SOHO/MDI DATA: IS THE SUN HOTTER AT ACTIVITY MAXIMUM?

Principal Investigator: Philip Goode
Big Bear Solar Observatory, New Jersey Institute of Technology

PROPOSAL SUMMARY:

The physics of solar irradiance change over the activity cycle is not well understood, and is the subject of controversy. The competing models are ones in which the sun is hotter at higher activity (e.g., Kuhn 2000), and ones in which the sun is cooler at higher activity (e.g., Spruit 2000). In the latter picture, higher irradiance is explained by a corrugated surface rendering the sun a more effective radiator. So, is the active sun hotter or cooler than the inactive sun?

Closely related to the issue of irradiance variations are global asymmetries in the brightness distribution near the limb, which were discovered by Kuhn, Libbrecht and Dicke (1988), and their picture is that the more active layers are hotter. Kuhn(1988) pioneered connecting solar luminosity variations to the variations in solar oscillation frequencies.

The heart of our proposal is to use seismic data from MDI, and ground-based data, to constrain the characteristics of the changes in the surface, as well as in the invisible layers beneath, to determine the physical origin of the variation of the solar irradiance. Further, we propose to probe and interpret the cause of the variation of the solar radius through the cycle. These efforts would be directly consistent with NASA's SoHO/MDI GI program.

Contents

A Background

The sun's irradiance has been carefully measured from space for more than twenty years, and it is about 0.1% greater at activity maximum than at minimum. Could the irradiance at the minimum of the next cycle be considerably less than either of the last two that were observed from space? Further, could the next maximum be much more irradiant? Of course, these are practical questions concerning our climate that strike to heart of the fundamental nature of the present sun. If we understood the physics of varying solar irradiance, we would be able to address both questions. In that context, we propose here to address the question, 'Is the sun hotter at activity maximum?'

The physics of solar irradiance change over the activity cycle is the subject of controversy. The competing models are ones in which the sun is *hotter* at higher activity (e.g., Kuhn 2000), and ones in which the sun is *cooler* at higher activity (e.g., Spruit 2000). In the latter picture, higher irradiance is explained by a corrugated surface rendering the sun a more effective radiator.

Closely related to the issue of irradiance variations are global asymmetries in the brightness distribution near the limb, which were discovered by Kuhn, Libbrecht & Dicke (1988), and their picture is that the more active layers are hotter. Kuhn(1988) pioneered connecting solar luminosity variations to the variations in solar oscillation frequencies.

To determine whether the sun is hotter at activity maximum, we propose to use global oscillation data exploiting a new formalism we developed, Dziembowski & Goode (2002). We are interested in slow and large-scale variations of the sun, which are reflected in the global modes that fairly sample large-scale changes in the sun.

Spherically symmetric changes in the sun are manifest in the shifts of centroid frequencies in the spectrum of solar oscillations through the solar cycle. Such shifts were first reported by Woodard & Noyes (1985) during the declining phase of cycle 21. This result has been confirmed and refined by many subsequent investigators – broadly, oscillation frequencies increase with increasing activity. One very recent inference from the frequency changes of the MDI solar f- (and p-)modes was that the sun actually shrinks with increasing activity, Dziembowski, Goode & Schou (2001). The determined rate of shrinkage, however, is too small to play a role in the variation of the irradiance.

The evolution of oscillation frequencies provides the most accurate measures of cycle dependent changes in the sun. The real challenge that remains is determining a precise connection between these global, seismic measures and characteristics of the dynamic sun. There are discrepant views as to the connection.

Naively, the issue would seem to be clear. That is, considering the sun to be a blackbody, we have

$$\frac{\Delta_{\min} L}{L} = \frac{4\Delta_{\min} T}{T} + \frac{2\Delta_{\min} R}{R}, \tag{1}$$

where the change, $\Delta_{\min}$, is with respect to activity minimum. Further, assuming that the irradiance varies like the luminosity and that $\frac{\Delta_{\min} R}{R}$ is negligible, one would conclude that the sun is hotter at activity maximum since the irradiance is greater there – by 0.1%. However, the truth is more subtle, and the $\frac{\Delta_{\min} T}{T}$ of our naive assumption is actually a proxy for some combination of the evolving magnetic field and turbulent pressure, as well as the evolving thermal structure. Thus, we have naively cast these three candidates as a temperature increase in the simple blackbody equation, while it could well be that the sun is actually cooler at activity maximum. As for neglecting the radius change, several efforts using different approaches have determined that the cycle dependent radius changes (Brown & Christensen-Dalsgaard 1998, Emilio et al. 2000, and Dziembowski, Goode & Schou 2001) are too small to matter for irradiance changes.

Thus, Eq. (1) simplifies to

$$\frac{\Delta_{\min} L}{L} = \frac{4\Delta_{\min} T}{T}. \tag{2}$$

A naive consideration of the candidates leads to difficulties with each. If we were to directly attribute the irradiance increase to a temperature increase, we have an immediate conflict with the seismic data. Namely, the hotter outermost layers expand, which implies a larger cavity and, thus, a lowering of mode frequencies – opposite to the observed frequency increase. If instead, the "temperature" increase were a proxy for a growing, near-surface magnetic field, the problems are more subtle. A growing near-surface field implies a higher speed of sound and, thus, higher mode frequencies. However, the r.m.s. field required to explain the frequency changes, as calculated by Goldreich et al. (1991), has long been regarded as being too large (see Kuhn 1998). Attributing the irradiance increase to changes in the turbulent pressure also has its appeal. The growing magnetic field suppresses convective flows and this lowering of the near-surface turbulent pressure implies a shrinking cavity (and increasing mode frequencies). However, the radius changes with growing activity are so small that changes in the turbulent velocity seem to be too small to account for the frequency increases (see Dziembowski & Goode 2002 and near the end of §B.1). A less naive approach to describing the irradiance changes yields clarifying arguments supporting each of the candidates.

