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THE CONTROVERSIAL SUN

ROGER K. ULRICH
Department of Astronomy, University of California at Los Angeles, Los Angeles, CA 90024

ABSTRACT The sun serves as an important test case for a variety of problems related to stellar structure and evolution as well as fundamental physics. The sun also influences the terrestrial environment through its varied outputs. These two aspects of the solar interior combine to generate a surprising level of controversy for such an inherently simple star. I review three topics each of which is the subject of some degree of controversy: 1) the solar neutrino problem, 2) the status of modeling and observational efforts to understand the solar cycle of activity and 3) observational efforts to detect and identify solar $g-$modes.

Keywords: Solar Neutrinos, Solar Activity Cycle, $g-$mode oscillations

INTRODUCTION

The title of this review which was assigned by the scientific organizing committee is perhaps surprising. As a middle-age main sequence star of modest mass, the sun is an unlikely candidate for controversy and would be considered one of the dullest astrophysical objects were it not the center of our solar system. There are two basic reasons that the sun is able to generate controversy: it is the primary source of energy for our planet earth and its proximity allows a level of detailed examination unique among the stars. These two factors motivate much of solar physics — we know the sun is not perfectly stable and want to estimate how it might change and we can use the relatively simple state of the solar interior to test theories under conditions not found in terrestrial laboratories. In this review I discuss three topics which are currently under active discussion in the community — the solar neutrino problem, observations and theory of the solar cycle of activity and the search for solar $g-$mode oscillations. Aspects of each of these topics remain unsettled and controversial.

SOLAR NEUTRINO OBSERVATIONS

The "solar neutrino problem"

The sun is a site to test physical theories under conditions not readily attainable in terrestrial laboratories. The best known test of our understanding of the supposedly simple physics of the solar interior has been through the observations of the neutrino capture rate on ^{37}Cl carried out by Davis (1978, 1987, Davis *et al.* 1989) in the Homestake gold mine. These observations have resulted in "the solar neutrino problem" in which the observed rate of capture of neutrinos of 2.1 ± 0.3 SNU (Rowley, Cleveland & Davis 1985) has been roughly a factor of $3\frac{1}{2}$ smaller than the predicted rate of 7.4 ± 2.8 SNU (Bahcall &

Ulrich 1988, Bahcall & Pinsoneault 1992, the ± 2.8 here is a 3σ error). The last reference above contains a detailed comparison between the theoretical results of Sienkiewicz *et al.* (1990), Sackmann *et al.* (1990) and Turck-Chièze *et al.* (1988) with the result that when each calculation is corrected to the same input physics, the predicted counting rates disagree by less than 3%. Reported results normally show a larger range than this because different investigators choose different best values for the uncertain parameters. The uncertainty in the theoretical counting rate is defined as an equivalent 3σ error largely because some of the quantities such as the opacity do not have an experimentally measured error.

For many years the ^{37}Cl experiment was the only direct probe of the deep solar interior and it provides just one measured quantity. With a single quantity a variety of mechanisms could be proposed to resolve the discrepancy between theory and observation. In part because of this long-standing discrepancy, a number of additional experiments to measure solar neutrinos are either being planned, under development or are in progress. Most significantly in the last category is the Kamiokande II Collaboration from which a positive detection is now available (Hirata *et al.* 1989, 1990a,b, 1991). This experiment uses a large purified water tank with photomultiplier tubes on the walls to detect the Cherenkov radiation from electrons recoiling from a neutrino-electron interaction. The Kamiokande II result is summarized by the equation: $r_{e-\nu} = [0.46 \pm 0.05(\mathrm{stat}) \pm 0.06(\mathrm{syst})]$ where the ratio $r_{e-\nu}$ is given by:

$$r_{\nu-e^-} = < \sigma\phi >_{\nu-e^-} / < \phi\sigma >_{\mathrm{standard}} .$$

<u>Theoretical and experimental errors</u>

It can be misleading to discuss both neutrino experiments simultaneously due to the way that the Kamiokande II scattering experiment have reported their results as a ratio $r_{\nu-e^-}$ of the observed rate to the predicted rate from a standard solar model. Theoretical uncertainties from the standard model are not included in the ratio; however, when the standard model is changed so must be the quoted value of $r_{\nu-e^-}$. This adds uncertainty to the quoted $r_{\nu-e^-}$ and reduces the significance of the difference between the observed value of $r_{\nu-e^-}$ and unity. In order to achieve a uniformity of presentation and illustrate the important point that the relative values of r for different experiments change in a correlated way, I express the results of the ^{37}Cl experiment in the terms of $r_{^{37}\mathrm{Cl}} = < \sigma\phi >_{^{37}\mathrm{Cl}} / < \sigma\phi >_{\mathrm{standard}}$ which for the current best numbers given above is $r_{^{37}\mathrm{Cl}} = [0.28 \pm 0.04]$. As with the $\nu - e^-$ experiment this experimental range does not include the theoretical errors.

The above two experiments at present have the best established results. Two experiments using ^{71}Ga as the target nucleus are in the early stages of operation. Predictions for this target nucleus include a large counting rate from the $p - p$ neutrinos which are not sensitive to the details of the solar model. The early results for one of these, the SAGE experiment, give a capture rate of 20^{+15}_{-20}(stat) $\pm$ 32(syst) SNU as compared to a predicted counting rate of 128^{+19}_{-16}SNU. As a ratio to the standard model this result can be expressed: $r_{^{71}\mathrm{Ga}} = < \sigma\phi >_{^{71}\mathrm{Ga}} / < \sigma\phi >_{\mathrm{standard}} = [0.16^{+0.12}_{-0.16}(\mathrm{stat}) \pm 0.25(\mathrm{syst})]$.

