BASIC MECHANISMS OF SOLAR VARIABILITY

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I. INTRODUCTION

Understanding and describing solar variability can be pursued in two different ways. One, the taxonomic approach, describes and catalogues the details of each of the manifestations of solar variability separately. The other, the global approach, considers the Sun as a system and deals with the entire ensemble of global solar properties, but with little detail. Whereas the first approach is preferred when information on the detailed behavior of one isolated phenomenon is required, (the rest of the system can be assumed to remain constant), the second approach is employed when completeness and self-consistency of the entire set of phenomena are important, and little guidance on specific physical mechanisms is required. This paper will explore the global approach.

The crudest means of looking at solar variability in the global approach is by means of a general virial theorem which includes magnetic and rotational terms in addition to the usual kinetic and gravitational terms. This treatment is interesting in that it readily shows the inter-relationships between the various global solar parameters. In particular, for the case where rotational and magnetic energy is negligible, it shows that radius and luminosity changes are simply related. The virial approach, however, requires that the system be fully relaxed (including having reached thermal equilibrium), which only applies for timescales far in excess of the year-to-decades timescales important for climatically significant processes. Consequently, it is not very useful for our purposes. On the other extreme of sophistication, we may envision a complete, time-dependent model of the Sun including rotation and magnetic fields valid for timescales between months (the turnover timescale for the convection zone) and billions of years (the timescale for evolution). Such a model would clearly be able to describe the solar variability we are interested in. However, it does not yet exist,and it is not clear whether it could be constructed within the capability constraints of even the fastest computers currently available.

In order to simulate the behavior of a changing Sun in a realistic way, we have used a perturbation analysis (the results are summarized in Endal *et al.* 1985). In this approach, we use a standard solar model and then vary several of the model parameters to mimic the sudden or gradual change of some physical property within the Sun. The evolution following the perturbation is followed in a physically self-consistent way, that is, hydrostatic and thermal processes occur in their normal timescales. This treatment has allowed us to determine the sensitivity of the various global parameters to physical processes affecting the solar interior, and it has guided us in defining the least complex global solar model which can address the question of climatically significant variability. Not surprisingly, magnetic fields play the crucial role. In this paper, I discuss the current status of the model, what we have already learned from it, and the future prospects.

II. THE STANDARD SOLAR MODEL

All physical models involve approximations, and so the best model for a process is the least complex system which properly addresses it. In stellar evolution, the standard model assumes spherical symmetry, and ignores the effects of rotation and magnetic fields. This type of modelling has been the cornerstone of the field of stellar structure and evolution, and it has been remarkably successful in explaining the theoretical basis for the observations of field stars, globular clusters and open clusters as summarized by their H-R diagrams (*cf.*, Schwarzschild, 1958). When applied to the Sun, this model produces a remarkably constant star bent on increasing both its size and luminosity on timescales of billions of years. Of course, the "standard Sun" does not change on a short term, does not rotate, and it has no magnetic activity of any type.

On the other hand, the Sun does rotate, it has a magnetic activity cycle, and its total irradiance does change at least in concert with the activity cycle, as observations carried out by instruments on board SMM (Wilson *et al.*, 1981), Nimbus 7 (Hickey *et al.*, 1981), and ERBE (Lee *et al.*, 1987) have demonstrated. In addition, there is evidence that the solar diameter may be also be changing, at least on timescales on the order of 90 years (Sofia *et al.*, 1985). Such a change would also affect the luminosity. In order to model these phenomena, the standard solar model is inadequate, and an upgraded model must be produced.

III. THE UPGRADED SOLAR MODEL

As we add complexity to our solar model, we must be mindful of following the "least complexity principle," namely, only incorporate into the model those elements that are essential to producing the desired behavior, which in this case is the short timescale variability. Clearly, magnetic effects must be included in order to produce the activity cycle. Moreover, since solar magnetic fields are thought to be produced by a dynamo mechanism, whose operation requires a differentially rotating magnetized flow, rotation must also be included. Finally, since the convective flow is not properly described by the mixing length theory of convection, a more realistic treatment of the convective flows is required. As stated earlier, these elements are in agreement with the results of the perturbation analysis of the standard solar model.

The above additions are extremely complex, but already substantial progress has been made in the implementation of some of the processes, individually. This implementation is described in some detail by Fox (1990), and it is based on research that our group has been carrying out over the past 15 years. For example, the rotating feature of the global code was developed by Endal and Sofia in the mid to late 70's (Endal and Sofia, 1976, 1978 and 1981), and this technique has been considerably extended recently at Yale University (cf., Pinsonneault *et al.*, 1989).

The work on convection has also been carried out by Chan, Wolff and Sofia (Chan and Wolff, 1982; Chan, Sofia and Wolff, 1982, and Chan and Sofia, 1984, 1986, 1987 and 1989). This work has yielded a set of numerical relationships between the thermodynamic and dynamical properties of the flow, which are currently being used for modeling the solar convection zone. Finally, Fox and associates have developed a code to evolve non-reactive global magnetic fields in a differentially rotating solar model; Theobald, Fox, and Sofia (1990) have succeeded in modeling the small scale magnetic interaction with compressible convection.

IV. FUTURE ACTIVITIES

All the elements have been developed, and they now must be joined together in a fully reactive, self-consistent upgraded solar model. The task is not trivial; besides the sheer size of the integrated code, a very broad range of time and space scales are considered at one time. Because of this, the task in its full generality is not likely to be overcome simply by the expanding capability of new computers. The most promising way to proceed is to study the properties of the microphysics (small scale flow, small scale convection, *etc.*) in order to obtain averaged relationships whose effects can be realistically incorporated in the global models without the requirement of a fine space and time mesh which makes their running impossible.

The expanded models must first be tested with a number of stars of different masses and ages to ascertain that the observational properties of star systems are properly reproduced by the new models. The next step is to refine the solar model by means of the large number of observational tools that will become available in the coming years. These tools include the helioseismological observations to be provided by the ground-based GONG project, by the SOHO satellite, and from the oscillation and diameter data to be provided by the SDS experiment both in its balloon-borne and satellite incarnations.

When the upgraded solar model can reproduce the variabilities that are known to occur, it will be run to follow the behavior of the solar luminosity over a period of a few hundred years. Finally, the luminosity variations produced by the model must be incorporated into climate models to determine the effect of solar variability on our climate. If this effect is properly validated with past data, it could be used for the purpose of forecasting future climate change. Whereas it is true that a lot of work remains to be carried out before the question of solar forcing of the terrestrial climate can be fully settled, it is also true that a comparable amount of progress has already been made. The importance of the results make it mandatory that we follow this task to the end of the road.

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