One way or another this thorny issue rests on an understanding of the response of the solar structure to an increasing magnetic field with increasing activity, but this is complicated. 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 an r.m.s., quadratic, near-surface magnetic perturbation, $< B^2 >$ of around $(250G)^2$, while the observations of Lin (1995) and Lin & Rimmele (1999) show an increase of the mean surface field, which is significantly weaker ($< B^2 > \sim (70G)^2$). Dziembowsi, Goode and Schou (2001) find a comparable $(200G)^2$ when describing the change in MDI mode frequencies from activity minimum to times of high activity. Like Goldreich et al. (1991), we assumed a growing, *isotropic*, random field. However, when Dziembowski, Goode and Schou assumed a growing, *radial*, random field, we found that the MDI frequency changes could be described as arising from a field that is consistent with the observed field changes. In addition, Brüggen and Spruit (2000) argue that one expects a lower subsurface temperature from an increasing magnetic field. So, a change in the thermal structure may contribute, as well, but opposite to the sense we naively envisioned above. Kuhn sees a critical role for the variations of the Reynold's stresses or turbulent pressure through the solar cycle. He also 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). Thus, all three candidates, or combinations thereof, merit careful consideration.

Clearly, we are lacking a basic understanding of how the frequency changes arise, and so, we also do not understand the origin of the aforementioned dynamical changes in the sun through the activity cycle. However, Dziembowski, Goode & Schou (2001) used SOHO/MDI seismic data to shed light on the character of the dynamical changes with rising activity by using f-mode (f-modes are the eigenmodes of the sun having no radial null points and these modes are asymptotically surface waves) and p-mode data to probe the evolution of the size of the sun as activity increases. We propose to use this knowledge to guide us to the correct approach to determining the nature of the dynamic changes giving rise to "$\frac{\Delta_{\min}T}{T}$" in the blackbody equation.

The heart of our proposal is to use seismic data from MDI to determine constraints on changes in the invisible layers immediately beneath the surface (and related ground-based data for the surface) to determine the physical origin of the variation of the solar irradiance. Further, we propose to probe and interpret the cause of the variation of the solar radius through the cycle. This effort would be directly consistent with NASA's SoHO/MDI GI program.

B Proposed Research

B.1 How does the sun's radius change during the solar cycle?

We propose to track the changes in the solar radius down the declining phase of this activity cycle. This is *not* the key part of what we propose, but rather the tracking is a by-product of our primary effort to determine whether the sun is hotter at activity maximum. The key effort is made *feasible* by our progress in using MDI data to determine the evolution of the sun's radius over the rising phase of solar activity. This effort has enabled us to determine sufficient constraints on the sun's near-surface dynamics to make it possible to determine whether the sun is hotter at activity maximum. We have found that the sun shrinks with increasing activity. Does it grow with declining activity?

All helioseismic determinations of the solar radius to date have relied on the following asymptotic relation for f-modes frequencies,

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

where the Δ now implies a difference between true and model values. With this, Schou et al. (1997) derived a helioseismic radius of the sun that is quite close to the photospheric radius deduced by Brown & Christensen-Dalsgaard (1998)from several years of transit observations. The seismic determination rests on the radius of the f-modes scaling with the sun's true radius, which allows us to compare true and model photospheric radii. These seismic and transit photospheric values are 300-400 km smaller than the long-used radius that has been applied in standard models of the sun. As reliable as the seismic radius determinations are, applying Eq.(3) to determine radius changes through the solar cycle is fraught with difficulties, which are largely related to the changes being near-surface and very small, even compared to the errors in the determination of the seismic radius.

Antia et al. (2000) pointed out that using Eq.(3) 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, which can change the seismic radius at the level of their quoted errors. 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. However, surface magnetic fields may also have significant effects on f-mode frequencies (Evans & Roberts, 1990; Jain & Roberts 1994). With these two sources of perturbation to f-mode frequencies, we must contemplate solar cycle changes beyond that of a simple radius change. The relative contribution of the near-surface changes are expected to increase with ℓ, because such changes should be inversely proportional to mode inertia, I_ℓ, which sharply decreases with ℓ.

There is another problem in applying Eq.(3) 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

$$R_\ell = \left(\frac{1}{I_\ell}\int r^{-3} dI_\ell\right)^{-1/3}. \tag{4}$$

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 cycle dependent changes, $\Delta_{\min} R_\ell \approx \Delta_{\min} R$, 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 are quite small and seem to be confined to the outermost part of the sun. Then, the inferred value of $\Delta_{\min} R_\ell$, now using Eq.(3) to compare cycle dependent changes, would refer to the range of depths beneath the photosphere corresponding to the range of ℓ's in the data sets. Antia et al. (2000) used modes in the 100–200 range, which translates to 10–6 Mm in depth. Their finding implies that this layer was moved downward by about 5 km during the two years they considered. The truth is, with these 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, we can overcome this problem.

To account for the effect of the near-surface changes on f-mode frequencies and possible differential changes, we use the formulation of Dziembowski, Goode & Schou (2001), who showed the benefit of modifying Eq.(3) into

$$\Delta_{\min}\nu_\ell = -\frac{3}{2}\frac{\Delta_{\min} R_f}{R}\nu_\ell + \frac{\Delta_{\min}\gamma_f}{I_\ell}, \tag{5}$$

where $\Delta_{\min} R_f$ denotes the radius change inferred from a particular set of f-modes. The γ_f are the spherically symmetric part of the near-surface perturbation of the f-mode frequencies. The γ_f are a weak function of frequency (the mode inertia, I_ℓ is a strong function of frequency). This type of formulation is standard in stuctural inversions. In general, the γ's are the coefficients of a Legendre expansion in even orders, after factoring out the mode inertia, Dziembowski and Goode (1991). These coefficients are a very useful representation of the near-surface, aspherical shape asymmetries implied by non-rotationally induced fine structure in the spectrum of MDI data (the so-called "even-a coefficients"). In this formulation, the parts of the frequency change due to the size change and the near-surface effects cleanly separate, and that removes the ℓ-dependent anomaly that would occur if we were to use Eq.(3), see Fig.1. However, the size change refers to a region 5-10 Mm beneath the solar surface, corresponding to the range of radii, R_l, from Eq. (4) for the MDI f-mode data. Thus, the evolving frequencies contain information about a band 5-10 Mm beneath the solar surface –the f-mode radius band, or heretoforward the "f-mode radius", which is not to be confused with the seismic radius. *However, the evolution of the f-mode frequencies can be used to reveal whether the sun's f-mode radius shrinks or expands. This turns out to provide a strong constraint on the nature of the perturbation driving the irradiance changes*