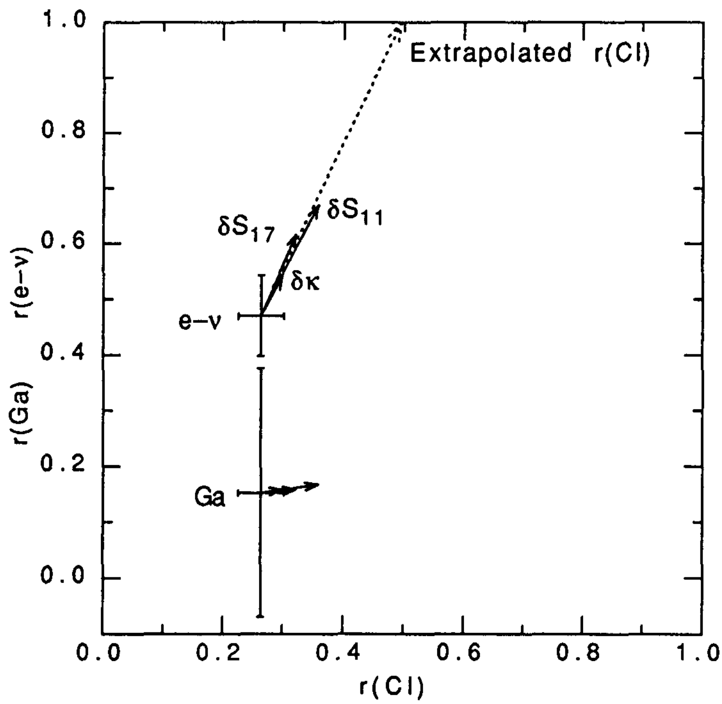

Fig. 1. This figure shows the ratios of observed counting rates to theoretical counting rates as computed from a standard solar model. Three different experiments are shown in this figure with the well established case of the ^{37}Cl serving as the reference. The error bars shown are just for the observations and do not include errors in the standard model. Theoretical errors are shown by the three solid arrows which represent 3σ changes in the r's resulting from the three most important theoretical uncertainties. This figure illustrates that errors in the standard model produce correlated changes in the r's. The dashed arrow indicates the direction and location of the extrapolated point where a change in the standard model would produce agreement with the $\nu - e^-$ scattering experiment. Note that the desired value of unity for the ^{37}Cl experiment is well away from the extrapolated point.

Neutrino propagation

Bahcall & Bethe (1990) have argued that the Kamiokande II result combined with the Homestake result probably requires a modification of the standard electroweak model with zero neutrino masses. The kernel of the argument is that the e-scattering Kamiokande II experiment has a threshold of about 7.5 MeV and is more dependent on the ^{8}B neutrinos than is the ^{37}Cl experiment. This means that in general for a change in some solar model parameter such as the $p-p$ or ^{7}Be$(p,\gamma)^8$B cross-section, the changes in the two r values will be

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related by $|\delta r_{\nu-e^-}| > |\delta r_{^{37}\mathrm{Cl}}|$. Since $r_{^{37}\mathrm{Cl}} < r_{\nu-e^-}$ a model based on a modified solar structure cannot yield unity for both r values simultaneously. Figure 1 shows this quantitatively where the r values for all three experiments are plotted with their experimental errors. The three arrows illustrate the changes in the r values which are brought about by taking $S_{1,1}$, $S_{1,7}$ and opacity variations to have their equivalent 3σ errors in a direction which goes to bring all the r's toward unity. The extrapolated point where $r_{\nu-e^-} = 1$ leaves $r_{^{37}\mathrm{Cl}} = 0.5$ which is significantly different from unity according to the errors of this experiment. Within the quoted detection rates and their errors this result is quite robust.

The strong correlation between changes in the different r's comes from the fact that the shape of the solar neutrino energy spectrum is not modified substantially by a change in the solar model. Only the relative number of each type of neutrino is modified and not the detailed energy dependence of each type. This is especially important for the ^{8}B neutrinos which dominate the counting rates for both the $\nu - e^-$ and ^{37}Cl experiments. Only by modifying the energy dependent shape of the ^{8}B neutrino flux can the r's be moved off the straight lines on Figure 1. The MSW effect (Mikheyev & Smirnov 1986; and Wolfenstein 1979) accomplishes this modification because according to this model the electron neutrinos ν_e emitted at the solar center are converted into a second flavor in an energy dependent manner. On the basis of this model the flux of neutrinos at the detector $(\phi_{\nu_e})_{\mathrm{detector}}$ is related to the flux at the source reaction $(\phi_{\nu_e})_{\mathrm{source}}$ by:

$$(\phi_{\nu_e})_{\mathrm{detector}} = (\phi_{\nu_e})_{\mathrm{source}} \exp(-\frac{C_{\mathrm{jump}}}{E})$$

where the value of C_{jump} is given by:

$$C_{\mathrm{jump}} = \pi \left| \frac{1}{n_e} \frac{dn_e}{dr} \right|^{-1} \Delta m^2 \sin^2\Theta_V \ ,$$

n_e is the electron density in the sun, Δm^2 is the square of the mass difference between the neutrino flavors and Θ_V is the neutrino mixing angle in vacuum. Bahcall and Bethe fit the ^{8}B result by choosing:

$$C_{\mathrm{jump}} = 10.5 \pm 5.5 \ \mathrm{MeV}$$

Since the value of the electron scale height is not model dependent, the value of C_{jump} then leads to:

$$\Delta m^2 = 1.0 \times 10^{-8} \sin^{-2}\Theta_V \ \ \mathrm{eV}^2 \ .$$

The modification of the high energy spectrum implied by this model is detectable by the Kamiokande experiment but at present the observational errors are too large to yield a constraint.

