GLOBAL MODELS OF INTERMEDIATE TIMESCALE VARIABILITY ON THE SUN

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ABSTRACT

In recent years a number of advances in both observation and theory have increased our understanding of the solar interior and how to model it. For climate studies, the timescale of interest for changes in the Sun ranges from decades to centuries. This paper attempts to highlight some of the theoretical advances that will contribute to the building of global models of the Sun's variability on intermediate timescales and describe what the current constraints on the important components are. Finally a short discussion presenting some implications for input to climate modeling will be presented.

INTRODUCTION

Standard models of the solar interior are constructed using the equations of stellar structure (Chandrasekhar[1]) and provide quite good agreement with the real Sun. They include a number of physical processes such as nuclear energy generation, radiative transfer, ionization, convection, etc. These physical processes are treated on a variety of timescales depending on their influence of the evolution of the Sun to the present epoch. Often approximations are used to establish the influence of processes shorter than the evolution timescale (of order millions to hundreds of millions of years). In addition, the accuracy of models can vary enormously depending on what features are being examined and what the corresponding observational limits are.

The very features that make current standard solar models suitable for studying stellar evolution are also the ones that prevent us from studying its variability on timescales of climatic significance. The key to upgrading current solar models for these studies is in identifying the components that are either missing or treated with inadequate approximations or invalid assumptions. In addition the numerical accuracy of models needs to be examined carefully.

In recent years, a number of advances in the understanding of solar interiors has taken place. Among these advances was the investigation of perturbations to solar models in both the convective efficiency and non-gas components to the pressure. These studies (e.g. Endal, Sofia and Twigg[2]) established guidelines for the type of disturbances that could be tolerated within the Sun, at what depth they were most and least effective, what the surface consequences for the solar radius and luminosity were and most importantly, what the timescale for the influence. Unfortunately they were difficult to constrain and true feedback or interaction between the physical processes could not be accommodated.

The emergence of helioseismology as a very tight constraint on solar models has improved the understanding of solar models in a number of areas, apart from the much higher numerical accuracy that is required. Improvements have been made in the treatment of the equation of state, nuclear reaction rates and cross sections, stellar opacities, surface boundary conditions and the solar chemical composition. In addition these studies have indicated the oscillation modes that sample the interface between the solar radiative and convective regions are particularly sensitive to structure changes and thus are an important constraint on models as will be discussed in later sections.

In addition, advancements in the understanding and modeling of stellar convection, stellar rotation and stellar magnetic fields (to be addressed in the following sections) are setting the scene for substantial improvements in solar and stellar models in the next few years.

INITIAL CONDITIONS

As the components of solar models are improved toward self-consistency one important consideration is the availability of suitable initial conditions for the variability study. Specifically that means a carefully calibrated solar model that has details of internal rotation and large scale magnetic fields that are consistent with known observational constraints. In addition a high degree of numerical accuracy is required; fortunately this aspect is well under control even though the current treatment of certain processes may be uncertain at the 5 to 30% level.

At our present level of understanding, a unique initial model is very unlikely. Thus, it will be important to understand the influence of variations in the initial models. The solar-stellar connection (Sofia and Endal[3]) should provide invaluable information as it has done so far for recent studies of internal rotation (Pinsonneault et. al.[4]). Helioseismology will also play an important role in detecting changes in the internal structure of the initial models.

One aspect of solar variability that is particularly important when attempting to construct global models is the timescale over which certain types of variations occur. A number of empirical studies (such as some presented at this meeting) propose a range of timescales for influencing climate and also suggest particular solar physical features that may be responsible for the variations (in nearly all cases, the solar magnetic field as represented by the sunspot record for example). By including all standard physical phenomena into a global model the timescale of interest then determines what level of approximations may be valid for the models.

