on the image's N-S axis, and then the result was projected onto even-order Legendre polynomials. The coefficients of this expansion are called β's. The overall normalization of the β's is arbitrary, and the temporal evolution of each β_k is meant to be compared to the corresponding γ_k. In Figure 4, we also show the corresponding γ's from the MDI data for the P_2, P_4, P_6 P_8, P_{10}, P_{12}, P_{14},P_{16}, and P_{18}, coefficients of that decomposition. We do not show the k=0 term because of problems in absolute calibration of β_0. In Figure 4, there is a stunningly close correlation between the γ's and β's for all orders ($k > 1$). If we do a similar decomposition of the BBSO Solar Disk Photometer, we find "β"'s that are quite close to those from the Ca II K decomposition (see Goode, et al. 2001), and ever so slightly closer to the γ's This might seem to imply a magnetic origin for the γ's, however, the case is not closed until we account for the physical origin of the γ's. However, the close agreement certainly means that the source of the γ's must also account for the $\beta' s$.

We note that we have calculated β's through mid-April of 2001 and find that the trends already apparently continue, including the P_6 asphericity now crossing zero, while the P_4 is now distinctly positive and the P_2 grows more negative. There is no great signature of the large active region that produced many flares, including the X20 flare of April 2, 2001. Rather, the increasing relative importance of the negative P_2 distortion implies a movement of activity toward the equator.

We emphasize that neither the Ca II K synoptic data nor the Solar Disk Photometer data have any sensitivity to the $k = 0$ term. The $k = 0$ term is the one that is related to luminosity and is critical in determining the cycle dependence of the solar irradiance. However, the $\gamma_{k=0}$ term is well-defined with respect to solar activity minimum and is accurately determined from the MDI data.

B.3 Variations in the Solar Luminosity

It would be of great interest to know what are the solar luminosity variations over the eleven-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 from BBSO Ca II K data (and data from the BBSO Solar Disk Photometer), we have seen a close correspondence of the β's to the corresponding $\gamma_{k>0}$'s from the p-mode data. Further, it is well-known that the BBSO Ca II K Index (see Lean, et al. 1998) is well-correlated with the observed irradiance variations. We would like to use the γ's as proxys for intensity, and this is reasonable because of the correlation between β_k and γ_k for $k \geq 1$. We can write the intensity as

$$I(\cos\theta) = I_0 + \Delta I_0 + \sum_{k=1} I_{2k} P_{2k}(\cos\theta) \tag{5}$$

where I_0 is the intensity at some chosen epoch (e.g. a 72-day average around activity minimum) and ΔI_0 is the "present" monopolar intensity with respect to the chosen epoch, and the I_{2k} are the various higher multipolarities of the intensity. One of the aims in

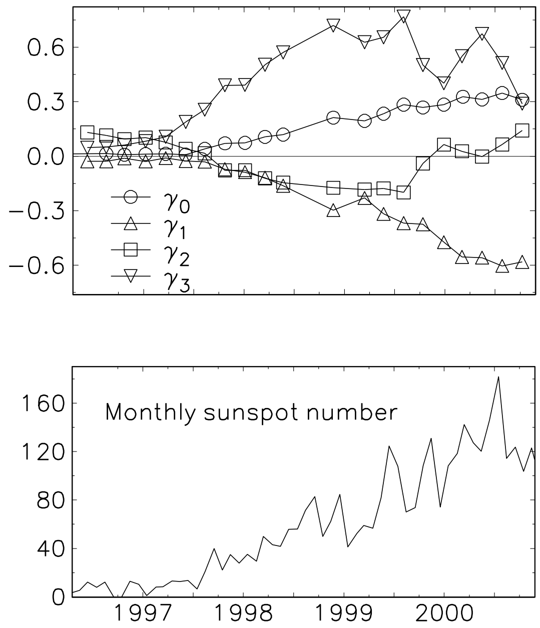

Figure 5: In the top panel, the behavior of γ_0 is shown as a function of time from the MDI data, and γ_0 is defined with respect to the 1996 activity minimum. The lower panel shows the corresponding sunspot number that γ_0 tracks closely, Dziembowski and Goode (2001). Also shown in the top panel are the evolution of γ_1 through γ_3.

