TITLE: TWO-DIMENSIONAL SOLAR MODELS: EVOLUTION AND HYDRODYNAMICS

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1. INTRODUCTION

We use the fully-implicit Euler-Lagrange two-dimensional code ROTORC to model evolution of the Sun. The code was developed by Deupree (1990, 1995) to model the evolution of rotating stars. The code operates in a quasistatic mode, taking timesteps on an evolutionary scale, or in a hydrodynamics mode, taking short timesteps to track dynamical instabilities at a given point in the evolution.

We first calculate a two-dimensional nonrotating solar evolution model using ROTORC, and compare the model structure with that of a one-dimensional model calculated with an updated version of the Iben (1963, 1965) evolution code (Guzik et al. 1995, 1996). We also calculate the evolution of a solar model with a slow initial rotation rate. We use the code's hydrodynamic mode to determine whether rotation rate gradients that may develop at the envelope convection zone base cause dynamical instabilities producing large-scale material flows and angular momentum redistribution.

2. CODE VALIDATION FOR NONROTATING SOLAR MODELS

We modified ROTORC to include 1) the OPAL Equation of State (Rogers et al. 1996); 2) updated OPAL (Rogers and Iglesias 1996) opacities; 3) Alexander and Ferguson (1994) low-temperature opacities; and 4) a convective envelope treatment based on the mixing length theory of convection.

Table 1 compares properties of the ROTORC solar model with a standard model using the one-dimensional Iben evolution code. The only physics differences are inclusion of diffusive helium and element settling in the 1D code, and use of newer reaction rates (Caughlan & Fowler 1988, instead of Fowler et al. 1967).

To match the current solar luminosity and radius more precisely, the ROTORC model will require slight increases in initial helium abundance and mixing-length/pressure scale height ratio. The remaining small differences between models can be entirely accounted for by differences in input physics. In particular, helium and element diffusion increases the central temperature and convection zone depth. The newer reaction rates also slightly increase the central temperature.

3. ROTATING SOLAR EVOLUTION MODEL AND HYDRODYNAMIC ANALYSIS

We next calculated the evolution of a solar model with 213 radial zones, and 10 angular zones, equally spaced from pole to equator. We chose ZAMS angular velocity \( \Omega_\odot = 3.46 \times 10^{-6} \text{/sec} \) (equatorial surface velocity 2.1 km/sec) to give an equatorial surface rate 1.87 km/sec (27 day period) at the current solar age, assuming local angular momentum conservation. We investigated a slow initial rotation rate since, first, there is no helioseismic evidence for a rapidly rotating core, or much deviation from the surface rotation rate throughout most of the solar interior, and second, we don't have a built-in angular momentum loss mechanism to spin-down the model from a rapid rotation rate. We also impose solid-body rotation in the convection zone, and neglect magnetic fields. Angular momentum conservation for evolutionary time steps presents challenges in models with low-mass surface convection zones. With the current practice of defining the convection zone boundary as the nearest mesh zone interface in the non-Lagrangian code, the amount of mass in the convection zone fluctuates slightly from one time step to the next. Attempts to modify the convection zone angular momentum to adjust for this are somewhat arbitrary and may affect angular momentum conservation near and just below the convective boundary. We show the rotation rate for one such model in Fig. 1. We use ROTORC's hydrodynamics mode to determine whether such a rotation gradient causes dynamical instabilities that result in organized coher-
ent flows that modify the velocity gradients. This investigation is relevant, because helioseismic evidence points to the existence of a rotation rate gradient at the convection zone base, and a transition between latitude-dependent differential rotation and solid-body rotation.

In the hydrodynamic analysis, we employed a variety of noise reduction techniques to isolate possible hydrodynamic flows at the convection zone base. Appropriate timesteps appear to be of order 0.001 yr. We found that circulation does occur initially, with velocities of a few cm/sec, and material flow from equator to pole below the convection zone base, and from pole to equator above the base. After 0.0425 yr, velocities have decayed away everywhere except in one radial zone at the convection zone base (extent ~ 0.006R_☉). During this time, a small amount of angular momentum is redistributed, but the maximum change in Ω is only ~ 0.3% (Fig. 2).

4. CONCLUSIONS

The excellent agreement between the structure of nonrotating solar evolution models using ROTORC and the updated Iben evolution code validates ROTORC for evolution of low-mass main-sequence stellar models with convective envelopes. For relatively small gradients in rotation rate near the solar convection zone base that may develop during evolution, we find that induced flows have velocities of only a few cm/sec, and decay away everywhere except in one radial zone after a few months, with only a small angular momentum redistribution. Any rotationally-induced flows that may cause substantial angular momentum transport and mixing must occur over a significantly longer timescale (i.e. at much slower velocities) than we can follow, and/or on very small spatial scales.

Now that we have validated ROTORC for evolution of solar models, we proceed to investigate the effects of rotation and rotationally-induced mixing on the structure and evolution of the more rapidly rotating δ Scuti stars.

REFERENCES

Caughlan, G.R. & Fowler, W.A. 1988, Atomic Nucl. Data Tables, 40, 283

Figure 1: Rotation profile of ROTORC solar model at 4.5 Gyr. The angular momentum loss from the convection zone with imposed solid-body rotation sets up a gradient at the convection zone base (R/R_☉ ~ 0.73). y-axis units 10^-6/sec

Figure 2: Fractional change in angular momentum after about 40 hydrodynamics timesteps (0.0425 yr). Very little angular momentum is redistributed before flow velocities decrease to < 0.1 cm sec⁻¹ everywhere except in the zone adjacent to the convective envelope boundary at M/M_☉ ~ 0.98. y-axis units 10^-3