THE SOLAR CYCLE

$\alpha - \omega$ dynamos and internal rotation

The relative quiescence of the sun allows us to take the stability of the sun as assured yet we do not satisfactorily understand the sun's magnetic cycle in which any variability must certainly be rooted. The solar cycle of activity is a complex process. Throughout each cycle sunspots and magnetic fields appear in a well-known pattern which is reasonably regular from one cycle to the next. This pattern has been the subject of many dynamo model studies which range from the semi-empirical, kinematic ones like the $\alpha - \omega$ model of Babcock (1961) and Leighton (1964, 1969) or more fundamentally based models like the calculations of Gilman & Miller (1986) and Glatzmaier (1984, 1985a,b). The primary distinction between kinematic and dynamic dynamo models is the treatment of the velocity field — in the kinematic models it is assumed as input whereas for the dynamical models, the velocity field is part of the modelling process. Reviews of dynamo theory with discussion of such issues have been given by Parker (1979), Krause and Rädler (1980), Gilman (1986) and Levy (1992).

Helioseismology now permits the measurement of the sun's internal rotation law and this new data provides either a critical check on the validity of the assumptions in the former case or a test of the derived results in the latter case. In fact virtually all kinematic $\alpha - \omega$ dynamo studies carried out prior to the availability of the helioseismology data successfully reproduced the solar cycle by assuming that the rotation rate in the solar convection zone increases inward (Gilman 1986). While there have been a number of studies of the sun's rotation law (Duvall *et al.* 1984, Duvall, Harvey & Pomerantz 1986, Brown *et al.* 1989 and Rhodes *et al.* 1990), the errors in the deductions from these earlier results have been large enough to permit the dynamo models to remain viable. Improved helioseismology data have permitted Thompson (1991), Schou (1991) and Korzennik (1991) to deduce internal rotation laws with smaller errors. Thompson (1991) and Schou (1991) both used the data of Libbrecht (1989) from Big Bear Solar Observatory (BBSO) while Korzennik (1991) used combined data from the Mt. Wilson 60-foot tower project described by Rhodes *et al.* (1990) as well as the BBSO data. Thompson (1990) and Schou (1990) obtain very similar results from the same data base from observations made in 1988 and 1986 while the Korzennik (1991) analysis uses data from 1988 with higher spatial resolution. The Korzennik (1991) analysis loses its ability to probe the latitude dependence of the rotation law due to its use of averages over all observed modes at each value of spherical harmonic degree ℓ. Thompson (1990) only gives results for 1988 while Schou (1990) gives results for both 1988 and 1986. The results from these two authors for 1988 are very similar. Figure 2 shows the rotation curves for 1988 from Schou (1990) in the upper panel along with a comparison between the equatorial results of Schou (1990) and Korzennik (1991) in the lower panel. In addition to the analysis of the combined data, Korzennik (1991) also compared the BBSO and Mt. Wilson data in the interior region where both give valid results. These show very similar depth dependence although the curve based on Mt. Wilson alone lies about 8 nHz below the combined curve shown in figure 2. This difference is larger than the errors. The indicated surface rotation points indicated by the arrows are from the doppler measurements made at the 150-foot tower. These are an extension of the results previously published by Ulrich *et al.* (1988).

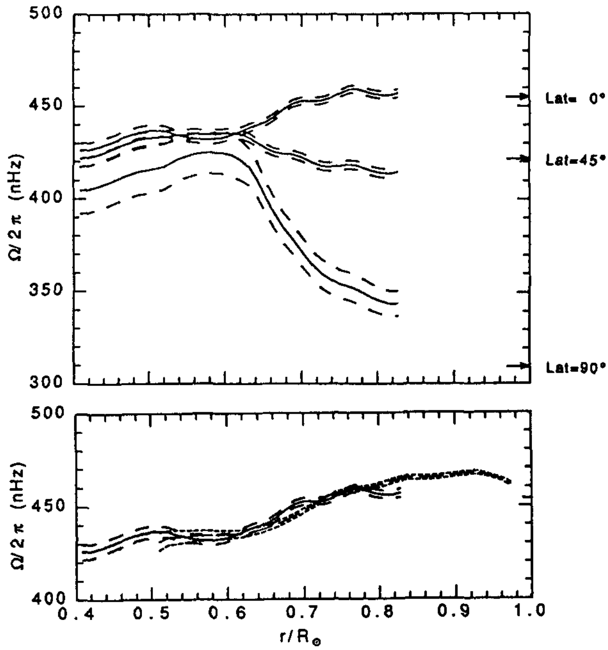

Fig. 2. A comparison between the deductions by Schou (1991) and by Korzennik (1991) of the 1988 rotation curve. The upper panel shows the latitude dependent results deduced by Schou (1991) which are based on observations by Libbrecht (1989). The lower panel repeats the equatorial results by Schou (1991) and also shows Korzennik's (1991) results which are based on combined observations from Mt. Wilson (Rhodes *et al.* 1990) and from BBSO (Libbrecht 1989). In both panels the most probable result is shown as a solid line and the errors of the deduction are indicated by the adjacent dashed lines. For Schou's results the dashes are long while for Korzennik's results, the dashes are shorter.

