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SUNSHINE, EARTHSHINE AND CLIMATE CHANGE
I. ORIGIN OF, AND LIMITS ON SOLAR VARIABILITY

PHILIP R. GOODE[1] AND W. A. DZIEMBOWSKI[2]
[1]Big Bear Solar Observatory, NJIT, 40386 North Shore Lane, Big Bear City, CA 92314, USA
E-mail: pgoode@bbso.njit.edu
[2]Warsaw University Observatory and Copernicus Center, Warsaw, Poland

ABSTRACT

Changes in the earth's climate depend on changes in the net sunlight reaching us. The net depends on the sun's output and earth's reflectance, or albedo. Here we develop the limits on the changes in the sun's output in historical times based on the physics of the origin of solar cycle changes. Many have suggested that the sun's output could have been 0.5% less during the Maunder minimum, whereas the variation over the solar cycle is only about 0.1%. The frequencies of solar oscillations (f- and p-modes) evolve through the solar cycle, and provide the most exact measure of the cycle-dependent changes in the sun. But precisely what are they probing? The changes in the sun's output, structure and oscillation frequencies are driven by some combination of changes in the magnetic field, thermal structure and velocity field. It has been unclear what is the precise combination of the three. One way or another, this thorny issue rests on an understanding of the response of the solar structure to increased magnetic field, but this is complicated. Thus, we do not understand the origin of the sun's irradiance increase with increasing magnetic activity. Until recently, it seemed that an unphysically large magnetic field change was required to account for the frequency evolution during the cycle. However, the problem seems to have been solved (Dziembowski, Goode & Schou 2001) using f-mode data on size variations of the sun. From this and the work of Dziembowski & Goode (2003), we suggest that in historical times the sun couldn't be much dimmer than it is at activity minimum.

Key words : Sun: activity—Sun: interior—Sun: oscillations

I. INTRODUCTION

The changes in the earth's climate depend on changes in the net sunlight reaching earth, and this net depends on the sun's irradiance and the earth's reflectance. In this paper, we discuss the state of our knowledge of the the physical origin of the sun's varying irradiance, and recent advances in that knowledge.

The variations in solar irradiance have been carefully measured from space for more than two decades, see Figure 1. The solar irradiance is about 0.1% greater at solar magnetic activity maximum than it is at activity minimum. This variation is generally regarded as being climatologically insignificant (for a review, see Lean 1997); nonetheless the physical origin of these changes has defied explanation.

Even though the variation over the last two cycles has been small, many have assumed that larger changes have occurred over historical times (again see Lean 1997). In detail, the sunspot number has been taken as a proxy for irradiance and it has been argued, for instance, that the sun was 0.5% less irradiant during Maunder Minimum (the time in the 17th century when a sunspot was rare). Lacking an understanding of the physical origin of irradiance variations, it is difficult to either endorse or criticize this picture.

Another view of the same problem comes from the fact that we do not know whether the sun is hotter or cooler at activity maximum when it is most irradiant. 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?

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

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

where the change, $\Delta_{\min}$, in luminosity (L), temperature (T), and solar radius (R) are each defined 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 in spite of our naive assumptions, $\frac{\Delta_{\min} T}{T}$ is actually a proxy for some combination of the evolving magnetic field, thermal structure and turbulent pressure. 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

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Corresponding Author: P. R. Goode

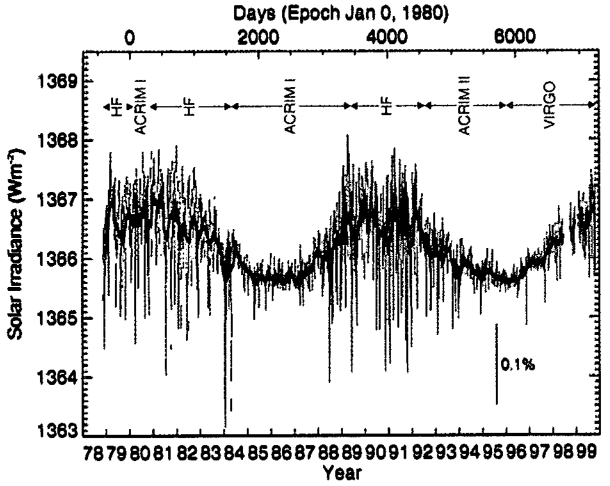

Fig. 1.— Measured solar irradiance (in watts per m^2) vs. time (Fröhlich 2000)

activity maximum. It turns out that the cycle dependent radius changes (Brown & Christensen-Dalsgaard 1998; Emilio et al. 2000; Dziembowski, Goode & Schou 2001) are too small to matter for irradiance changes, but the seismic study of radius change turns out to provide a critical clue in determining the physical origin of cycle variation.