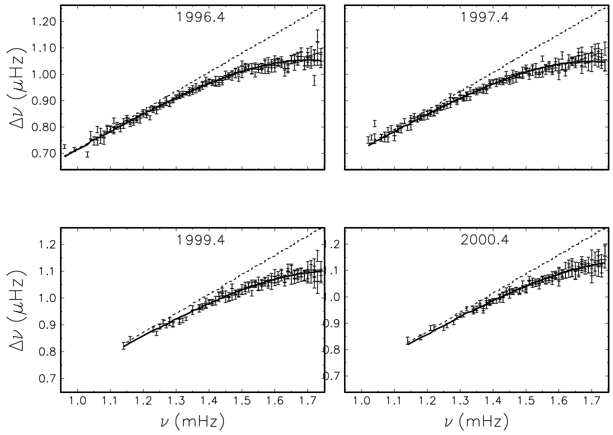

Figure 1: Differences between measured and calculated f-mode frequencies as a function of frequency. The error bars show estimated standard deviations of measured values. The dates correspond to the center of the individual 72-day long MDI measurement periods. The solid line represents the fit to Eq. (5). The solid line is barely visible because it passes through the data points. The dashed straight line represents the part of the fit attributed to the difference between the true solar radius and that adopted in the model for each epoch.

Table 1: Contributions to f-mode frequency shifts during the rising phase of cycle 23

ℓ	ν_ℓ[mHz]	I_ℓ	$\Delta\nu_R[\mu$Hz]	$\Delta\nu_\gamma[\mu$Hz]
100	1.02	381	0.010	0.0012
130	1.15	165	0.011	0.003
200	1.43	39.	0.014	0.012
300	1.74	9.4	0.017	0.050

with evolving solar activity. To determine the photospheric radius change from the seismic data, we must use the near-surface data to tell us whether the last few megameters of the sun contracts or expands with increasing activity. The change of the photospheric radius is the sum of the two.

In Fig. 1, we see that the departure from the linear relationship implied by the radius adjustment sharply increases with ν. Antia et al. (2000) considered only modes with $\nu < 1.44$ mHz, and it seems that the departure from a straight line is still small. However, this is somewhat misleading because we purposely used a model with a much too large radius. As we see in Table 1, at the level of changes of a few nanohertz (i.e. radius changes of a few km), the difference is quite significant. We emphasize that high ℓ-modes are important because with increasing ℓ, R_ℓ approaches the solar radius. For such modes, including γ_f is essential, which implies that we have to rely on Eq.(5) rather than Eq.(3). With Eq.(3), we get a much poorer fit, and the correction to the solar radius is larger by some 20 km. This illustrates the trade-off – increasing ℓ moves us closer to the surface, but such high ℓ's are more strongly contaminated.

In detail, we found from our linear fit, with the γ_f,

$$\frac{dR_f}{dt} = (-1.51 \pm 0.31) \quad \text{km/y}, \tag{6}$$

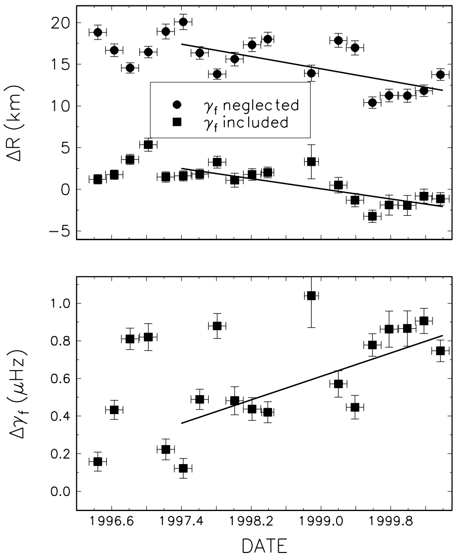

Figure 2: *Upper panel*: Variation of solar radius between 1996.4 and 2000.4 inferred from f-mode frequencies with and without the γ_f-term. Two straight lines represent linear fits to the data starting from 1997.4 when the rise of cycle 23 began. We presume that the apparent one year periodicity in the points is an artifact (Schou 2001). *Lower panel*: Corresponding variation of γ_f, which describes remaining near-surface contribution to f-mode frequency variations.

and without the γ_f-term,

$$\frac{dR_f}{dt} = (-1.82 \pm 0.64) \quad \mathrm{km/y}.$$

The values are similar to those found by Antia et al. (2000), and it is fair to say that at a depth of from 6 to 10 Mm the f-mode radius of the sun shrank by some 4 to 6 km during the rising phase of this activity cycle.

How reliable is this finding? The main concern is the role of the near-surface perturbation and the cross-talk between the two terms on the right side of Eq.(5). In the lower panel of Fig. 2, we show the γ's. The linear fit for γ, which is visibly poorer, but not too bad, yields

$$\frac{d\gamma_f}{dt} = (0.180 \pm 0.051) \quad \mu\mathrm{Hz/y}. \tag{7}$$

The relative contribution of the two terms to overall f-mode frequency variations depends on ℓ. Again, in Table 1, we compare these two contributions, denoted by$\Delta\nu_R$ and $\Delta\nu_\gamma$ for selected ℓ-values. The increasing role of $\Delta\nu_\gamma$ is a consequence of decreasing mode inertia. It should be noted that $\Delta\nu_\gamma$ yields an appreciable contribution to $\Delta\nu$ even for modes with $\ell \leq 200$.

Even 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, we write the Lagrangian change of the local radius in the form

$$\Delta_{\min} r(r_0) = r - r_0 = -\int_{r_b}^{r_0} \frac{\Delta_{\min}\rho}{\rho} \left(\frac{x}{r_0}\right)^2 dx, \tag{8}$$

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 $\Delta_{\min}\rho$ denotes the horizontally averaged change of density. We obtain a more revealing form of Eq.(8) by expressing $\Delta_{\min}\rho$ in terms of the averaged entropy and magnetic field changes.