Based on the above deduced internal rotation pattern, it is clear that models based on the assumption of an inwardly increasing rotation rate must now be rejected. These depend on an increasing inward rotation rate and although there is a small zone with $d\Omega/dr < 0$ just below the surface of Korzennik's curve, this region is far smaller than previously assumed. Boyer and Levy (1992) have used a flat rotation law and shown that the oscillatory magnetic field loiters in mid-latitudes. Such behavior represents a serious deficiency of dynamo theory. The failure of the kinematic $\alpha - \omega$ dynamos as a result of the new helioseismology data is a manifestation of the lack of constraints from the full system of MHD equations typical of the kinematic approach. More fundamentally based dynamic models as discussed by DeLuca & Gilman (1991) generally produced dynamo behavior incompatible with the solar dynamo. Alternative ideas have been discussed by Gilman, Morrow & DeLuca (1989). Durney, DeYoung & Passot (1990) and DeLuca & Gilman (1991) have argued that the solar dynamo operates at the base of the convection zone. Recently a kinematic model based on the observed constraints of the solar velocity field which uses meridional

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circulation in place of the ω gradient has been developed by Wang, Sheeley & Nash (1991, WSN hereinafter). Since this model does not rely on a gradient in ω, many of the degrees of freedom associated with the $\alpha - \omega$ models are avoided. This model includes several other changes to the Leighton (1964, 1969) description of the kinematic dynamo for which reference is best made to the WSN paper.

Meridional circulation

The WSN model produces stable oscillations only for surface meridional flow at a rate of roughly 10 m/s and a return subsurface flow of about 1 m/s. While some questions about the nature of solar velocity observations remain, the analysis by Ulrich *et al.* (1988) which extends the earlier results of Duvall (1979) and Howard & LaBonte (1982a) indicates there is little doubt about the reality of an effect which very strongly resembles meridional circulation. The Ulrich *et al.* (1988) analysis derives the meridional circulation velocity by comparing the north-south trend of limb shift to the east-west limb shift. Points are paired in the east-west direction to cancel solar rotation and when the observed magnetic field in λ5250 exceeds 20 gauss for either point, both points were not used.

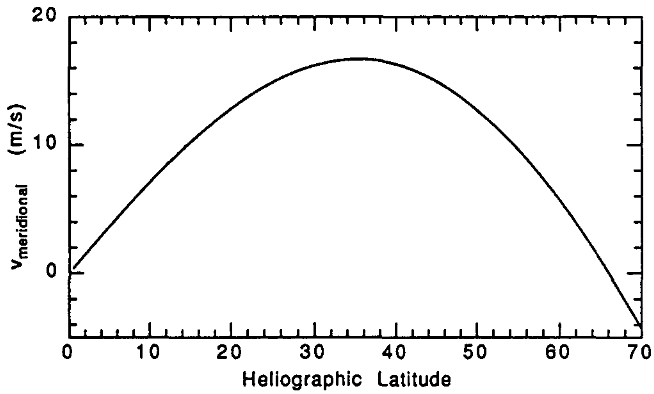

Fig. 3. The meridional circulation law determined from the Mt. Wilson 150-foot tower synoptic velocity observations. This law provides the baseline velocity pattern against which deviations are studied below. The velocity shown here is parallel to the local solar surface. Deviations from this law are calculated including projection effects and the apparent tilt of the solar axis of rotation.

In Ulrich *et al.* (1988) we discussed the meridional circulation for the entire 21-years available at that time. The data prior to 1982 had been influenced by a less well controlled entrance slit assembly and exhibited a substantial time dependence. Following the upgrade of the entrance slit assembly in 1982 we noted that much of the variation ceased but due to the declining phase of the solar cycle this could have been a result of less activity on the solar surface. With additional data we are now able to state that the meridional circulation pattern is relatively stable and has not shown continuing large variations. Figure 3 shows the average meridional circulation law which we have now fixed so that we can study deviations in a separate format presented below. This circulation law is appropriate to λ5250 and may not apply to other lines. Deviations from this law are significant but are at the 20% level instead of the factor of 3 level found in the pre-1982 data. This circulation law is generally consistent with the WSN assumptions although it does differ in detail. For the purpose of the kinematic calculations of WSN this circulation law can be regarded as consistent with their model although it would be desirable to examine the consequences of including our current rotation law. Note however that we do not have reliable observations of the circulation rate near the poles due to foreshortening and the difficulty of removing the effects of scattered light.

Although doubts have been expressed by Gilman (1992) that the meridional circulation is a result of material motion, only by invoking a limb shift function which depends on latitude could this circulation velocity be absent from the solar surface. There are only two ways that high latitudes differ from lower latitudes: their higher level of magnetic activity and their lower centripetal acceleration. Since magnetically affected points are not used and the meridional circulation is present during 1986 when there was little activity, the centripetal acceleration difference is the only remaining distinction and this effect is so small that is unclear how it could affect the line formation process. I conclude that material motion in the form of meridional circulation is the most likely explanation for the limb shift difference.

Comparison of the WSN dynamo to observations

The dynamo model of WSN assumes symmetry between the northern and southern hemisphere and provides the time dependent magnetic field pattern for only one hemisphere. In their publication they show the time dependence over a number of full magnetic cycles after the dynamo has stabilized and compare the results with the data from the Wilcox Solar Observatory after artificially extending that data set to one full 22-year cycle. The Mt. Wilson synoptic program now has 24 years of fully reduced data which can be compared to the WSN model without extension. Since the model does not include any longitudinal information and has been symmetrized, we have averaged the magnetic field as a function of latitude over each solar rotation and then multiplied the southern hemisphere by -1 and added it to the northern hemisphere. The publication by WSN includes figures which show the time and latitude dependence of the magnetic field in an overly compressed format. The authors of that paper have kindly provided a modified display of their model in a format which permits a more satisfactory comparison to the observations.