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 investigations. One very recent inference from the frequency changes of the solar f-modes was that the sun actually shrinks with increasing activity, Dziembowski, Goode & Schou (2001).

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

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 ($< B^2 > \sim (70G)^2$). Instead, 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). Clearly, we have been 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. This knowledge can be used to guide us to the nature of the dynamic changes giving rise to "$\frac{\Delta_{\min}T}{T}$" in the blackbody equation.

II. THE ORIGIN OF THE CHANGING HELIOSEISMIC RADIUS OF THE SUN

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

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

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 radius that has been used in standard models of the sun. Applying Eq.(2) to determine radius changes through the solar cycle is fraught with difficulties.

A key problem in applying Eq.(2) in a search for the radius variations correlated with activity follows from the fact that the induced modifications are quite non-uniform, and each f-mode has it is own radius, R_ℓ, which is given by

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

For the MDI 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 $\Delta_{\min}R_\ell$ is quite problematic. When the f-mode frequencies were used to refine the value of the radius for modelling 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 ΔR in Eq.(2) would refer to the range of depths beneath the photosphere corresponding to the range of ℓ's in the data sets.

III. FORMAL DETERMINATION OF THE RATE OF SOLAR SHRINKING FROM F-MODES

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.(2) into

$$\Delta_{\min}\nu_\ell = -\frac{3}{2}\frac{\Delta_{\min}R_f}{R}\nu_\ell + \frac{\Delta_{\min}\gamma_f}{I_\ell}, \tag{4}$$

where ΔR_f denotes the radius change inferred from a particular set of f-modes. In this formulation, the parts of the frequency change due to the size change and the near surface effects cleanly separate and remove the ℓ-dependent anomaly that would occur if we were to use Eq.(2). 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. (3) 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. Since the f-modes propagate horizontally in the high frequency asymptotic limit, they can be thought of as being confined to the f-mode band. Whereas, p-modes propagate vertically near the surface and are "trapped in a cavity". The evolution of the f-mode frequencies can be used to reveal whether the sun's f-mode radius shrinks or expands. To determine the photospheric radius change from the seismic data, one must also treat the region above the f-mode band, as did Dziembowski, Goode & Schou (2001), but here our interest is the behavior of the f-mode band.

In Figure 2, we show the variations of the f-mode radius and γ_f inferred from f-modes from the truncated data sets. The rise of the current activity cycle began in 1997.4, which was marked by a sharp rise of the seismic activity indicators (Dziembowski et al. 1998, or the upper panel of Figure 3 here). There is a corresponding sharp rise of p-mode frequencies beginning at this time. That is why we choose 1997.4 to begin our linear fits in Figure 2.

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

$$\frac{dR_f}{dt} = (-1.51 \pm 0.31) \quad \text{km/y}, \tag{5}$$

and without the γ_f-term,

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

implying that at 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.

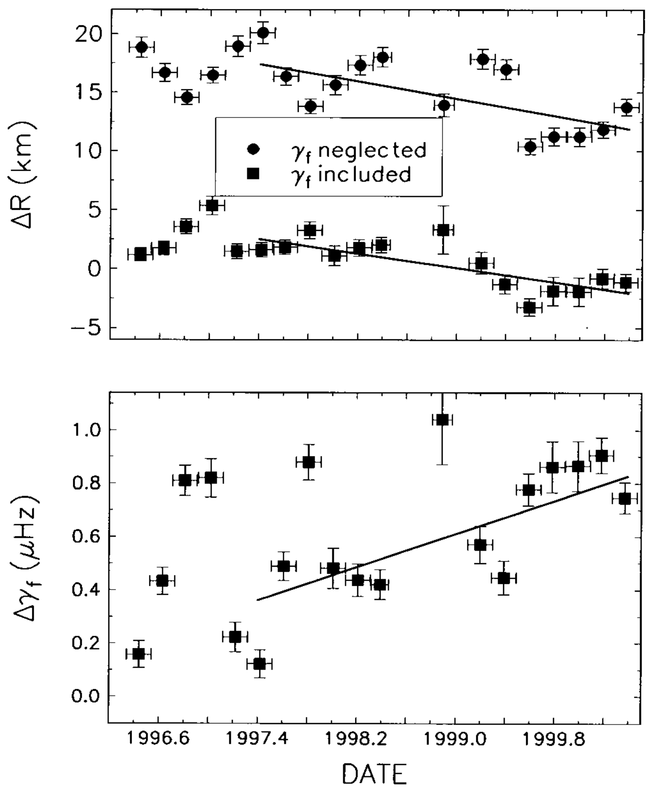

Fig. 2.— *Upper panel:* Variation of solar radius between 1996.4 and 2000.4 inferred from f-mode frequencies with and without the γ_f-term. Two straight lines represent linear fits to the data starting from 1997.4 when the rise of cycle 23 began. *Lower panel:* Corresponding variation of γ_f, which describes remaining near-surface contribution to f-mode frequency variations.