For the horizontally averaged gas pressure in the presence of a random, r.m.s. magnetic field, we have *generalized* the treatment of Goldreich et al. (1991), so that the random field is *not necessarily isotropic*,

$$\Delta_{\min} P_g = -\Delta_{\min}(\beta P_m), \tag{9}$$

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 r.m.s. field.

With the use of thermodynamical relations, we determine

$$\Delta_{\min} r = \int_{r_b}^{r_0} \left[\frac{1}{\Gamma_1} \frac{\Delta_{\min}(\beta P_m)}{P_g} + (-\rho_T) \frac{\Delta_{\min} S}{c_p} \right] \left(\frac{x}{r_0} \right)^2 dx, \tag{10}$$

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

$$\frac{\Delta_{\min} S}{c_p} = \frac{\Delta_{\min} T}{T} - 0.4 \frac{\Delta_{\min} P_g}{P_g}.$$

If we attribute all of the shrinking to thermodynamic effects, how big can it be? The irradiance from an active sun is higher than average. If the same is true about luminosity then we should have $\Delta_{\min} S < 0$. Hence, a negative contribution to $\Delta_{\min} r$. However, this must be very small. Roughly, the increase in luminosity from activity minimum to maximum is given by the thermodynamic relation between heat loss and entropy decrease ($dQ = TdS$)

$$\Delta_{\min} L \sim \frac{\Delta_{\min} S}{\Delta_{\min} t_{\rm cyc}} \int_{\rm CZ} T dM_r,$$

where the integral yields the mean temperature of the convection zone, $\Delta_{\min} S$ is entropy change, $\Delta_{\min} t_{\rm cyc}$ is the length of the solar cycle and $\Delta_{\min} L$ is the luminosity change. The thermal timescale of the convection zone, the time for the energy stored in the convection zone to be released by the luminosity is given by

$$\Delta_{\min} t_{\rm CZ} \sim \frac{1}{L} \int_{\rm CZ} c_p T dM_r.$$

Combining the two, we have

$$\frac{\Delta_{\min} S}{c_p} \sim \frac{\Delta_{\min} L}{L} \frac{\Delta_{\min} t_{\rm cyc}}{\Delta_{\min} t_{\rm CZ}} \sim 10^{-3} \frac{10}{10^5} = 10^{-7}.$$

This corresponds to a radius change on the order of 0.1 km over the rising phase of the cycle, which is an order of magnitude, or so, smaller than the result we have just seen. A more acceptable explanation for the f-mode radius change would 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 – as deduced from the f-mode data. For an isotropic field ($\beta = 1/3$) the increase implies expansion – contrary to what is deduced from the f-modes. Thus, we have a non-trivial constraint on the change of the internal magnetic field and its geometry, implying the minimum increase to account for the rate of the shrinking corresponds to $\beta = -1$* . Then, we have $\Delta_{\min} < B >_{\rm rms} = (\overline{\Delta_{\min}(B_r^2)})^{1/2}$. Again, an isotropic random field would seem to be precluded for the region of the f-mode radius and the region immediately beneath, because it implies an expansion, rather than a contraction.

It must be emphasized that any inference regarding the change of the solar radius itself 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 in hand provide some information about changes in this layer through the γ_f. Similar, but much more accurate information is available in the p-mode data, which we now consider.

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 are considering here. However, from p-modes one may make a much more precise determination, than from f-modes, of the near-surface perturbation. For p-modes, we call it $\Delta_{\min}\gamma_p$, and it describes frequency changes caused by a variable perturbation localized near the surface. Again, $\Delta_{\min}$ is with respect to the activity minimum (1996.4 in the SOHO/MDI data set). For the spherically symmetric part of the p-mode γ's, we have, following Dziembowski, Goode & Schou (2001),

$$\frac{d\gamma_{p,0}}{dt} = (0.149 \pm 0.008) \quad \mu\text{Hz/y}. \tag{11}$$

The dependence of $\gamma(\nu)$ yields an important constraint on the localization of the source of solar cycle variations in p-mode frequencies. The subscript "0" in the Eq.(11) serves as a reminder that we are considering the spherically symmetic part of the γ spectrum (P_0). Later, we will discuss the use of the aspherical parts (P_2, P_4, etc.).

Following our generalized form of Goldreich et al. (1991), we 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 the change of γ_p,

$$\begin{aligned}\Delta_{\min}\gamma_p &= \frac{1}{8\pi^2\nu}\int d^3\vec{x}|\mathrm{div}\vec{\xi}|^2\{P\Gamma_1(1+\Gamma_\rho)\rho_T\frac{\Delta_{\min}T}{T} \\ &+ [1-\beta\Gamma_1(\Gamma_P+\Gamma_\rho\rho_P)-\beta(\Gamma_1-1+\Gamma_1\rho_P)]\Delta_{\min}P_m\}.\end{aligned} \tag{12}$$

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 $\Delta\gamma_p$ arises. As a first guess we interpret $\Delta\gamma_p$ in terms of magnetic field changes. Later, we will discuss other sources of the p-mode frequency changes.

In our generalized formulation of Goldreich et al., we considered two values of β, -1 and 1/3, and the following form for the depth, D, dependence of magnetic field increase

$$\Delta_{\min} < B >_{\rm rms} = \begin{cases} B_b & \text{if } D \geq D_b \\ B_b + \lambda \left(\frac{D - D_b}{D_b - D_m} \right) & \text{if } D_t < D < D_b \\ \Delta_{\min} < B >_{\rm rms} (D_t) & \text{if } D \leq D_t \end{cases}$$

where $D_m = -0.49$Mm denotes D at the temperature minimum, and B_b, D_b, and λ were determined by fitting the three terms in the series given just above. For D_t we adopted either D_m or 0.