ADVANCES IN CONVECTION MODELING

Most of the important timescales for solar variability correspond to the range of timescales that exist in the solar convection zone (which occupies the outer $\approx$ 30% by radius and $\approx$ 2% by mass of the Sun). The current treatment of convection is by use of the mixing length theory (MLT). Although the MLT is adequate for evolutionary models of stars, it has limitations in the treatment of certain physical processes, such as rotation, magnetic fields and ionization which are probably vital to the global models to be constructed. In addition, many of the assumptions of MLT have been under scrunity for many years but without any firm conclusions or a proven replacement theory.

One significant recent advance on this area is due to Chan and Sofia. In a series of papers (Chan and Sofia[5,6,7]) they explored not only the validity of the MLT formalism but attempted to derive expressions for fluctuating quantities (such as temperature, velocity, etc.) in terms of local mean quantities just as the MLT does, but by using detailed models of fully compressible, deep and efficient convection (which applies over most of the solar convection zone).

For example, they found that, in agreement with MLT, that the mixing length does scale with the local pressure scale height and not the density scale height, and that in a region of efficient convection the total heat flux comprises two major components, the enthalpy flux and kinetic energy flux. The enthalpy flux can be roughly computed from the superadiabatic gradient and vice versa. However, in disagreement with MLT, the kinetic energy flux is downward directed for much of the convection zone and is not simply related to local quantities like other MLT relations. In addition the production of kinetic energy can be derived from local quantities but the dissipation of kinetic energy is non-local.

An example of the results from this study is given in Fig. 1 where the covariance of the vertical velocity and temperature fluctuation about the horizontal mean is shown versus the product of the mean vertical velocity and mean temperature. This is an important relationship that does not appear in MLT which assumes that the mean vertical velocity vanishes.

For solar cycle timescales an important variation in the total irradiance is due to the presence of sunspots and faculae on the solar disk. Although it is unlikely that this modulation of the irradiance produces direct changes in the earth's climate, the influence of redistributed heat flow through the solar convection zone on a long enough timescale could well have consequences for the solar structure (radius and luminosity) at the level that would produce secular changes.

The solar convection zone is a very complex physical system and only recently have detailed numerical models of variations in its heat transport been possible. Preliminary results from these studies (Fox, Sofia and Chan[8]) indicate that on small scales the heat flux that is diverted around an area of intense magnetic field does partially re-appear at the solar surface and does not seem to be stored within the convection zone over long timescales (more than tens of thousands of years). There are many uncertainties when considering solar magnetic fields, particularly their internal distribution and it is as yet unclear how important that distribution is for models of solar variability which should depend on more global properties like the total magnetic flux within the solar convection zone, for example.

Fig. 2 shows an example of one simulation from Fox, Sofia and Chan[8]. The horizontally averaged surface flux (in solar units) is shown as a function of time. Once the blocking begins a short relaxation time is evident after which the surface flux oscillates with an time integrated average quite close to the undisturbed value and certainly well above the value that would result from total blocking (represented by the dash line). This simulation is still very idealized and cannot reflect the true solar environment. Nevertheless, important information on the dynamics of diverted heat flow can be obtained.

In this regard it is important to understand what influence a time varying large scale internal magnetic field would have on heat transport (and thus structure) in the solar convection zone. A first principles effort to extend MLT is difficult but an extension to the existing attempt of using detailed numerical models seems straightforward.

The influence of small scale magnetic fields on compressible convection is also a field that is growing rapidly. The concentration of magnetic flux on the solar surface has been evident even in simpler models for quite a while, however more complex features such as magnetic reconnection, the influence of anisotropic magnetic resistivity and the production of Alfven and magneto-acoustic waves are now part of recent modeling efforts (Theobald, Fox and Sofia[9]). Fig. 3 shows two snapshots of a simulation involving magnetic fields, the vector potential in two dimensions just maps out the lines of magnetic force and the velocity vectors are overlayed.

This figure shows magnetic field concentration (where contour lines are close), expulsion (where lines are absent) and magnetic reconnection (compare the two frames and note where single line contours become closed loops).