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.(4). 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

$$\frac{d\gamma_f}{dt} = (0.180 \pm 0.051) \quad \mu\text{Hz/y}. \tag{6}$$

The relative contribution of the two terms to overall f-mode frequency variations depends on ℓ.

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

$$\Delta r(r_0) = r - r_0 = -\int_{r_b}^{r_0} \frac{\Delta\rho}{\rho}\left(\frac{x}{r_0}\right)^2 dx, \tag{7}$$

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. We obtain a more revealing form of Eq.(7) 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, r.m.s. magnetic field we have followed Goldreich et al. (1991), but generalized their approach so that the pressure of the random field is not necessarily isotropic, but rather is composed of a horizontal component, $\overline{B_h^2}$, and a radial component, $\overline{B_r^2}$,

$$\Delta P_g = -\Delta(\beta P_m), \tag{8}$$

where

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

is the 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. We consider two limiting cases, β=1/3 for an isotropic, random, rms field and β=-1 for a radial random field.

With the use of thermodynamical relations, we determine

$$\begin{aligned}\Delta r &= \int_{r_b}^{r_0} \left[\frac{1}{\Gamma_1} \frac{\Delta(\beta P_m)}{P_g} \right. \\ &+ \left. (-\rho_T)\frac{\Delta S}{c_p} \right] \left(\frac{x}{r_0}\right)^2 dx, \end{aligned} \tag{9}$$

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

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

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 $\Delta S < 0$ and a cooler sun at activity maximum. Hence, a negative contribution to Δr. 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 ($dQ = TdS$)

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

where the integral yields the mean temperature of the convection zone, ΔS is entropy change, $\Delta t_{\rm cyc}$ is the length of the solar cycle and ΔL 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

$$\Delta t_{\rm CZ} \sim \int_{\rm CZ} c_p T dM_r/L.$$

Combining the two, we have

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

This corresponds to a radius change of order 0.1 km, or so, 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 the field geometry implying the minimum increase to account for the rate of the shrinking corresponds to $\beta = -1$. Then, we have $\Delta < B >_{\rm rms} = (\overline{\Delta(B_r^2)})^{1/2}$. 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. The radial random field is also the most economical in accounting for the frequency changes. In particular, the rms field required is less than 100 G, as compared to the roughly 250 G isotropic field required. Of course, this fact by itself is not compelling. Do we have other evidence?

In Eq. (4), the γ term represents the near-surface perturbation arising from the growing field, changing thermal structure and turbulent pressure. Using p-modes this can be generalized to account for the P_2, P_4, etc. perturbations of the sun's shape with growing activity. A decomposition of the MDI oscillation data is shown in Figure 3. It is clear that the shape asymmetries rise with increasing activity. It is also clear that the spherical symmetry changes more slowly than the aspherical parts. If instead, one calculates the γ's, assuming β=-1 and 1/3, one finds the same general behavior as Figure 3 with β=-1. However, for β=1/3 the spherical and aspherical γ's are quite comparable is magnitude. Perhaps the most interesting aspect of Figure 3 is that at activity minimum the γ's vanish, and recalling that for the P_0 term that the oscillation frequencies have the same value at different activity minima, we conclude that there are no shape asymmetries at activity minimum or radial changes from minimum to minimum. Therefore, it is difficult to imagine how the modern sun could be less irradiant than it is at activity minimum. Of course, there is no apparent limit on an ever-more active sun being ever-more irradiant. However, we are still left with the question of how small can the field growth be and still account for the frequency and irradiance changes?

IV. ROLE OF TURBULENT PRESSURE IN FREQUENCY CHANGES THROUGH THE CYCLE

The requirement on the field is further reduced by the combined effects of thermal and turbulent pressure changes induced by the field's growth with increasing activity. The mechanism is the same for both, namely the growing field blocks the heat flow to the surface and suppresses turbulent flow, while the turbulent flow helps to support the radius; both of these effects reduce the size of the cavity, which increases the oscillation frequencies with increasing activity. Thus, the combined effects of the thermal and turbulent pressure changes with increasing activity can account for part of the perturbation, which serves to reduce the required field growth. However, one must consider the possibility that either the changes in the thermal structure alone, or changes in the turbulent pressure alone would be sufficient to account for the evolution of the solar frequencies.