The WSN model results are shown in the top panel of figure 4. Nearly matching observed results are shown in the middle panel of this figure while a more natural display of the observed magnetic field is given in the bottom panel. The observed fields over this extended period of time include some systematic effects at the 20- 40% level as a result of changes in the instrument calibration procedure. Prior to 1982 the fields should be multiplied by 1.4. Between 1982 and April, 1987 a variable factor between 1.2 and 1.4 should be applied. Overall due to saturation in the λ5250 line the observed field in these plots needs to be multiplied by a scale factor change of 3.5 (Ulrich 1992). Due to the fluxtube character of the solar field and the low spatial resolution of the observations, the absolute magnitude of the field is not easy to compare to a theoretical model. Within the above limitations of the observations, the agreement between the

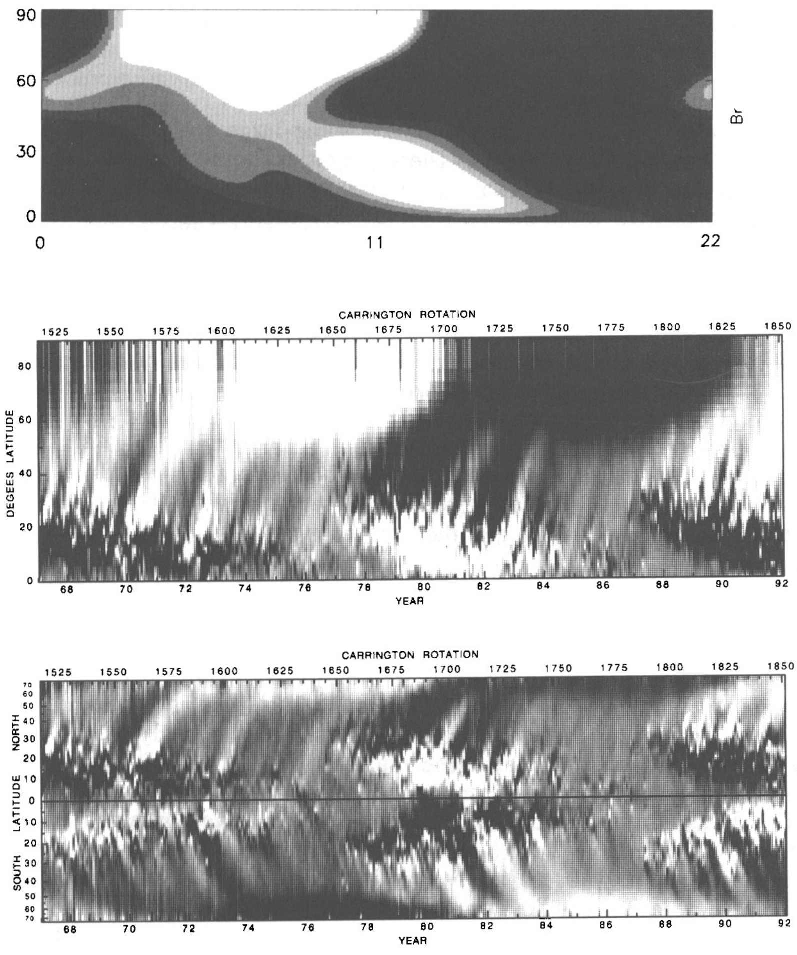

Fig. 4. Comparison of the Wang, Sheeley & Nash (1991) dynamo model to 24 years of magnetic observations from Mt. Wilson. The top panel gives the WSN model for B_r from their figure 1. The time interval shown is 22 years. The center panel gives the observations for 24 years after folding the north and south hemispheres together in an antisymmetric manner. Each resolution element in the center panel plot represents a bin of latitude width originally 1/34th of the projected solar diameter and temporal duration of one equatorial solar rotation period. The pixels have been stretched in latitude to match the WSN format. The bottom panel shows the unfolded average magnetic field without the latitude stretching. This panel indicates that some of the distinct features of the middle panel actually are found only in one hemisphere while others are more nearly antisymmetric.

model and the observations is quite striking and indicates that this approach to the solar dynamo is promising. The primary deficiency in the model is the lack of the strong surges of the magnetic field toward the poles as were seen in 1970-72, 1981-83 and which appear to be starting again this year. We have looked for a corresponding change in the meridional circulation velocity and do not find any clear signal.

Large scale velocity details

Associated with the solar cycle should be some large scale velocity patterns. Some dynamo theories indicate that these velocities should have the form of giant cells in the shape of a banana shaped roll (see for example Gilman & Miller 1986 and Gilman, Morrow & DeLuca 1989). In fact the search for such large scale patterns is especially difficult because their long lifetime and spatial extent over the solar image makes it easy for systematic instrumental effects to masquerade as solar signals. Removal of systematic instrumental effects can very easily alter or remove the largest scale velocities. There is also the effect of magnetic fields on both the properties of the spectral lines and the dynamics of the material. Bogart (1987) has discussed this last problem while Ulrich (1991) has shown that a very good correlation exists between a large scale downward flow of matter and the absolute value of the magnetic field. Scherrer *et al.* (1986) concluded that they could not find giant cell velocities because of the confusion from the magnetic effects. High spatial resolution observations by Title *et al.* (1987) show that the magnetic field modifies the properties of the velocity field in a fundamental way.

The only large scale velocity pattern in addition to the differential rotation and meridional circulation found in the solar data is that of the torsional oscillations originally discovered by Howard & LaBonte (1980). This velocity pattern is not found in the dynamical dynamo theories but has been discussed in a qualitative way by Snodgrass & Wilson (1987). An important case of the difficulty of correcting systematic effects is that of the study of the torsional oscillations where there was a disagreement between LaBonte & Howard (1982b) who found two features in each hemisphere and Snodgrass (1985) who found only one. The LaBonte & Howard (1982b) results may have contained an artifact from the fitting function used to correct for systematic effects. In order to avoid such artifacts, we now use a procedure in which all differential rotation and meridional circulation coefficients are held fixed based on their values derived from an average over the solar cycle ending in 1985. The only parameters which are now adjusted for each observation are the overall rotation rate and the scattered light corrections.

