EVOLUTION OF THE SUN WITH MIXING BY HYDRODYNAMIC INSTABILITIES

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Following Schatzman and Maeder (1981) we compute the evolution of the sun with partial mixing by hydrodynamic instabilities. Instead of simply assuming a turbulent diffusion coefficient which is a constant multiple of the viscosity, we incorporate some of the properties of hydrodynamic instabilities. This puts limits on the amount of diffusion that can be obtained, and makes it dependent on time and position in the star.

The hydrodynamic instabilities considered are due to differential rotation, which in turn is due to the assumed spin-down of the star's convection zone by a magnetic stellar wind.

In the present study, we consider mixing by the ABCD (Knobloch and Spruit, 1983) instability, since it is the most generally occuring instability. Two different recipes were considered for its mixing efficiency, both of which imply a significant mixing effect. Since nothing is known about the actual nonlinear development of this instability, it is still possible that both recipes overestimate the mixing effect. In both recipes the rotation rate $\Omega_s(t)$ of the convection zone is specified as a function of time, in such a way that it agrees roughly with the observed rotation rates of G stars of various ages (Skumanich, 1972). Ω is assumed to be a function of r (the radial coordinate) and t only. The condition for marginal stability is then of the form

$$\partial\Omega/\partial r = f(r,\Omega,\nu), \qquad (1)$$

where ν is the microscopic viscosity. In recipe A (the most optimistic recipe) it is assumed that strong turbulence results if $\partial\Omega/\partial r$ exceeds (1) even by a small amount, so that (1) is approximately satisfied all the time. $\Omega(r,t)$ can then be calculated directly from (1) and $\Omega_s(t)$. The angular momentum transport that is taking place then follows from $\Omega(r,t)$, and it is assumed that the effective diffusion coefficient for chemical constituents is the same as the effective angular momentum transport coefficient. In the more "realistic" recipe B it is assumed that the instability reaches such an amplitude that it is in a condition

A. Maeder and A. Renzini (eds.), Observational Tests of the Stellar Evolution Theory, 523–524.

of marginal stability under the influence of the turbulence which it has created (ν replaced by ν_t in (1)).

For the models we calculated the neutrino flux N_ν, the quadrupole moment coefficient J_2, the lithium-depletion factor f_{Li} and the period spacing P_o of g-modes. The results are:
i) A substantial reduction of N_ν occurs with recipes A and B, though not as large as the observed reduction.
ii) The lithium depeletion is much too high. This is due to the rapid initial spin-down rate which causes a high diffusion rate.
iii) J_2 is below its observed upper limit only for the most optimistic recipe A.
iv) The period spacing of g-modes is too high in models with a low N_ν.

From these results we conclude that:

1. In order to satisfy both the constraints on Li-depletion and J_2, a mechanism is needed which transports angular momentum much more effectively than Li. This is presumably a magnetic field.
2. The low neutrino flux can probably not be explained by turbulent mixing (see also Berthomieu et al., 1983).

REFERENCES

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DISCUSSION

Cox: What are the suggestions?

Spruit: The suggestions we make are:
1) There is something in the star which transports angular momentum without mixing, presumably a magnetic field. 2) The low ν-flux is probably not due to mixing. The reason for the first of these is that with a diffusion coefficient that is required for the lithium-depletion, not enough angular momentum can be transported out of the stars so J_2 is much too high. The reason for the second is the limited success of the recipes used in mixing in the center. Stronger constraints however follow from observations of the period spacing of g-modes, which allows only a small amount of mixing.