A detailed understanding of small scale interaction of magnetic fields and convection should aid in our understanding of the important regenerative phase of the solar cycle (and thus the global) magnetic field.

It will be important to ascertain the influence of the latitude dependence of not only solar cycle phenomena but the solar magnetic field in general since the simplification to one dimensional models and thus uniform radius changes would ease the numerical burden on the global models.

MAGNETIC FIELDS

Magnetic fields are perhaps the key to understanding solar variability. The large scale component is certain important for secular changes whereas the small scale component (as manifested by the activity cycle field) seems only important for shorter timescales. However, it is the regenerate phase of the solar cycle, from small scale to large scale that could introduce some randomness into the Sun's global field. The irregular modulations of the solar activity cycle as shown by the sunspot record over two centuries provides some support to this point as does the evidence from other "solar-type" stars that have turned on and turned off their activity cycles over decade timescales (Baliunas[10]).

Magnetic fields are also important as part of the initial conditions for a study of solar variability, as mentioned above. Models have been produced which follow the evolution of various initial magnetic fields in the context of a rotating Sun (Fox[11]). One feature of these calculations is the implied presence of a large scale magnetic field beneath the solar convection zone, see Fig. 4 (Fox and Bernstein[12] Fox, Niznik and Bernstein[13]). One improvement to be added to the present calculation is the combined interaction of internal rotation and a large scale magnetic field in the radiative interior. There is strong evidence (observational and implied theoretical) for the existence of internal differential rotation and large scale magnetic fields in solar-type stars.

One constraint on interior magnetic fields that is yet to be fully developed is helioseismology. Except for very high field strengths (of order MGauss) the direct impact on oscillation mode frequencies is small. However changes in the solar structure (which may be position dependent) due to magnetic fields are likely to produce measureable changes in the oscillation frequencies. In addition there are, as yet still only suggestive, variations of oscillation frequencies (at particular wavelengths) over the solar cycle (Libbrecht and Woodard[14]).

INTERNAL ROTATION

The details of internal velocity motions are a secondary consideration to solar variability since they primarily contribute to other physical features (particularly magnetic fields). Their inclusion in global models is therefore essential for completeness. Fortunately this is one area that has made significant progress in recent years also. After the founding work of Endal and Sofia[15], Pinsonneault et al.[4,16] have provide an increasingly complete understanding of rotating stars (and specifically solar-type stars). These studies also provide a robust framework in which to develop and test the combined interaction of rotation and magnetic fields in solar-type stars. Many of the constraints utilized in these recent studies are also necessary for the study of variability.

One very important result of this study is the implication from more evolved stars that the Sun cannot be rotating as a solid body. Fig. 5 shows the computed periods of rotation for solar-type sub-giant stars, the upper curve is the theoretical prediction of periods if the stars at the solar age were rotating as solid bodies at the solar equatorial rate, the symbols represent observations (which are all upper limits) of those type of stars. The lower curve is the theoretical prediction that allows internal differential rotation, see Pinsonneault et. al.[4] for more details. Recently this argument has become even more convincing from a study of horizontal branch stars (Pinsonneault et al.[16]).

Because the convection zone is an important component for our studies, the treatment of larger scale circulations will need to be improved. At present, for evolutionary purposes, the convection zone (not the interior) is assumed to rotate as a solid body and not have any latitude dependence. The level of detail that may be required in treating rotation, as with the solar dynamo itself, in the context of solar variability is still unclear.

CLIMATE IMPLICATIONS

For the global solar variability models to have a bearing on climate modeling they must have at least two properties; proven accuracy and predictability. Naturally, internal accuracy of the variations is a separate issue from agreement with solar observations. Even if we are limited to a 3 to 5 year predictability (as for empirical solar activity forecasting, Schatten and Sofia[17], Layden et al.[18]) of solar luminosity variations, this should be a significant advance over the present situation for short term climate. For input to longer term climate predictions we must rely on the limited observational constraints that we presently have to calibrate the models.

