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Mechanisms for global solar variability

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Abstract. The solar interior contains a variable magnetic field produced by the dynamo effect. This field contributes to the internal pressure and energy, and modifies the convective flows, thus affecting convective and turbulent energy transport. As a consequence, it modifies the structure of the solar interior, and thus all the global (stellar) parameters. Although these variations are inevitable, the amplitude of the changes depend critically on largely unknown properties of the fields, such as location, strength, configuration, etc. Thus, the field properties must be inferred from the observed changes of the global parameters, and they can be tested by helioseismological observations. We will describe the current codes that model these features of the solar interior, the current status of the observations, and the work both in the models and in the observations necessary to provide a robust understanding of the solar variability produced by internal processes.

Key words. Solar variability – Solar global parameters – Total Solar Irradiance

1. introduction

The short term variability (days to a year) of the total solar irradiance (TSI) can be explained by solar surface features such as sunspots, faculae, and networks. However, the long term TSI variations (years to millenia) have to invoke the internal structural variations of the Sun caused by the magnetic field variations in the solar interior (e.g., Sofia 2004). The solar internal structural changes modify solar global parameters, including solar luminosity, solar effective temperature, and solar diameter. Solar luminosity variations give rise to TSI variations. In this paper, we focus on the long term variations of the Sun.

2. Theory

To study the variability of the solar interior, we must look at the Sun as a star. As such, it is characterized by a few global parameters, not all independent from each other, that fully identify its first order properties. These parameters are: mass, age, chemical composition, luminosity, diameter, and effective temperature. The luminosity, L, directly affects the TSI, a quantity of fundamental importance for climate change.

Because evolutionary changes of the Sun are very slow (the characteristic timescales are in the range of hundreds of millions of years), variations of the solar interior on timescales of millennia can only occur as a consequence of variations of large scale internal (presumably dynamo) magnetic fields in the convection zone. Since the magnetic fields affect internal energy, pressure, and dynamics of the convection (including turbulence), they affect the structure of the solar interior, and thus the global parameters on relatively short time scales (Sofia 2004).

To model internal solar changes, it is necessary to use the numerical techniques developed to study the structure and evolution of stars (Cox and Giuli 1968), augmented to include the effects that are usually neglected in stellar studies, such as magnetic fields and turbulence, and possibly rotation. Since these modifications are rather complex, they have been implemented gradually over the years, starting out in the form of perturbation studies too numerous to reference, and concluding with the fully self-consistent method described in detail by Lydon and Sofia (1995), and further expanded by Li and Sofia (2001), Li et al. (2002, 2003), Sofia et al. (2005).

We address the model uncertainties by considering four types of models:

(I) Models with no turbulence,
(II) Models in which only the radiative loss of a convective eddy is assumed to be affected by turbulence,
(III) Fully-turbulent models, in which both turbulent pressure and turbulent kinetic energy are included, but magnetic fields are not linked to turbulence,
(IV) Magnetically-modulated turbulent models, in which the influence of magnetic fields on turbulence is taken into account.

3. Observations

We use five types of data to select models. We list them in ascending degree of reliability.

3.1. An anti-phase cyclic variation of solar radius

Radius determinations from f-modes indicate small changes in radius with a phase opposite to that of solar activity (Dziembowski et al. 1998, 2000, 2001; Antia et al. 2000, 2001). Similarly, the most recent analysis of direct measurements by MDI (Kuhn al. 2004) also indicates small changes in anti-phase with activity cycle. Recent results of an extensive reanalysis of the SDS data (Egidi et al 2005) also indicate changes in opposite phase with the activity cycle, but substantially larger than the helioseismological ones. Because of these discrepancies, *we have so far only assumed that the solar radius varies in anti-phase with solar activity.*