comparing the γ's with the synoptic data is to determine to what extent

$$I_{2k} = \text{constant} \times \gamma_k. \tag{6}$$

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

$$\Delta I_0 = \text{constant} \times \Delta\gamma_0. \tag{7}$$

The relations between the γ's and the I's are 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. In Figure 5, we show a plot of $\Delta\gamma_0$ vs. time from the 1996 activity minimum using the MDI data. It is clear that $\Delta\gamma_0$ increases with sunspot number through the rising phase of the cycle and is consistent with an increasing irradiance with increasing activity. Since the β's and γ's agree in such detail for $k > 1$, we assume this would be true for $k = 0$. We emphasize the critical nature of $\Delta\gamma_0$, as it is the term that we anticipate being proportional to the relative luminosity (relative to the 1996 activity minimum here). Again, we can't determine the critical quantity, β_0, from the Ca II K data or the Solar Disk Photometer data. We plan to track the γ's down the declining phase of the cycle, and that should strengthen the phenomenological approach to determining the irradiance.

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

Of course, such results would be interesting, but phenomenological information, and what one really needs to believe this approach, is to know the physical origin of the near-surface asphericity. Recently, Dziembowski, Goode and Schou (2001) have found new and significant constraints on the nature of the forcing by using MDI f-mode data.

B.4 The Seismic Radius of the Sun

A seismic radius of the sun has been determined by Schou, et al. (1997) using MDI f-mode data. The f-modes are confined to the sun's near surface region, and as such they provide a new, and powerful probe of the sun's near-surface. All helioseismic determinations of the solar radius, until recently, have relied on the following asymptotic relation for f-modes frequencies,

$$\frac{\Delta\nu_\ell}{\nu_\ell} = -\frac{3}{2}\frac{\Delta R}{R}. \tag{8}$$

Antia et al. (2000) pointed out that using this relation for modes with ℓ extending up to 300, as Dziembowski et al. (1998) did, is not justified because significant departures from $\nu \propto R^{-1.5}$ are present in higher ℓ's. The departure increases with ℓ, which as Brown (1984) first suggested could be accounted for as an effect of turbulence in the upper convective zone. Detailed models of this effect have been developed by Murawski & Roberts (1993a, 1993b). (For the most recent work on the subject see Mędrek & Murawski 2000). However, surface magnetic fields may also have significant effects on f-mode frequencies (Evans & Roberts, 1990; Jain & Roberts). With these two sources of perturbation to f-mode frequencies, we must contemplate solar cycle changes, in f-mode frequencies, beyond that of a simple radius change.

There is another problem if one attempts to apply Eq.(8) in a search for the radius variations correlated with activity. This problem follows from the fact that the induced modifications are quite non-uniform, and each f-mode has its own radius, R_ℓ, which is given by

$$R_\ell = \left(\frac{1}{I_\ell}\int r^{-3} dI_\ell\right)^{-1/3}. \tag{9}$$

For high degree modes, the f-mode radii are close to the solar radius. The values of R_ℓ/R range from 0.9883 at $\ell = 100$ to 0.9946 at $\ell = 300$. While we have $R_\ell \approx R$, a corresponding approximation for ΔR_ℓ is quite problematic. When the f-mode frequencies were used to refine the value of the radius for modeling the sun, we could expect an approximate, homologous relation, $R_\ell \propto R$. But such a relation cannot be expected in the case of the activity induced changes, which we believe to be confined to the outermost part of the sun. The truth is, with the f-mode data, we cannot say anything about what happened in the layers above. Thus, we have no information about the evolution of the photospheric radius of the sun. However, there is a silver lining to this cloud.

We can determine the radius variation using a modified version of Eq. (4) in which we account for the effect of the near-surface changes on f-mode frequencies and possible differential changes,

$$\Delta\nu_\ell = -\frac{3}{2}\frac{\Delta R_f}{R}\nu_\ell + \frac{\Delta\gamma_f}{I_\ell}, \tag{10}$$

where ΔR_f denotes the radius change inferred from a particular set of f-modes, and $\Delta\gamma_f$ is the near-surface perturbation defined with respect to activity minimum (hence the Δ).