In Fig. 3 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 $\gamma_p(\nu)$ 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). For the latter case, to explain the p-mode frequency increase between minimum and maximum, we require an increase of the r.m.s. magnetic field growing from 200 G in the photosphere to 840 G at 4.25 Mm. The corresponding numbers of Goldreich et al. are 250 and 1000 G.

For $\beta = -1$, the required field is significantly smaller than for β=1/3, and it is arguably consistent with the observed photospheric values for the r.m.s. field growth observed by Lin and Rimmele (1999). Certainly, β=-1 is the most economical form of the field to account for the cycle-dependent frequency changes, but does either argument imply that we can exclude an isotropic random field in the outermost layers? Well, f-mode radius shrinking with increasing activity argues for β=-1, and it is difficult to imagine how the buoyant field, which is expected to be radial at the surface, in the mean, and constrained to be predominantly radial beneath 5 Mm below the surface, would become isotropic in the 5 Mm band in between. Further, the p-modes contain not only the spherically symmetric part of the near-surface term, γ_0, but also higher order terms, γ_1(P_2-distortion), γ_2(P_4-distortion), etc., which are plotted in Fig. 4. We note that the low-order, asymmetric γ's are generally much larger than γ_0. This is true for the calculated γ's for β=-1, but not for β=1/3, Dziembowski and Goode (2002). Thus, the problem of a too large photospheric field growth seems to be resolved. But what about the role of the changes in thermal structure and turbulent pressure with rising activity?

In the bottom panel of Fig. 3, we plot the relative temperature changes, which give the same local contributions to $\Delta\gamma_p$ 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 r.m.s. $\Delta T/T$ at the 10^{-3} level. Such a temperature decrease would be a significant contributor to the observed frequency increase. Brüggen

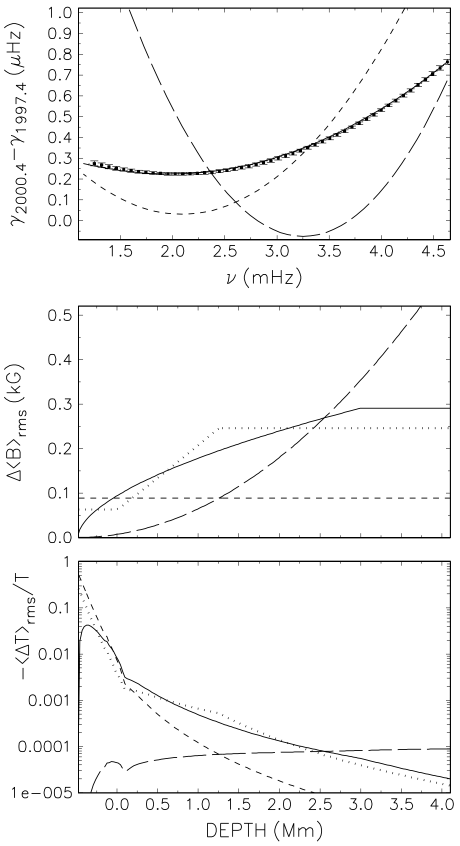

Figure 3: In the top panel, points with the error bars represent $\Delta\gamma_0(\nu)$ inferred from p-mode frequency differences between 2000.4 and 1997.4. The weak frequency dependence in the γ's arises because the perturbation acts near the surface – reflecting the virtue of this representation of the frequencies. 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.

and Spruit (2000) argue that one expects a lower subsurface temperature from an increasing magnetic field. Such 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, which in turn yields shrinkage because decreasing the turbulent pressure suppresses its forcing of a larger radius. However, it is difficult to see how the changing turbulent pressure can play a dominant role in the frequency changes, because if we attempt to attribute the observed modal frequency variations to random velocity changes, the required velocity changes seem too large. That is, about 75 km of the radius of the sun is due to the effect of turbulent pressure

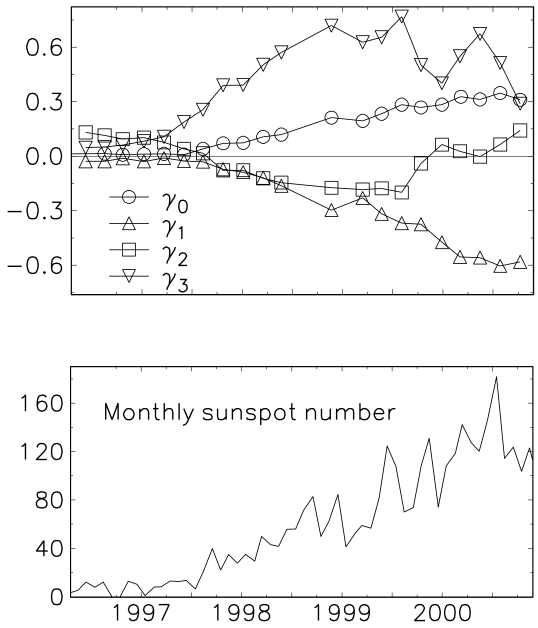

Figure 4: In the top panel, the behavior of γ_0 is shown as a function of time from the SOHO/MDI data, γ_0 is defined with respect to the 1996 activity minimum. The lower panel shows the corresponding sunspot number, which tracks γ_0 closely. Also, shown in the upper panel is the evolution of γ_1 through γ_3 – the P_2, P_4 and P_6 shape asymmetries, which are generally much larger than that for P_0.

(Stein 2002). The radius shrinks by about 3% of that value in going from minimum to maximum, and the turbulent pressure is about 15% of the total pressure at the surface. So attributing 15% of the 3% to turbulent pressure implies an 0.4% change in the turbulent pressure or 0.2% change in the velocity (Stein 2002). However, a velocity decrease on the order of 10% seem to be required to account for the frequency shifts (Dziembowski and Goode 2002). Furthermore, an overall 10% change in the convective velocities seems to large to be physically reasonable.

Based on our result of a more physically reasonable magnetic field describing the frequency changes, and apparent limitations on the role of the turbulent pressure, we are ready to probe the question of whether the sun is hotter at activity maximum.

B.2 Is the sun hotter at activity maximum?