Global models will primarily both be constrained by and predict changes in the solar radius (on climate timescales) that can be calibrated by luminosity variations. Additional constraints will results from helioseismology networks (because they use both intensity and doppler measurement) and combined irradiance and diameter measurements.

After suitable calibration, predictions can be envisioned once the appropriate global contributors and their timescales are identified.

CONCLUSIONS

It is clear that global models of solar variability are complex, but necessarily so since the phenomena to be explained are beyond the capabilties of current standard models. However, we have identified the essential components that make up such a global model and in addition we are able to model all of these components at either the detailed (small length and time scales) level or the evolutionary level (long length and time scales). The important task of bridging the gap between the two scales is well underway and significant progress has been made in a number of areas. In addition, the development and integration of the model components are quite well constrained by detailed surface observations, the link between the Sun and Sun-like stars and helioseismology.

Of immediate interest are topics such as convection and magnetic field modeling, solar global magnetic fields (in both radiative and convective regions) and using helioseismology to constrain the initial models. We should expect to see substantial progress in these areas in the next few years.

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Fig. 1. Covariance of the temperature deviation and vertical velocity versus the product of the mean temperature and the mean vertical velocity. The different symbols represent variations in the character of the convective layer, such as depth, stratification, etc. so that the implied relation seems valid over a range of conditions.

Fig. 2. Time history of the solar surface output flux (normalized) comparing an undisturbed region with one in the presence of a flux blocking object (like a small sunspot). After an initial relaxation time of about one hour, the surface output flux is within about 1% of the solar value The dashed curve represent the output flux if total blocking had occurred. The oscillation in the disturbed output flux is due to heat diffusion within the flux blocking object, see Fox, Sofia and Chan[8] for details.

Fig. 3. Two snapshots of the contours of the magnetic vector potential overlayed with the velocity vector field in a time dependent two-dimensional simulation of the interaction of convection and magnetic fields near the solar surface. The contour lines represent lines of magnetic force. Regions of intense field are found where the lines are closely spaced, and field free regions are those where the lines are widely spaced. Evidence of magnetic reconnection is also visible by comparing the two frames and can be seen toward the centers of the circulation patterns (closed contour lines).

Fig. 4 Illustration of a typical poloidal field (left hemisphere) and toroidal field (right hemisphere) configuration calculated from the global evolution of an initially dipolar magnetic field, under the influence of internal (differential) rotation, subject to a perfectly conducting outer boundary.

Fig. 5. Surface rotation period of subgiant stars as a function of effective temperature. compared with predictions of solar models including internal rotation (solid) and those assuming solid body rotation (dash). See Pinsonneault et al.[4] for more details.