Applying this equation to MDI f-mode data, Dziembowski, Goode and Schou (2001) found that a depth of from 6 to 10 Mm the sun shrank by some 4 to 6 km during the rising phase of this activity cycle. More precisely, we found

$$\frac{dR}{dt} = (-1.51 \pm 0.31) \text{ km/year} \tag{11}$$

The depth of 6 to 10 Mm is the range of depths of the f-modes. This result for the f-mode radius may come as a surprise, since they are often regarded as surface waves. However, it is only asymptotically that the dispersion relation for high-degree f-modes approaches that for surface gravity waves. The two types of modes are essentially different. While the latter are discontinuity modes that see the same gravity for each horizontal wave number, the f-modes see different effective gravities depending on ℓ.

What is important for the problems at hand is that the rate of shrinking provides a strong constraint on the origin of the sub-surface asphericities. In particular, as small as it seems, a shrinking of the sun's radius during the rising phase of activity is not easy to explain. To investigate, one may write the Lagrangian change of the local radius in the form

$$\Delta r(r_0) = r - r_0 = -\int_{r_b}^{r_0} \frac{\Delta\rho}{\rho} \left(\frac{x}{r_0}\right)^2 dx, \tag{12}$$

where r_b is the radius at the bottom of the layer perturbed by activity, and r_0 is the radius at a specified fractional mass, M_r/M, at activity minimum and $\Delta\rho$ denotes the horizontally averaged change of density. One obtains a more revealing form of Eq.(12) by expressing $\Delta\rho$ in terms of the averaged entropy and magnetic field changes.

For the horizontally averaged gas pressure in the presence of a random magnetic field one has, after Goldreich et al. (1991),

$$\Delta P_g = -\Delta(\beta P_m), \tag{13}$$

where

$$P_m = \frac{\overline{B_h^2} + \overline{B_r^2}}{8\pi}$$

is magnetic pressure and

$$\beta = \frac{\overline{B_h^2} - \overline{B_r^2}}{8\pi P_m}$$

is a measure of the statistical anisotropy of the field.

With the use of thermodynamic relations, one determines

$$\Delta r = \int_{r_b}^{r_0} \left[\frac{1}{\Gamma_1}\frac{\Delta(\beta P_m)}{P_g} + (-\rho_T)\frac{\Delta S}{c_p}\right] \left(\frac{x}{r_0}\right)^2 dx, \tag{14}$$

where ρ_T denotes the logarithmic derivative of density at constant pressure. The remaining thermodynamic quantities have their standard meanings. At the relevant depths, the gas is nearly ideal. Thus, one may use $\rho_T = -1$, $1/\Gamma_1 = 0.6$, and find

$$\frac{\Delta S}{c_p} = \frac{\Delta T}{T} - 0.4\frac{\Delta P_g}{P_g}. \tag{15}$$

The irradiance from an active sun is higher than average. If the same is true about luminosity then we should have $\Delta S < 0$. Hence, there is a negative contribution to Δr. However, this must be very small. If ΔS refers to the whole convective zone then a 10^{-3} luminosity increase translates to an annual decrease in $\Delta S/c_P$ of 10^{-7}. Another possibility is an increase in the superadiabatic gradient, $\nabla_{\rm con} - \nabla_{\rm ad}$, but this seems unlikely too. The annual decrease of $\Delta R_f = 1.5$ km refers to the layer of $r/R = 0.988 - 0.995$. Thus, ΔR_f must arise mostly beneath $r = R_{137} = 0.988R$. At this depth, according to a mixing-length model, $\nabla_{\rm con} - \nabla_{\rm ad} \approx 2 \times 10^{-4}$, which rapidly decreases going inward. We would need an order of magnitude increase in the superadiabatic gradient to account for our rate of shrinking.

A more acceptable explanation might be a variation in the magnetic field. The consequences of a magnetic field increase depend on β. For a purely radial field ($\beta = -1$), the increase implies contraction. For an isotropic field ($\beta = 1/3$), the increase implies expansion. The field geometry implying the minimum increase to account for the rate of the shrinking corresponds to $\beta = -1$. Then, we have $\Delta < B >_{\rm rms} = \sqrt{\Delta \overline{(B_r^2)}}$, and assuming a constant rate across the lower convective zone, we infer

$$\frac{d < B >_{\rm rms}}{dt} \approx 7.2 {\rm kG/y}.$$

The value at R_{137} may be reduced, for instance, to 1 kG/y if one allows an exponential increase of the rate to about 43 kG/y at the base of the convection zone.