We have developed a new formalism for describing the frequency changes in the spectrum of solar oscillations, and here we propose to exploit that formalism. The starting point of our new development is the variational principle for stellar oscillations in which we treat the effect of stellar magnetic fields as a small perturbation. We have developed a similar formulation that includes various forms of the velocity field. However, from our preliminary analysis, Dziembowski and Goode (2002), we have shown that the role of global flow changes, including rotation and meridional circulation, are far too small to play a role. Further, as discussed above, acceptable changes of the turbulent velocity also seem too small to be significant. Thus, we are left with the magnetic field and temperature. The two are not independent. However, for the spherically symmetric part, the link goes though the condition of thermal equilibrium, which is difficult to treat. For the aspherical part, the link is simple and follows from the condition of mechanical equilibrium. Thus, we can express the even-a coefficients in terms of the magnetic field alone.

Specifically, we consider a small-scale magnetic field assuming uncorrelated field components, but allowing the vertical component (depending on r) to be statistically different from the two horizontal (depending on θ and ϕ) ones. This formulation is the same as that of Goldreich et al. (1991), except that we generalize to an uncorrelated field, as before, and here we further *take into account the angular dependence of the field* so as to analyze the even-a data. Our averaged values, $\overline{B_j^2}$, are thus treated as general functions of r and slowly varying functions of the co-latitude. The latter dependence is represented in the form of a truncated Legendre polynomial series,

$$\overline{B_j B_k} = \delta_{jk} \sum_{k=0} [\delta_{rk} \mathcal{M}_{r,k}(r) + \frac{1}{2} \mathcal{M}_{H,k}(\delta_{\theta k} + \delta_{\phi k}] P_{2k}(\cos\theta), \tag{13}$$

where we include only seismically detectable (the ones that are symmetric about the equator) terms.

Each of the k-components gives rise to a P_{2k} distortion of the sun's structure. For $k > 0$, the hydrostatic equilibrium condition suffices to determine the distortion of all thermodynamical parameters.

In particular, for the $k > 0$ component of the relative Lagrangian perturbation of the temperature, we have

$$\begin{aligned} \left(\frac{\Delta T}{T}\right)_k \quad = \quad & \frac{1}{8\pi\chi_T} \left\{ \mathcal{M}_{r,k} \left[1 + 2\chi_\rho \left(\frac{d\ln \mathcal{M}_{r,k}}{d\ln r} \right) - \left(\frac{d\ln\rho}{d\ln p} \right) \right] \right. \\ & \left. - \mathcal{M}_{H,k} \left[1 + \chi_\rho \left(\frac{d\ln \mathcal{M}_{H,k}}{d\ln r} \right) - \left(\frac{d\ln\rho}{d\ln p} \right) \right] \right\}, \end{aligned} \tag{14}$$

where the Δ is with respect to the spherical sun. We emphasize here that for $k = 0$, the meaning of Δ is different. It is usually taken to be with respect to activity minimum. Here we adopted the standard notation with χ_T and χ_ρ, denoting the logarithmic derivatives of pressure with respect to temperature at constant density, and that with respect to density at constant temperature, respectively.

If the magnetic perturbation is significant only in the layers well above the lower turning points for all p-modes considered, then all the frequency changes, $\Delta\nu$ and the even a coefficients, may be expressed through the γ's using kernels that are ℓ-independent. Owing to a different constraint from hydrostatic equilibrium, we have different expressions for γ_k, depending on whether $k = 0$ or $k > 0$. In the former case, the temperature perturbation is treated as an independent parameter. In that case, we have

$$\gamma_0 = \int \left(\mathcal{K}_{0,T} \frac{\Delta T}{T} + \mathcal{K}^B_{0,r} \Delta\mathcal{M}_{r,0} + \mathcal{K}^B_{0,H} \Delta\mathcal{M}_{H,0} \right) dD, \tag{15}$$

where D is depth. All the kernels, $\mathcal{K}$, may be expressed in terms of parameters of the standard solar model and the radial eigenfunctions of its p-modes.

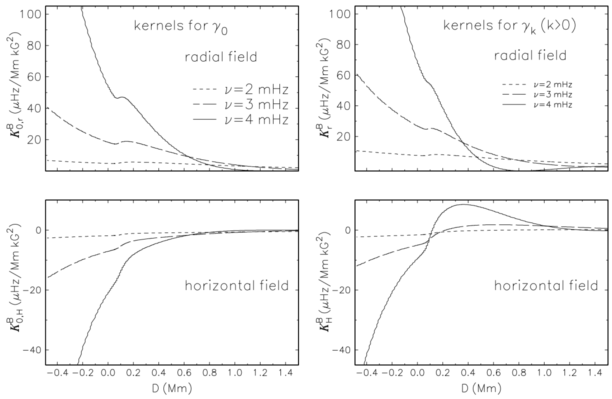

Figure 5: Kernels for the γ's at three selected frequencies plotted as functions of the depth in outer part of the standard solar models. The left panels are for the spherically symmetrical case, and the right panels are for the aspherical case.

Goldreich et al.(1991) considered only changes in centroid frequencies. They pointed out that to explain the frequency increase between 1986 and 1988, a 1% decrease of the photospheric temperature is needed ($\mathcal{K}_{k,T}$ is always < 0). They regarded this requirement as being incompatible with observations, and adopted the changing magnetic field as the sole cause of the frequency increase; they found that the field increase must be about 250 G at the photosphere, and steadily growing to about 1 kG at a depth of 10 Mm. Their numbers refer to the case of a statistically isotropic field ($\mathcal{M}_{H,k} = 2\mathcal{M}_{r,k}$). A much more modest field increase (< 100 G at the photosphere) would result for an inwardly growing, purely radial field (Dziembowski, Goode & Schou, 2001), as discussed before.

For $k > 0$, the temperature perturbation may be eliminated, and we have a simpler expression,

$$\gamma_k = \int (\mathcal{K}_r^B \mathcal{M}_{r,k} + \mathcal{K}_H^B \mathcal{M}_{H,k}) dD. \tag{16}$$

For Eq.(16), note that the kernels are the same for all k's. This follows both from $k \leq \ell$ and our assumption that the perturbation is significant only above the inner turning points of the oscillations.