Beginning in 1986 the Mt. Wilson synoptic program has been pursuing a program of regular observations throughout each day instead of just once per day as was the case previously. We refer to this effort as the "fast-gram" program because we have modified the usual setup to use a larger entrance aperture and a faster scanning speed. The purpose of the larger number of observations is to reduce the noise in the average velocity which results from the supergranulation and 5-minute oscillations. Ideally the solar velocity should be sampled continuously so that these more rapidly varying velocities would cancel. In our case we are only sampling the velocity field at intervals varying between 30 minutes and several days so that the velocity from both oscillations and supergranulation is essentially random. The net effect of these rapidly varying velocity fields then decreases as $N^{-1/2}$ where N is the number of redundant observations. Due to this nature of the cancellation, we obtain a reduction by factor of three in the effect of these velocity fields with 10 redundant observations but would have to make 100 redundant observations to achieve another similar reduction. Each observation is set up individually and reduced individually rather than as an automated image sequence. Consequently, the practical maximum has proven to be just over 20 observations in a single day. Even an automated observing sequence would only improve this number slightly and would introduce the penalty of poorer calibration. With 15 to 20 observations we have in fact realized the anticipated reduction in the noise effect of the rapidly varying velocity fields and are now able to study the torsional oscillations and meridional circulation in detail over the time period of 1986 to present. There has been a modest improvement in the quality of the magnetic observations as a result of the additional data but because there is no analogue to the oscillations for the magnetic field, the gain in noise is not crucial.

The results of the fast-gram program are shown in figure 5. The velocities have been resolved into zonal and sectoral components where the zonal velocities are parallel to the solar equator and represent deviations from the steady differential rotation rate and the sectoral velocities are parallel to lines of constant heliographic longitude and are a combination of any residual downdraft effect from magnetic regions, giant cells if present and variations in the meridional circulation rate. This resolution was made using the method described by Ulrich *et al.* (1988). One feature of the algorithm not mentioned in that earlier paper is the fact that points for which the absolute value of magnetic field exceeds 20 gauss in $\lambda5250$ are omitted from the calculation. This test should prevent the bulk of the magnetically induced motions from influencing the results however, there may be some effect from weaker fields which are included. In order to obtain a result which is sensitive primarily to the largest scale motions, the circumference of the sun is divided into bins 60° wide in longitude and the average zonal and sectoral velocity within the bin is computed from equations (11) and (12) of Ulrich *et al.* (1988). The resulting averages are then plotted as a function of the time of the central meridian passage of the bin center. Each point includes all observations for which the bin was visible during that particular solar rotation and is thus an average over roughly 10 days.

The top panel of figure 5 shows the zonal velocity with the grey-level plot being set up so that full black denotes 7.5 m/s faster than average rotation and full white denotes 7.5 m/s slower than average rotation. The torsional oscillation pattern is very clear in the dark diagonal band approaching the equator. The peak of this rotation enhancement moves in a straight line versus time on this plot and is surprisingly smooth. The previous torsional oscillation results which did not have the benefit of the fast-gram data suggested a much more chaotic pattern. Successive Carrington rotation numbers are indicated along the top of each panel and assist in the search for periodic effects such as might be the signature of giant cells. The only feature which readily appears is the series of black/white patches near the north pole between 1986 and 1987.5 and again near the south pole between 1990 and 1991.5. These represent a polar crossing flow. The sectoral velocities described below also show evidence of this flow and furthermore the phasing of the approach velocity is consistent with the phasing of the zonal velocity. The highest latitudes in 1991 begin to show an increase in the rotation rate that may be the beginnings of the next torsional oscillation