Thus, what we have inferred from the f-mode frequency change is a non-trivial constraint on the internal magnetic field change. Let us note, again, that if the field increase were predominantly isotropic, we would see an expansion rather than a contraction.

So far, we have solved a forward problem in which we guessed limiting forms of the perturbation, including the field. We propose to first focus on the selected forms of the radial field, since this perturbation implies shrinking in the f-mode region and it also has the smallest mean. We have considered various forms of an inward growing field beneath the f-mode region, but we need to consider the behavior in the region above and match that to the region below, as inferred from the f-mode integral constraint. This we propose to do. If this works, we will also try to solve for the field by using regularized least-squares techniques, Dziembowski et al. (1994). But this approach may be too sophisicated for the present time.

The inference of Dziembowski, Goode and Schou (2001) regarding the solar radius change is limited by the lack of accurate information about what happened in the outer 4 Mm of the solar interior. This is the region where we may expect the largest activity induced variations for two reasons. First, the rapid decline of gas pressure and second, the thermal structure of this layer is more susceptible to changes in the efficiency of the convective energy transport induced by the field changes. The f-mode data we have at hand provide some information about changes in this layer through the $\Delta\gamma_f$. Similar, but much more accurate information is available in the γ_0's of the MDI p-mode data.

B.5 Using the γ's from the MDI p-modes

The γ_k's contain the p-mode information on the near-surface perturbation. To begin this section, we focus on the $\gamma_{k=0}$ because they contain information about the perturbation that is directly comparable to that from $\Delta\gamma_f$. That is, both are spherically symmetrical, and therefore equivalently sample the near-surface. Since $\gamma_{k=0}$ must be defined with respect to some epoch, we call them $\Delta\gamma_{p,0}$ and define them with respect to the 1996 activity minimum for the MDI data. The reason we focus on $\gamma_{k=0}$ is that the p-mode spectrum of MDI frequency data is about 13 times richer than that for f-modes. Unfortunately, p-modes are not directly useful for determining changes in the solar radius. The simple relation, $\nu \propto R^{-1.5}$ would be valid for p-modes only if the changes were homologous throughout the whole sun. This is far from the truth for the changes we have considered here. However, from p-modes one may make a much more precise determination, than from f-modes, of the near-surface perturbation. The dependence of $\gamma(\nu)$ yields an important constraint on the localization of the source of solar cycle variations in p-mode frequencies.

As a motivating attempt, we follow Goldreich et al. (1991), and we attempt to link the frequency change to the change of the mean squared magnetic field and a Lagrangian change of a single thermodynamic parameter. For the latter, we prefer to use temperature rather than entropy, which was used by Goldreich et al. From Eqs. (14) and (15) of Goldreich et al., we get the following expression for $\Delta\gamma_{p,0}$,

$$\begin{aligned}\Delta\gamma_{p,0} \;&=\; \frac{1}{8\pi^2\nu}\int d^3\vec{x}|\mathrm{div}\vec{\xi}|^2\{P\Gamma_1(1+\Gamma_\rho)\rho_T\frac{\Delta T}{T}\\&+[1+\Gamma_1(\Gamma_P+\Gamma_\rho\rho_P)\\&-\beta(\Gamma_1-1+\Gamma_1\rho_P)]\Delta P_m\}.\end{aligned} \tag{16}$$

Here, we denote by Γ_P and Γ_ρ, the logarithmic derivatives of Γ_1. The ideal gas equation cannot be used in the layers where most of the contribution to $\Delta\gamma_{p,0}$ arises.

Goldreich et al. (1991) explained the p-mode frequency changes during the rising phase of cycle 22 in terms of magnetic field and temperature changes, with the former being dominant and causing the frequency increase. They invoked a chromospheric temperature increase to explain the reversal in the increasing trend in $\Delta(\nu)$. We do not see such a trend in the MDI data. Thus, as a first guess we interpret $\Delta\gamma_{p,0}$ in terms of magnetic field changes. Later, we will discuss the other candidates for the source of the p-mode frequency changes.

As a forward problem, we consider two values of β, -1 and 1/3, and the following form for the depth, D, dependence of magnetic field increase

$$\Delta <B>_{\mathrm{rms}}=\begin{cases} B_b & \text{if } D \geq D_b \\ B_b+\lambda\left(\frac{D-D_b}{D_b-D_m}\right) & \text{if } D_t < D < D_b \\ \Delta <B>_{\mathrm{rms}}(D_t) & \text{if } D \leq D_t \end{cases}, \tag{17}$$

where $D_m = -0.485$Mm denotes D at the temperature minimum, and B_b, D_b, and λ were determined by fits to $\Delta\nu$. For D_t we adopted either D_m or 0.