3.2. An in-phase cyclic variation of the solar photospheric temperature

The measurements of Gray & Livingston's (1997a, b), while free from the surface magnetic feature, depend on a calibration coefficient that relates the variation of the photospheric temperature to the variation of the depth of the observed spectral lines. They obtained this correlation coefficient empirically from observations of six stars with colors identical to the Sun (Gray & Livingston 1997a). However, Caccin, Penza and Gomez (2002) noted that the gravitational acceleration g for all these stars was not the same, and through theoretical calculations they found a g dependence of the correlation coefficient. This leaves an uncertainty which affects the amplitude of the 11 year variation of the temperature. Because of this uncertainty, *we only use the phase of this change and not the amplitude as the criterion that our models must satisfy.*

3.3. An in-phase cyclic variation of solar luminosity (e.g., Fröhlich 2000)

We assume that all of the 11 year changes in solar irradiance are the result of solar luminosity changes, although some fraction of the change is expected to be due to surface features.

3.4. A constant position of the CZ base

The position of the base of the convection zone can be determined very precisely by inversions of solar oscillation frequencies (Christensen-Dalsgaard, Gough & Thompson 1991; Basu & Antia 1997). Helioseismic data obtained over the past seven years do not show any observable change of the position of the convection zone base with time (Basu & Antia 2000; Basu 2002). The errors in the measurements would allow changes of less than a few parts in 10^{-4}, thus the constraint we use from these results is

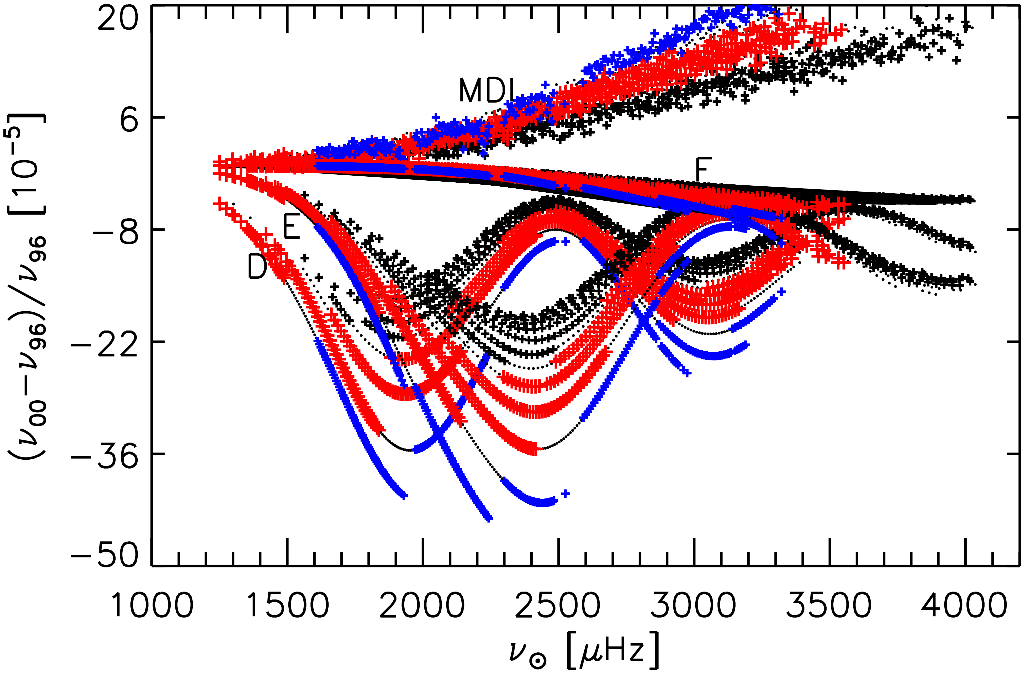

Fig. 1. P-mode frequencies of the MDI observations (see http://quake.stanford.edu /˜ schou/anavw72z/) and the models in categories I, II and III.

that the change of position of the convection zone base in our models must not exceed a few parts in 10^{-4}.

3.5. An in-phase cyclic variation of low- and medium-degree solar p-mode oscillation frequencies (Schou et al. 1997)

We find these observations to be by far the most sensitive diagnostics of solar models at the present time. Therefore, we use these data as the critical test for our models.