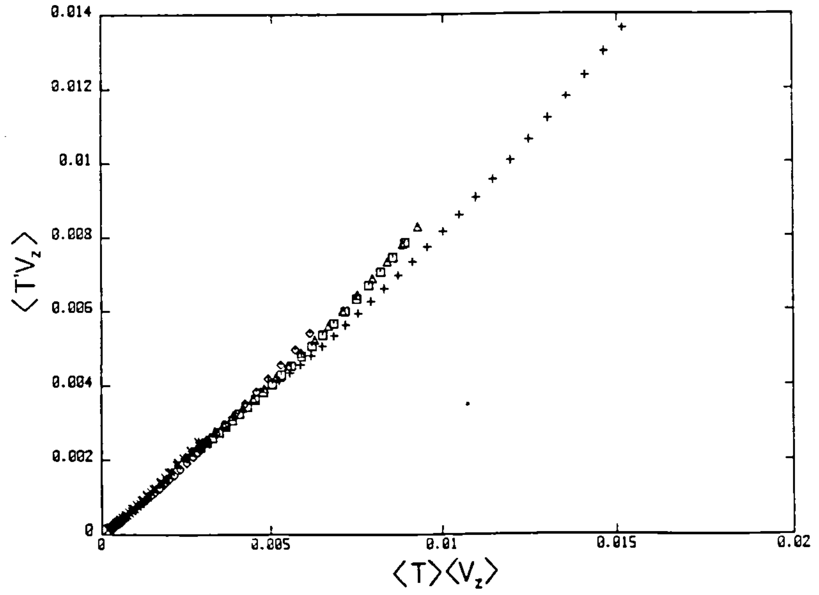
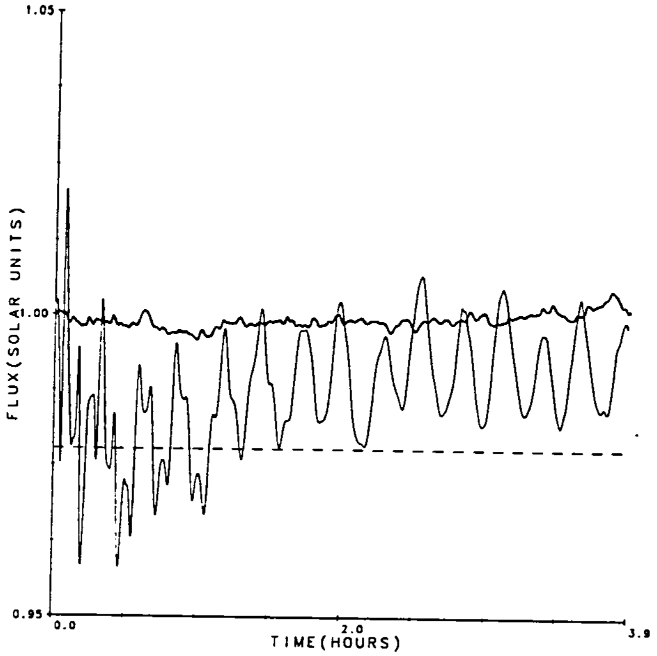


Fig.1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2.0
3.9
TIME(HOURS)