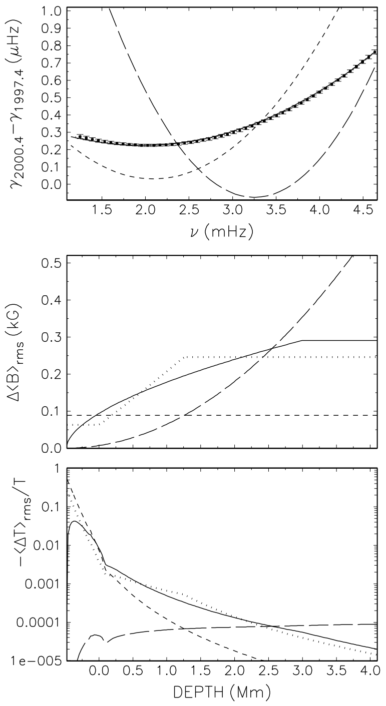

Figure 6: In the top panel, points with the error bars represent $\Delta\gamma_0(\nu)$ inferred from p-mode frequency difference between 2000.4 and 1997.4. The lines correspond to various distributions of the averaged magnetic field, shown in the middle panel. The solid and dotted lines are within the error bars in the top panel. The bottom panel shows the relative temperature decreases required to cause similar frequency shifts as the corresponding magnetic field increases

In Fig. 6, we show two examples of the field's changing behavior that would be consistent with the observed γ's, and compare them with two cases that are clearly inconsistent. One of the two inconsistent cases is a depth independent increase, and the other is an example of the field gradually increasing to about 3 kG at 8Mm. In all four examples, we used $\beta = -1$. We see that indeed the $\gamma_{p,0}(\nu)$ provides a strong constraint on the localization of the source of frequency changes, but clearly not a unique answer. For the two fitted cases, the inferred values of B_b are 290 and 250 G. Corresponding values of $B_{\rm ph} \equiv \Delta < B >_{\rm rms}$ (0) are 62 and 94 G. An equally good fit was obtained with the choice $\beta = 1/3$. The result for $\beta = 1/3$ is not significantly different from that found by Goldreich et al. (1991). To explain the p-mode frequency increase between minimum and maximum, we require an increase of the rms magnetic field growing from 0.2 kG in the photosphere to 0.84 kG at 4.25 Mm. The corresponding numbers of Goldreich et al. are 0.25 and 1 kG.

In the bottom panel of Fig. 6, we plot the relative temperature changes, which give the same local contributions to $\Delta\gamma_{p,0}$ as the corresponding changes in the magnetic field. We see that the required change of temperature is unacceptably large in the atmospheric layers. However, in sub-photospheric layers we cannot exclude the rms $\Delta T/T$ at the 10^{-3}

level. Such a temperature decrease would be a significant contributor to the observed frequency increase. Brüggen and Spruit (2000) argue that one expects a lower subsurface temperature from an increasing magnetic field, and that the effect should be searched for by means of helioseismology. A contribution from temperature decrease would lower the requirement for the magnetic field increase in the sub-photospheric layers.

Yet another potential contributor to the frequency increase is a decrease in the turbulent velocity. Roughly, the relative change in the turbulent velocity, $\Delta v_t/v_t = q$, has the same effect as a relative temperature change $\Delta T/T = 0.5q\mathcal{M}^2$, where $\mathcal{M}$ is the turbulent Mach number. In the sub-photospheric layers, $\mathcal{M}$ is in the 0.1–1 range. Thus, the effect may be significant, and we may expect a decrease in v_t, with increasing activity, because the magnetic field should inhibit convection.

To explain the p-mode frequency increase between minimum and maximum, we require an increase of the rms magnetic field growing from 0.2 kG in the photosphere to 0.84 kG at 4.25 Mm. The corresponding numbers of Goldreich et al. are 0.25 and 1 kG.