Dziembowski, Goode & Schou (2001) showed that the changes in the thermal structure required to account for the frequency increases with increasing activity are of order $\Delta T/T \sim 10^{-2}$ at the photosphere, or about an order of magnitude larger than allowed by observation. Thus, too large changes required in the thermal structure to account for the frequency evolution, but the changing thermal structure does reduce the growth in the field that is required to account for the frequency changes.

Dziembowski & Goode (2003) have shown that a growth in the turbulent pressure of about 1% from activity minimum to activity maximum is sufficient to account for the frequency growth with increasing activity. This is well within observational limits. We are currently checking to see if this is self-consistent with the effect of the growing near-surface field. If so, we may place a different limit on the required growth of the field.

If one were to assume that the growing field accounts for the frequency changes, we have seen that a growing, radial random field is the most economical, and that if one increases the horizontal component of the growing, near-surface random field there must be a concomitant increase in the radial component. This is troubling because a pure radial random field seems too simple, while increasing the horizontal component implies too large a field growth. The role of the turbulent pressure would seem to circumvent this problem because the role of the field would be to suppress the turbulent pressure and shrink the radius.

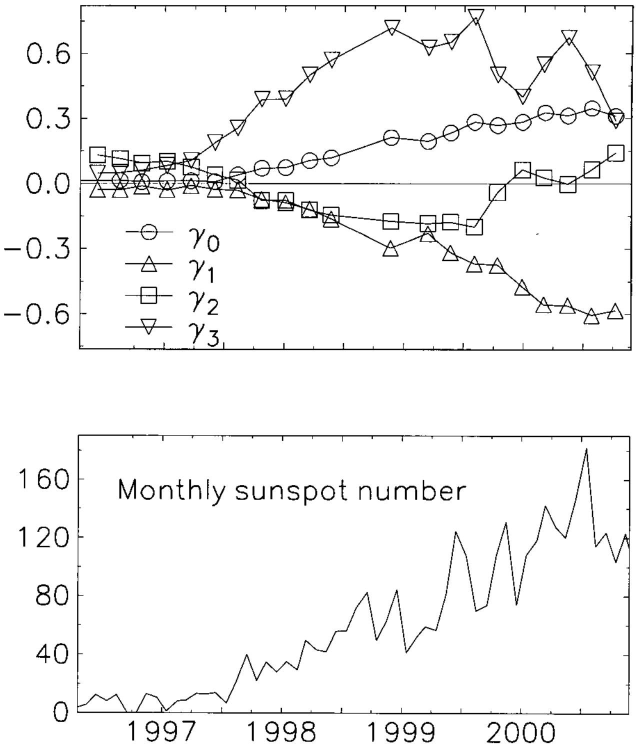

Fig. 3.— In the top panel, the behavior of γ_0 is shown as a function of time from the SOHO/MDI data, γ_0 is defined with respect to the 1996 activity minimum. The lower panel shows the corresponding sunspot number, which tracks γ_0 closely. Also, shown in the upper panel is the evolution of γ_1 through γ_3 – the P_2, P_4 and P_6 shape asymmetries, which are generally much larger than that for P_0.

V. CYCLE DEPENDENT CHANGES IN THE SOLAR RADIUS

As for the radius itself, 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 5 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. Combining the shrinkage of the f-mode radius with the implied contraction of the outer few megameters, Dziembowski, Goode & Schou (2001) calculated an implied photospheric radius shrinkage of 2-3 km/year with rising activity. This rate is not fundamentally inconsistent with the growth rate of about 5.9±0.7 km/y determined by Emilio et al. (2000) from the direct radius measurements based on SOHO/MDI intensity data due to difficulties inferring the satellite value. Both results, however, imply a negligible contribution of the radius change to the solar irradiance variations of Eq. (1).

Furthermore, the two estimates of the radius change between maximum and minimum activity are by two orders of magnitude less than found by Nöel (1997) from his measurements with the astrolabe of Santiago. He finds the difference between the 1991 (previous maximum) and 1996 radii, which exceeds 700 km. The data from the Solar Diameter Monitor (Brown & Christensen-Dalsgaard 1998) are inconsistent with such large variations, although there is a hint of possible radius increase of some 30 km during 1987. On the other hand, a theoretical constraint on radius given by Spruit (1994) is even tighter than than from helioseismology. The number he quotes for the maximum to minimum difference is $2 \times 10^{-7} R_\odot = 0.14$ km.