Fig.2

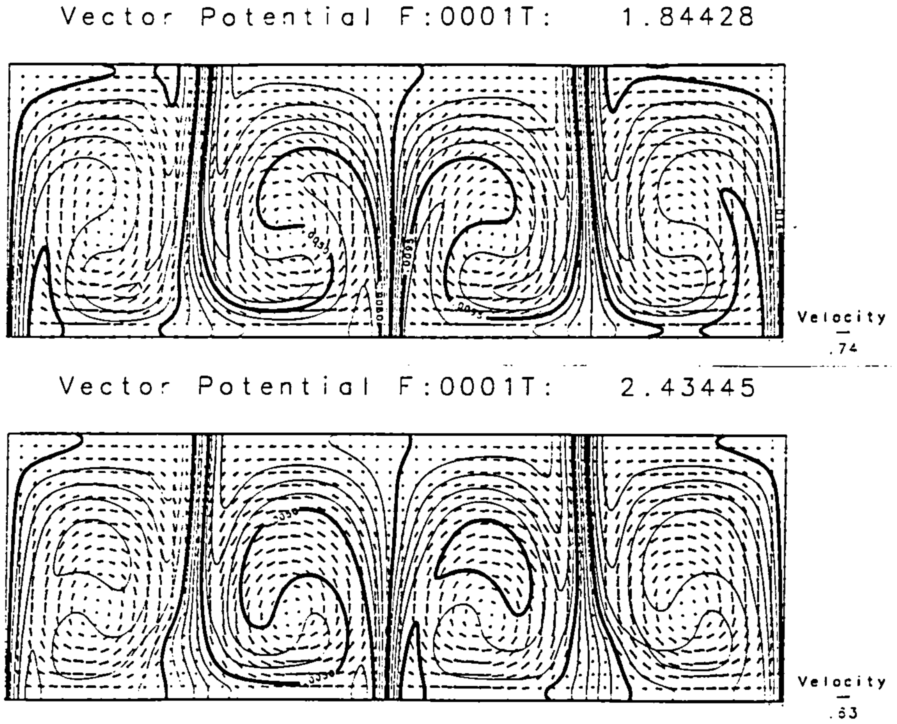
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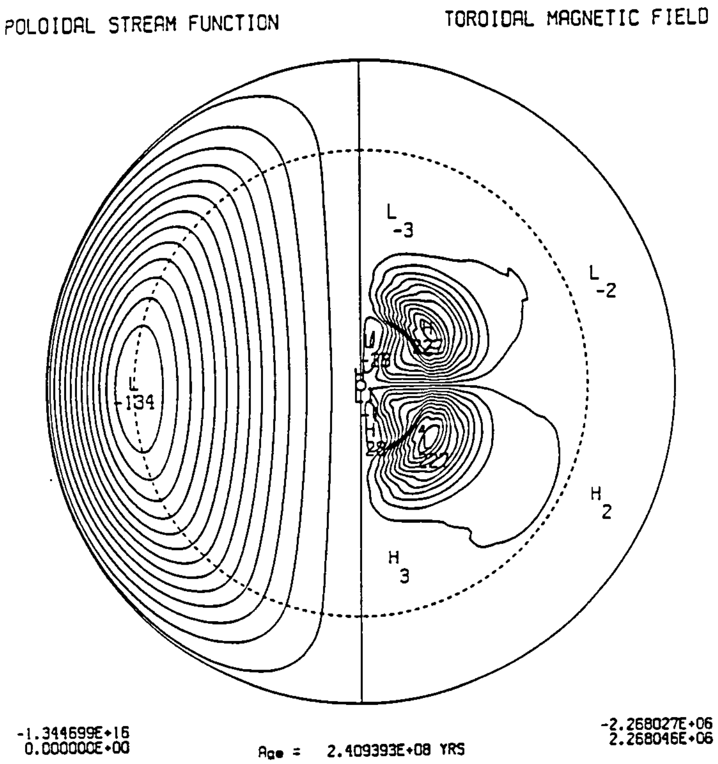
Fig.3

Fig.4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TOROIDAL MAGNETIC FIELD
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L -134
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H 3
H 28
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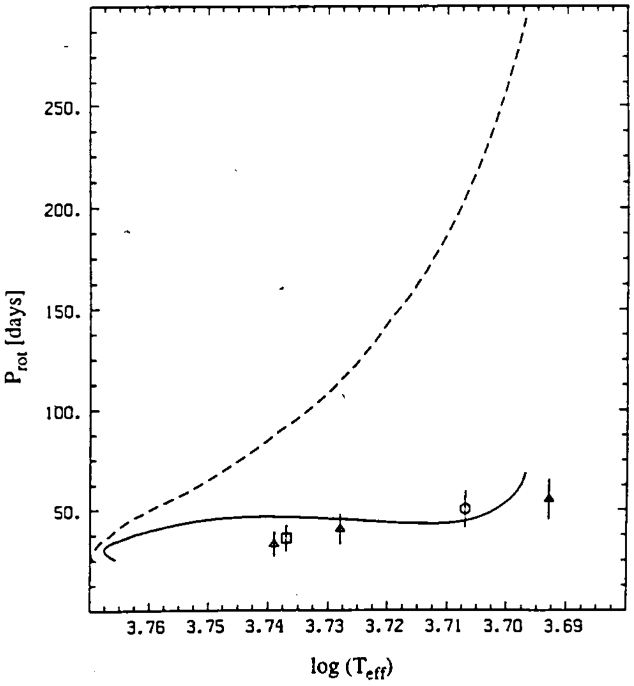
2.268046E+06

Fig.5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log (T_{eff})