We have developed similar formulae for the $\gamma_{k>0}$ and we proposed to first test them using the same form of the field introduced in this section, but matching it with the field below as inferred from the seismic radius shrinking. They will provide different, and perhaps stronger constraints. If this works then we propose to fit the field using regularized least-squares solutions, as we have done to determine the sun's internal structure, Dziembowski et al. (1994). Using the equations for $\gamma_{k>0}$, to illustrate their power we have performed one simple, forward test by alternatively assuming mean magnetic field and mean radial velocity changes, assuming they are depth independent mean values down to a depth of 1 Mm, and vanish beneath. For, γ=1 μHz at ν = 3 mHz, we find for β=-1 either one requires an r.m.s. radial component of the magnetic field of +190 G or an r.m.s. velocity of -360 m/s. The minus sign indicates that γ and the velocity behave in different senses. For an isotropic field (β=1/3), we find 450 G or -340 m/s. The velocities seem too large, as does the isotropic field. According to simulations, the r.m.s. velocity of convection at 0.5Mm is 2 km/s (vertical) 1 km/s (horizntal). At 0 Mm the numbers are higher by some 30 percent and at 1Mm lower by the same amount. The required fractional decrease is thus 0.15 - 0.30. The efficiency of the convective transport would be reduced, hence the irradiance by unacceptably large amount. If the number were an order of magnitude less, random velocities would seem to be a strong candidate to be the source of the γ's. Nonetheless, our choice is an overly simplified velocity field, and we will fit more complicated ones – basically ones either that grow or decrease with depth, as we did for the field in Eq(17), and will do for the temperature. In the simple example, however, the radial field seems not unreasonable. Now many of the pieces in this proposal would seem to point one toward the magnetic field and away from either the turbulent velocity or the temperature as being causal in the dynamical changes manifest in the f-modes and p-modes through the solar cycle. However, we need to do a thorough and self-consistent evaluation of the perturbations to determine the truth – including connecting the near-surface perturbation from the p-mode γ's to the f-mode layer and below. This we propose to do because we can, now that we have sufficient MDI f-mode and p-mode data in hand, along with the requisite formalism. Our efforts will be further strengthened by MDI data taken down the declining phase of this activity cycle.

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D Curricula Vitae

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Positions Held:

1997-present: Director, Big Bear Solar Observatory

1996-present Visiting Associate, Physics, Math and Astronomy, Caltech

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

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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

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Ten Selected Publications

Does the Sun Shrink with Increasing Magnetic Activity?, Dziembowski, W.A., Goode, P.R., and Schou, J., 2001, ApJ, in press.

Signatures of the Rise of Cycle 23, 2000, Dziembowski, W.A., Goode, P.R., Kosovichev, A.G., and Schou, J., 2000, ApJ, 537, 1026.

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D.2 Wojciech A. Dziembowski

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Married 1967 to Anna Dziembowska (present name)
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Education:

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Employment and Positions:

1997-present: Professor, Warsaw University
1983-1997: Professor, Copernicus Astronomical Center(CAC)

1987-1992: Director, CAC

1981-1984: Deputy Director, CAC

1977-1983: Senior Scientist (Dotzent), CAC

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1963-1967: Graduate Student, CAC

1962-1963: Research Assistant, Department of Astronomy, Jagiellonian University

Ten Selected Publications

Does the Sun Shrink with Increasing Magnetic Activity?, Dziembowski, W.A., Goode, P.R., and Schou, J., 2001, ApJ, in press.

Signatures of the Rise of Cycle 23, 2000, Dziembowski, W.A., Goode, P.R., Kosovichev, A.G., and Schou, J., 2000, ApJ, 537, 1026.

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D.3 Leonid V. Didkovsky

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1975-1987: Leading Engineer, Laboratory of Physics of the Sun, Crimean Astrophysical Observatory Academy of Sciences of the USSR.
1987-1990: Research Scientist, Laboratory of Experimental Astrophysics, Crimean Astrophysical Observatory Academy of Sciences of the USSR.
1990-1996: Senior Scientist, Laboratory of Experimental Astrophysics, Crimean Astrophysical Observatory.
1996-Current time: Science Deputy Director of the Crimean Astrophysical Observatory
2000-Current time: Research Professor at the Big Bear Solar Observatory

Ten Selected Publications

1. Didkovsky, L.V. "Proper Motion of Sunspots Observed with the Michelson Doppler Imager", 2000, Solar Physics, submitted.