In Fig.5, we show these kernels in the outer layers of the sun. We note that the strong sensitivity to the frequencies emphasizes the probing power of the $\gamma(\nu)$. We remark that the relative success of fitting frequency differences with a constant γ reveals that the dominant perturbation must be located in a region in which all the kernels are not too different. That is, just beneath the photosphere. Further, a critical point is that after inspecting the kernels, one can easily see that they imply that *a radial field increase in the outer layers will lead to a frequency increase, while an increase of the horizontal field is very likely to have an opposite effect*. That is, since oscillation frequencies increase with increasing activity, the behavior of the kernels tells us the most economical form of the field to describe the frequency changes. In the outer layers, the signs of the kernels are $\mathcal{K}_{k,r}^B > 0$ and $\mathcal{K}_{k,H}^B < 0$. Thus, the most economical requirement is a purely radial field. The novel and significant aspect of our present formulation is that instead of searching for the magnetic field through frequency dependent γ coefficients, we

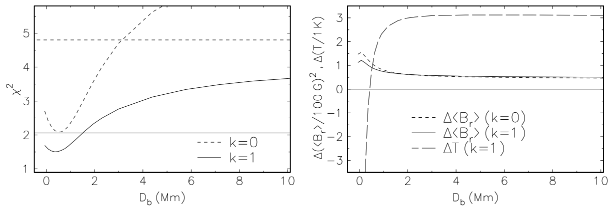

Figure 6: Left panel shows the χ^2 from fitting γ_0 (P_0) and γ_1 (P_2 shape asymmetry) to Eqs.(15) and (16) with B_r given by Eq.(17) with D_b treated as the adjustable parameter. Flat dashed and solid lines are for constant γ's. Right panel shows the implied field intensity and the temperature change with respect to activity minimum, as determined for P_2 applying Eq.(17) to Eq.(14).

now express γ directly through the magnetic field parameter that we propose to infer.

As an illustration of this new approach to show the probing power of the γ's, we consider a simple functional form of the depth dependence of the radial field,

$$\Delta_{\min} < B >^2_{\mathrm{rms}} = \begin{cases} B_b^2 & \text{if } y > 1 \\ B_b^2 y^2 (3 - 2y) & \text{if } y \le 1 \end{cases} , \tag{17}$$

where

$$y = \frac{D_{\mathrm{Tm}} - D}{D_{\mathrm{Tm}} - D_b},$$

and where D_{Tm} is the depth at the temperature minimum, and D_b is the adjustable parameter. In Fig.6, we show the behavior of χ^2 with varying D_b. In the left panel, we show the value of χ^2 for k=0 and 1 for a range of choices of D_b. The two minima are at about the same value of D_b with the k=0 term showing a more robust minimum. In the right panel, we show the implied radial field intensity as a function of D_b, as well as $\Delta_{\min} T$ (for the P_2 distortion). In our simple example, $\Delta_{\min} T$ goes steeply through zero in the region of the minimum of χ^2.

Of course, for understanding the origin of Kuhn, Libbrecht & Dicke's (1988) latitudinal temperature bands, as well as solar irradiance variation, it is essential to determine the temperature change at the base of the solar photosphere during the solar cycle. In our illustrative example, we get $\Delta_{\min} T < 0$ for $\Delta_{\min} B > 0$ corresponding to the χ^2 minimum. This would mean that the active latitudes are cooler. However, from the left panel of Fig.6, it is clear that we are not far from the place where $\Delta_{\min} T$ changes sign, so we must regard the illustrative finding as inconclusive. We see in Fig.6 that the minimum of χ^2 is much better determined from the centroid data, but we are unable to determine $\Delta_{\min} T$ for $k = 0$ because we have only considered the magnetic field term in Eq. (15). We propose to treat the condition of thermal equilibrium in the sun's outer layers in order to include both the temperature and magnetic field terms in Eq.(15), and to constrain the surface averaged temperature change. Further, we propose a more thorough analysis of the MDI data, as well using constraints on $\Delta_{\min} B_r$ from BBSO Ca II K and the BBSO Solar Disk Photometer data (see Fig.7). Naturally, for the irradiance problem we have to know $(\frac{\Delta_{\min} T}{T})_0$.

A supplementary approach to the problem of the relationship between activity and temperature that we propose is an analysis of multi-color photometry data from the Solar Disk Photometer (SDP) at BBSO. Ken Libbrecht (Caltech) designed the SDP to improve upon the Mt.

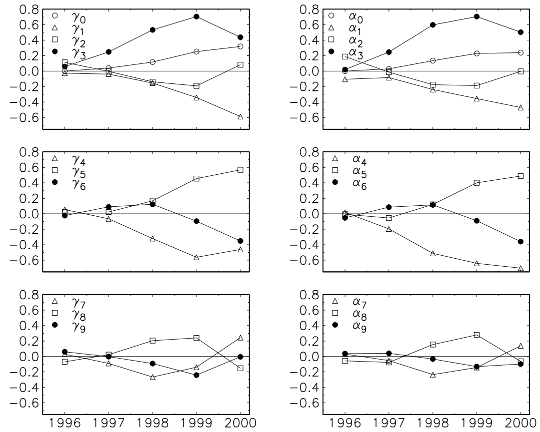

Figure 7: Right panels show the Legendre polynomial expansion of the photometric signal following the analysis in Goode et al. (2002). Left panels show the corresponding γ's. The latter were averaged to the time frame of the α's. The γ's reflect the near-surface shape distortion, Legendre coefficient by Legendre coefficient (P_0, P_2, P_4, etc.). The α's reflect the equivalent surface distortion as determined from the SDP.

Wilson Limb Photometer by allowing detection of not just the limb, but a number of successive annuli on the solar disk – ranging from the limb, to as small as about half the disk radius. With these data, we reproduce Kuhn's temperature bands (as did Woodard and Libbrecht 1993), but since we have superior information about limb darkening it should be easier to disentangle the various contributions to the signal. In Fig.7, we demonstrate the correlation between the Legendre coefficients from the photometer and from seismology, Goode et al. (2002). The prospect for determining temperature follows from the fact that we have three-color data, and the geometrical effect may be handled from information on the limb darkening. The fact that we have both α_0 and γ_0 is significant because it provides a tool to link irradiance variation to luminosity variation. Obtaining α_0 is a triumph of the SDP.