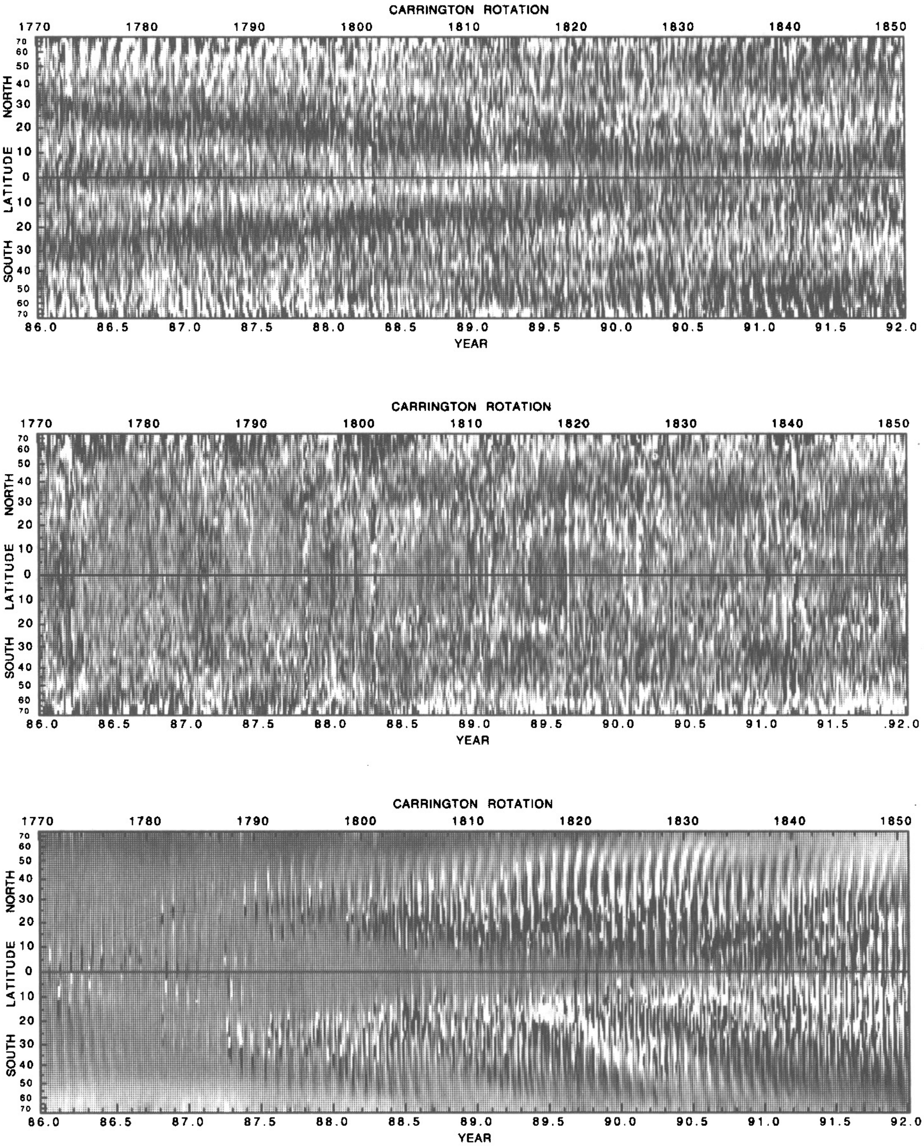

Fig. 5. This figure shows the results of the "fast-gram" program at Mt. Wilson. Longitudinal information is retained through the use of bins 60° wide. The top panel gives the zonal velocity which is the change in rotation rate. Black → 7.5 m/s faster than average rotation, white → 7.5 m/s slower than average rotation. The middle panel gives the sectoral velocity which corresponds to changes in the average line-of-sight velocity. Black → 7.5 m/s approach velocity, white → 7.5 m/s recession velocity. The bottom panel gives the magnetic field averaged over the same longitude bins.

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band. At the same time the remnants of this cycle's rotation enhancement band have not dissipated near the solar equator. Thus there appear to be two torsional oscillation bands of enhanced rotation present at the same time.

The middle panel of figure 5 shows the sectoral velocity. The encoding of the velocity has receding velocity of 7.5 m/s as white and approach velocity of 7.5 m/s as black. The regular occurrence of noisiness in the January to March time of year is related to the typical weather conditions which reduce the number observations that we can make. During the period of low activity in 1986, there is little evidence of any velocity. Based on the appearance of this figure, giant cells must have a surface velocity less than about 2 m/s. As solar activity begins in 1988, a large scale pattern appears in this figure with a structure which is not expected from leakage of the directly induced downdraft velocity from the magnetic fields which are less than our limit of 20 gauss. Because we do not alter the global meridional circulation solution, the approach velocities at high latitude represent an actual change in the spectral line position rather than a shift in the global fit. Interpreted literally, the motion at this phase represents a net flow of material towards the regions of greatest activity with excess poleward motion at low latitude and a reduction in poleward motion at the highest latitude. Note however that maximum velocities represented by these deviations are smaller than the meridional circulation velocity shown in figure 3.

Finally the bottom panel of figure 5 shows the magnetic field averaged over the same bins as the upper panels. This figure is very similar to the bottom panel of figure 4 except that some longitude information is now retained. This longitude information is actually of interest because the tilt associated with the generation of the polar field is quite evident. In fact the gradual rotation of the position angle of the bipolar regions clearly plays the anticipated role in the reversal of the solar dipole field. Also of considerable interest is the fact that the very quiet region below the zone of solar activity follows the position of the maximum in rotation rate enhancement seen in the top panel. This maximum seems to be the boundary between the active and quiet parts of the solar surface.

After differential rotation, the torsional oscillations are the most prominent large scale velocity feature on the solar surface. Dynamic dynamo models do not show such a pattern of motion and this may be a clue as to deficiencies in these models. The regularity of the torsional oscillation pattern shown in figure 5 indicates that some underlying organization is present in the solar interior. Previous torsional oscillation maps were too noisy to permit the recognition of this regularity.

THE SEARCH FOR g-MODES

General considerations

The field of helioseismology has matured to the point where its controversies are at a very detailed level as long as only the five-minute band data is used. It is in the search for the g-modes that much controversy as well as promise remains. The value of detection and identification of a large number of g-modes could be enormous. Because the modes should have great purity due to the concentration of their kinetic energy in the quiet deep interior, the frequencies may be measurable with very great precision. This in turn will provide unprecedented quality information about the solar interior structure and dynamics. In addition,

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the gravity wave frequency is sensitive to the density and pressure gradients and will be strongly influenced by the presence of any irregularities in composition that may be left from the time of solar system formation.

In a general way the need for observations of $g-$modes to analyze the solar interior is well known. Figure 2 illustrates the problem. This figure shows the rotation rate only for those parts of the solar interior where the inversion is reliable. The plot stops at $r = 0.4R_{\odot}$ because the errors become too large due to the restriction of the available data to the $p-$modes alone. The inversions for the sun's internal sound speed also show a growth in the error for the same part of the interior although present results are able to distinguish between models and the sun at an interesting level (Gough 1984, 1986, Christensen-Dalsgaard *et al.* 1985, Brodsky & Vorontzov 1988, Vorontsov 1988, Thompson 1991). Hill, Gao and Rosenwald (1988) discussed an inversion method of studying composition gradients through their effect on the mean molecular weight.