2. Didkovsky, L.V. " Short-Period Variations in Proper Motion of Sunspots Observed with SOHO (MDI)", 2000, Astronomical Journal (Russia), in press.

3. Haneychuk, V.I., and Didkovsky, L.V. "Torsional Oscillations in Sunspots Derived from MDI data", 2000, Submitted to the SOHO-10 Workshop.

4. Didkovskii, L.V. et al. "The first results of solar observations made in the Crimean Astrophysical Observatory using a magneto-optical filter", 1996, Izv. Vyssh. Uchebn. Zaved. Radiofiz. (Russia), vol.39, no.11-12 p. 1374.

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10. Didkovskii, L.V. "The internal differential rotation of the Sun: the p-modes frequency splitting in the measurements of brightness oscillations", 1989, PIS'MA V ASTRONOMICHESKIE ZHURNAL Translated in: SOVIET ASTRONOMY LETTERS, vol.15, no.12, p. 1115.

E Current and Pending Support

Phil Goode is PI on three active grants. The three constitute the backbone grants to operate Big Bear Solar Observatory. The first is from NASA-SR&T and covers from May 1, 2000 through April 30, 2003. This grant is entitled "Studies of Solar Magnetic Fields" and is for $1,190K. The second is from NSF-ATM and covers from March 15, 2001 through March 14, 2004. The latter grant is entitled "Solar Activity and Atmosphere from BBSO" and is for $778K. The third is from NASA to support the earthshine project, and is for $325K covering September 1, 1998 to August 31, 2001. He has one pending proposal for $464 K with NASA to renew the earthshine project.

F Statements of Commitment from Collaborators

F.1 Wojtek Dziembowski

Date: Tue, 17 Apr 2001 08:25:02 +0200 (CEST)
From: Wojciech Dziembowski <wd@astrouw.edu.pl>
To: Phil Goode <pgoode@bbso.njit.edu>
Subject: Proposal

Dear Phil,

I acknowledge that I am identified by name as a collaborator in the investigation entitled 'The Helioseismic Butterfly Diagram and Sources of Solar Variability from SOHO/MDI Data' that is submitted by Philip Goode to the NASA solicitation NRA-01-SEC-01, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extend and justification of my participation as stated in this proposal will be evaluated during peer review in determining the merits of this proposal.

Wojtek Dziembowski

F.2 Leonid Didkovsky

I acknowledge that I am identified by name as a collaborator in the investigation entitled 'The Helioseismic Butterfly Diagram and Sources of Solar Variability from SOHO/MDI Data' that is submitted by Philip Goode to the NASA solicitation NRA-01-SEC-01, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extend and justification of my participation as stated in this proposal will be evaluated during peer review in determining the merits of this proposal.

Leonid Didkovsky

G Budget Summary and Details

	1st Year	2nd Year	3rd Year
PI: Philip Goode	$27,000	$27,945	$28,923
Consultant: W. Dziembowski	$8,000	$8,000	$8,000
Collaborator: L. Didkovsky	$10,000	$10,350	$10,712
Fringe Benefits	$3,750	$3,881	$4,017
Supplies	$1,000	$1,000	$1,000
Domestic Travel	$2,000	$2,000	$2,000
Publications	$2,000	$2,000	$2,000
Subtotal	$52,750	$54,176	$55,652
Total (incl. Overhead)	**$77,279**	**$79,639**	**$81,809**
			$238,727

The fringe benefits are 5% for summer and 24% for staff. The overhead rate is 46.5% in the first year, 47% in the second year, and 47% in the third year.

H Summary of Personnel Commitments and Costs

For each year, the direct labor in the proposal is two months of summer salary for Philip Goode to perform his part of the work, and three months each year to support NJIT Research Professor Leonid Didkovsky who is employed by the Big Bear Solar Observatory. Dr. Didkovsky will reduce the Ca II K synoptic data and the Solar Disk Photometer Data. There is an annual $8000 consulting fee for Dziembowski's five weeks of work.

The travel budget covers travel to one professional meeting per year ($2000) for Dr. Didkovsky.

The consultant is Prof. W.A. Dziembowski. He will spend five weeks in Big Bear each year working on this project with Didkovsky and Goode. His consulting fee, including travel and per diem is $8000 for the five weeks.

There is also a $2000 annual budget to cover page charges.