VI. CONNECTING THE INSIDE OF THE SUN TO ITS ATMOSPHERE

The γ's represent the near-surface perturbation, which evolves over the activity cycle. One may ask how they are connected to solar atmospheric conditions. To determine this, we use the Ca II K data from Big Bear Solar Observatory. The Ca-line data are a chromospheric measure of solar activity. To compare them to the γ's, we translate the Ca-line data into a different representation. We project the Ca-line signal onto the axis of rotation and average individual days into sets that correspond to the temporal length of the MDI data. We then project the averaged signal onto symmetrical Legendre polynomials (P_2, P_4, etc.). The results shown in Figure 4 reveal an extremely close relation between what happens immediately beneath the solar surface and the well-know atmospheric manifestations of solar activity.

VII. CONCLUSIONS

Careful, helioseismic studies of the sun's changing size provided the critical clue needed to resolve the long-standing problems associated with a seemingly too large field growth required with increasing activity to account for changes in the solar oscillation frequencies. This leads to a clearer view of the physical origin of the changing solar irradiance.

The growing, near-surface magnetic field alters the turbulent pressure, which seems sufficient to account for the increasing p-mode and f-mode frequencies with increasing solar activity. Further, the shrinking solar surface/convection zone seems to be cooler with increasing activity. This is consistent with the picture of Spruit (2000) in which increasing solar activity corrugates the surface of the sun making it a more effective radiator (note: this says nothing about how the temperature of, say, the corona changes with increasing activity). Since Figures 3 and 4 reveal a smooth surface at activity minimum, it is difficult to imagine a sun that was significantly dimmer during the holocene than it is at any activity minimum. On the other hand, greater solar activity would seem to imply greater irradiance.

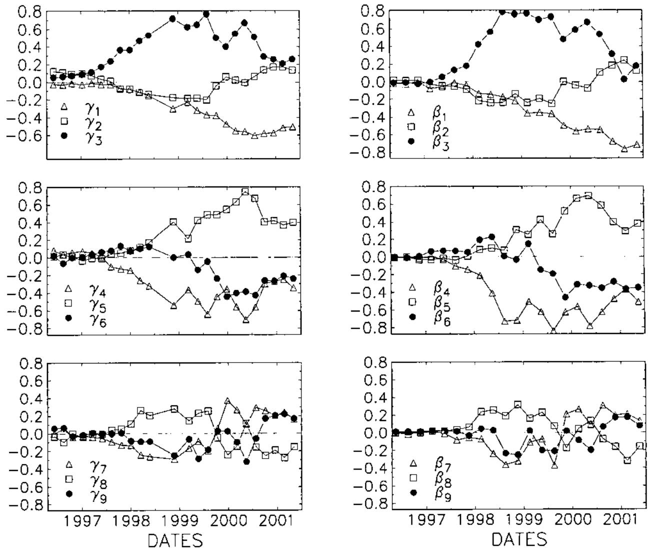

Fig. 4.— In the left panels, the behavior of γ_k ($k > 0$) is shown as a function of time from the SOHO/MDI data. The right panels show the corresponding β's. It is clear that there is detailed agreement to P_{18} (or γ_9), which bears out the close relation of what happens just beneath the surface to what happens in the atmosphere.

Confining changes in the sun's irradiance to a 0.1% band over the solar cycle would seem to argue for some indirect effect of solar activity causing the solar cycle signature in ice core data (Ram & Stoltz 1999). This argument is strengthened by the conclusion here that larger downside wanderings of irradiance would seem to be precluded. Several terrestrial mechanisms for amplifying the solar signal's influence on climate have been suggested. Among these, it has been suggested that changes in EUV radiation are tied to ozone (Haigh 1994), to changes in storm-tracks and atmospheric circulation (Bromage & Butler 1997), or changes in the earth's global electric circuit (Tinsley et al. 1989). However so far, the possible causal role of each mechanism remain ambiguous at best. Another mechanism that has received some attention in the past few years was proposed by Svensmark & Friis-Christensen (1997). They studied satellite cloud cover data from the International Satellite Cloud Climatology Project (ISCCP) and measured a 3-4% greater cloud cover at solar activity minimum. They argued that the source of the excess cloud cover is the relatively greater galactic cosmic radiation (GCR) at activity minimum which arises from the sun's magnetic field being weaker at activity minimum and, thereby, being less effective in shielding the earth from cosmic radiation. According to their argument, the relatively greater cosmic radiation creates relatively more ions, which somehow have a correspondingly greater cloud-seeding effect. But the true amplification mechanism is not yet clear, and this is why it is important to determine global measures, and their temporal evolution, of the terrestrial atmosphere, like the earth's reflectance and greenhouse gas spectrum.

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