Mode identification

The identification of those parts of the observed signal which correspond to globally coherent solar oscillations has proven to be a very challenging part of studying low frequency solar oscillations. This task is called mode identification. It is complicated by the absence of any simple tools for distinguishing between solar oscillation modes and other non-coherent sources of signal such as terrestrial atmospheric effects, instrumental drifts, solar supergranulation and solar active regions. Depending on the details of the observational dataset, each of these could produce a time varying signal which is comparable to what is observed. Theoretically the solar oscillation modes should have such a large number of frequencies that their spectrum should not be superficially different from a noise spectrum. This is in marked contrast to the situation with the $p-$mode oscillations where the solar signal stands out clearly against the noise background.

Three means of distinguishing between a solar mode signal and a noise signal have been used: a) mode frequencies should have long term stability, b) mode frequencies should obey asymptotic relationships, and c) the highest amplitude peaks in the power spectrum may be of solar origin. Of these criteria, only a) is reliable due to the high inertia of the $g-$modes. Identifications based on criteria b) and c) have been published by Scherrer and Delache (1983), Frölich and Delache (1984), Isaak *et al.* (1984), Pallé and Roca Cortés (1988) and van der Raay (1988). Application of criterion a) has led to a serious questioning of the identifications. Henning and Scherrer (1988) compared successive years of applying the procedure of Scherrer and Delache (1983) and found that few of the mode frequencies agreed. Garcia, Pallé and Roca Cortés (1988) carried out a cross-correlation between the power spectra from the first and second half of the 1984 to 1987 and found no correlation. A good discussion of $g-$mode observations and analysis has been given by Pallé (1991).

Although there has been some general agreement between the asymptotic parameters derived from all these observations, the frequencies found by the different groups do not agree with each other to within the errors of measurement. Fossat *et al.* (1988) have provided a very useful discussion of the statistical testing for $g-$modes. Hill *et al.* (1991) give a very extensive discussion of these searches for $g-$modes as well as the studies by the Santa Catalina Laboratory for Experimental Relativity by Astrometry (SCLERA) and studies of the 160-minute oscillation. I will not review the SCLERA results here because many of the essential publications of the data from this effort are not generally available and because the power spectrum sample published by Bos and Hill (1983) is very difficult to reconcile with other observations of global solar velocities. First, the internal rotation law provided by Hill, Bos and Goode (1982) from the identified multiplets is in strong disagreement with the $p-$mode results shown above. Second, the amplitudes of the signal seen in the SCLERA system are substantially larger than found in any other global solar oscillations. The coherence analysis by Bos and Hill (1983) indicated that 98% of the power they detect is globally coherent so that essentially every peak in their power spectrum is to be treated as a candidate for identification. The power spectral density (PSD) given by Bos and Hill (1983) for these peaks is equivalent to a velocity PSD of 8×10^5 $(m/s)^2$ Hz^{-1} at a frequency of 465μHz. The integrated sunlight velocity systems give a PSD of 10^2 $(m/s)^2$ Hz^{-1} at this same frequency (Jiménez *et al.* 1988). This difference is attributed by the SCLERA project to the dependence of the eigenmodes on height in the solar atmosphere (see the Hill *et al.* 1992 review for references and further discussion). If the vertical mode structure in the solar atmosphere involved such a large amplification factor, there should be similar differences between spectral lines formed at different depths and in the infrared continuum. Comparisons between the Na and K spectral lines by Isaak *et al.* (1988) and infrared brightening observations by Deming *et al.* (1988) and Kopp *et al.* (1992) do not show any large effects.

Solar noise reduction

The GOLF experiment on SOHO (Gabriel *et al.* 1991) will be a space-based search for low velocity amplitude solar oscillations using a Na resonance cell. One important component of this experiment is a study of solar noise sources with the hope of at least partial compensation for the incoherent or non $g-$mode portion of the solar signal. This is a delicate project due to the risk of removing the $g-$mode signal along with the solar noise. To avoid this risk the compensation for incoherent signals needs be derived from information other than the observed velocity. Following the model proposed by Harvey (1985) for these noise sources, we identify two processes which are major contributors: active regions and supergranulation. In the case of the active regions the magnetic fields and associated line profile changes can provide the needed additional information. Early studies of the global velocity signal by Claverie *et al.* (1982) detected a variation with a 13 day period. These were quickly interpreted by Andersen & Maltby (1983) and Edmonds & Gough (1983) as being the result of the passage of active regions across the solar disk. Both interpretations recognized the fact that the effect depends on the spectral line used for the observations. Also the only effect included in the model was the darkening associated with the sunspot groups and the velocity was derived from the positions and areas of the sunspot assuming the intensity of the line radiation is changed only inside the umbra and penumbra. Both studies were able to account for the observed effects. In particular Andersen & Maltby (1983) model the velocity signal with errors generally less than half the size of the induced changes. The task for modelling the effect for the Na D lines is complicated by the fact that even small magnetic fields can alter the line profile. Studies to develop a reliable model of this effect for the GOLF experiment on SOHO are currently in progress.

The supergranulation is more difficult because its signal is a pure velocity with a disorderly spatial structure. In this case no correlated non-velocity signal is available from which an equivalent velocity correction can be calculated. Unfortunately, the supergranulation is probably the largest contributor of an incoherent signal. The only strategy which might help with the supergranulation is to take advantage of the center-to-limb amplitude dependence and isolate that part of the global signal which comes from the limb. Such a plan might be possible through the analysis of the imaged data from the Solar Oscillation Imager on SOHO.

CONCLUSIONS

It is clear there will continued intensive study of the solar interior. Our understanding of past controversies is improving but as with any field with new techniques of observation, new controversies are generated more quickly than the old ones are put to rest. New solar neutrino observations will clarify the nature of the solar neutrino problem, improved internal differential rotation studies from helioseismology will guide the development of dynamo models and we look forward to a more definitive observational search for the g−modes.

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