Finally, let us remark that in the discussion of the seismic method of field and temperature determination, the kernels were regarded as being ℓ-independent. But our formalism is, in fact, more general. In particular, it is valid for solar f-modes. Furthermore, for the low-order Legendre polynomial distortion, the formalism is useful for assessing the effect of a deeply buried magnetic field. We propose to use this more general formalism to set a reliable upper limit for the field near the base of the convective zone. Furthermore, with this formalism we can tell more about the field in the bulk of the convection zone, as Dziembowski, Goode & Schou (2001) indirectly inferred from the f-mode frequency changes.

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D Curricula Vitae

D.1 Philip R. Goode

Address:

Department of Physics
New Jersey Institute of Technology (NJIT)
Newark, New Jersey 07102
(201) 596-3565
pgoode@tesla.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, 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

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

Changes in the Solar Oscillation Frequencies During the Current Activity Maximum: Analysis and Interpretation, 2002, in *IAU Colloquium 185, Radial and Nonradial as Probes of Stellar Physics*, C. Aerts and J. Christensen-Daalsgard eds., in presc.

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D.2 Wojciech A. Dziembowski

Born:	January 14, 1940, Warsaw, Poland
Family:	Married 1967 to Anna Dziembowska (present name). Sons Stefan born 1973 and Andrzej born 1974.
Education:	M.Sc. Jagiellonian University, Cracow, 1962 Ph.D. Warsaw University, 1967.
Address:	Warsaw University Observatory Al. Ujazdowskie 4, 00-478 Warszawa, Poland Phone (22) 629-40-11, ext.108. Internet wd@astrouw.edu.pl
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 1969-1977: Research Associate, CAC 1967-1969: Research Associate, Columbia University, NYC 1963-1967: Graduate Student, CAC 1962-1963: Research Assistant, Department of Astronomy, Jagiellonian University

Ten Selected Publications

Changes in the Solar Oscillation Frequencies During the Current Activity Maximum: Analysis and Interpretation, 2002, in *IAU Colloquium 185, Radial and Nonradial as Probes of Stellar Physics*, C. Aerts and J. Christensen-Daalsgard eds., in press.

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D.3 John R. Varsik

Address:

Big Bear Solar Observatory
New Jersey Institute of Technology (NJIT)
40386 North Shore Lane
Big Bear City, California 92314
(909) 866-5791
varsik@bbso.njit.edu

Education:

University of Hawaii, Manoa
Honolulu, Hawaii
Ph.D. (Astronomy), December 1987

Stanford University
Stanford, California
B.S. (Physics), June 1979

Positions Held:

1997- present: Associate Research Professor, NJIT
1995-1997: Research Associate, National Solar Observatory, Sacramento Peak
1994-1995: Assistant Scientist, Caltech
1988-1994: Solar Observer, Caltech

Ten Selected Publications

The Big Bear Solar Observatory's Digital Vector Magnetograph, Spirock, T., Denker, C., Chen, H., Chae, J., Qiu, J., Varsik, J., Wang, H., Goode, P.R., and Marquette, W.: 2001, ASP Conference Series, *Advanced Solar Polarimetry*.

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E Current and Pending Support

Phil Goode is PI on four active grants. 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-LWS for $464 K and covers July 1, 2001 - June 30, 2004, and is entitled "Earthshine Measurements of the Earth's Albedo". The fourth grant is from NSF-INT for $36K covering June 1, 1999 through May 31, 2002. This grant is entitled U.S. - Korea Cooperative Research in Solar Physics" and covers scientific enchange between Big Bear and Seoul National University.

None of the three grants supports the work proposed here, since it relies almost exclusively on the use of MDI oscillation data.

F Statements of Commitment from Collaborators

F.1 Wojciech Dziembowski

```
Date:  Fri, 03 May 2002 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 'SOHO/MDI Data:  Is the Sun Hotter at Activity
Maximum?'  submitted by Philip Goode to the NASA solicitation
NRA-02-OSS-01-SECGIP, and that I intend to carry out all responsibilities
identified for me in this proposal.  I understand that the extent 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 John Varsik

I acknowledge that I am identified by name as a collaborator in the investigation entitled 'SOHO/MDI Data: Is the Sun Hotter at Activity Maximum?' that is submitted by Philip Goode to the NASA solicitation NRA-02-OSS-01-SECGIP, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be evaluated during peer review in determining the merits of this proposal.

John Varsik

G Budget Summary and Details

	1st Year	2nd Year	3rd Year
PI: Philip Goode	$14,000	$14,500	$15,000
Consultant: W. Dziembowski	$12,000	$12,000	$12,000
Collaborator: J. Varsik	$8,000	$8,400	$8,800
Fringe Benefits	$2,620	$2,741	$2,862
Supplies	$1,000	$1,000	$1,000
Domestic Travel	$3,000	$3,000	$3,000
Publications	$2,000	$2,000	$2,000
Subtotal	$42,620	$43,641	$44,662
Total (incl. Overhead)	**$62,651**	**$64,152**	**$65,653**
			$192,456

The fringe benefits are 5% for summer and 24% for staff. The overhead rate is 47%.

H Summary of Personnel Commitments and Costs

For each year, the direct labor in the proposal is one month of summer salary for Philip Goode to perform his part of the work, and two months each year to support NJIT Research Professor John Varsik who is employed by the Big Bear Solar Observatory. Dr. Varsik will reduce the Ca II K synoptic data and the Solar Disk Photometer data. There is an annual $12,000 consulting fee for Dziembowski's six weeks of work.

The travel budget covers travel to one professional meeting per year for Drs. Goode and Varsik ($3,000).

The consultant is Prof. W.A. Dziembowski. He will spend six weeks in Big Bear each year working on this project with Varsik and Goode. His consulting fee, including travel and per diem is $12,000 for the five weeks.

There is also a $2,000 annual budget to cover page charges.