4. Confrontation between theory and observations

4.1. Tests of global parameter variations

A detailed description of the tests of our models is presented in a recent paper (Li et al. 2003). We will not reproduce it here. Instead, we will highlight some of the principal features of our tests.

The radius test. Regardless of the limitations of the radius data (we do not trust the amplitude of the changes), it conclusively eliminates all models in categories I and II.

The temperature test. Although the amplitude of the photospheric temperature variation over the activity cycle cannot be totally trusted, the phase information alone rules out all models in category III.

The luminosity test. The luminosity requirements also rule out all models in category III.

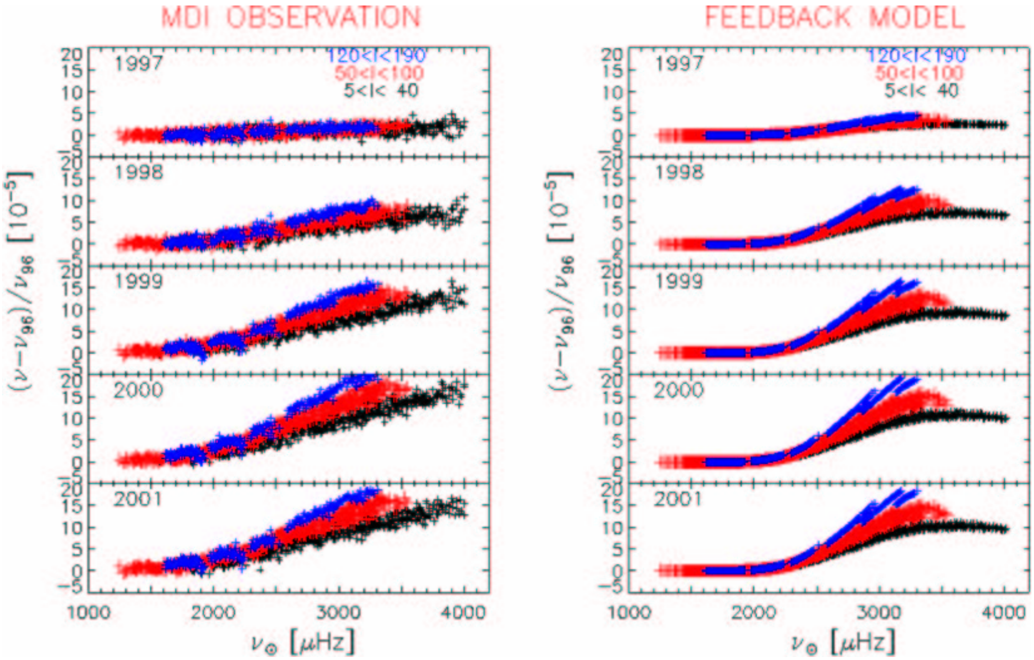

Fig. 2. P-mode frequencies of the MDI observations (see http://quake.stanford.edu /~ schou/anavw72z/) and the best model.

4.2. The helioseismic tests

The CZ base test. This information rules out all models which have a magnetic field stronger than 10^5 G at the base of the convection zone.

The p-mode frequency change test. As stated earlier, this test is the most sensitive, and most categorically rules out all models in categories I, II and III, as shown in Fig. 1. *Only category IV can pass all the tests.* The observed p-mode frequencies and the calculated ones for our best model are shown in Fig. 2.

5. Conclusions

The principal conclusion of our calculations is that there is sufficient redundancy in the data to insure uniqueness of the solution, even with the current incompleteness of the observations. We also find that the most difficult requirements to satisfy are those provided by helioseismology. This should not be surprising, since the helioseismological data are by far the most precise. Consequently, we expect that as the global parameter data improve in reliability, and the helioseismological data improve in quantity, we should be able to derive a more refined understanding of the physics of solar variability on timescales of years to millennia. Since a key objective of this work is to obtain the relationship between the variations of the global parameters, such understanding is very important.

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