DIFFERENTIAL ROTATION WHEN THE SUN SPUN FASTER

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ABSTRACT

When the sun was younger it rotated more rapidly than its current rate. The sun gradually loses angular momentum through its magnetized wind, though the spindown rate in the past is somewhat uncertain. Here we look at the effects of more rapid rotation upon turbulent convection and the ability to establish differential rotation throughout the bulk of the convection zone. For simplicity we adopt the radial stratification of the present-day sun and examine global scale convection in a zone extending from 0.72 to 0.97 solar radii. Our 3-D simulations of compressible turbulent convection are carried out with the Anelastic Spherical Harmonic (ASH) code on massively parallel supercomputers. We report on the structure of convection and the differential rotation contrast achieved in a variety of cases rotating from one to two times the current solar rotation rate. We find that a strong differential rotation contrast is achieved, even for more rapid rotation, with a monotonic decrease of angular velocity from the equator to high latitudes.

1. MOTIVATION

The sun in the past must have rotated faster than it currently does, given that it has been gradually losing angular momentum through its magnetized wind. Here we examine the effects of more rapid rotation upon global-scale convection and consider how differential rotation is established within the bulk of the convection zone. Since global magnetic dynamo action in the interior is thought to depend on the differential rotation achieved by the convection, our study provides some perspective on that ingredient for the sun in the recent past.

2. APPROACH

Our 3-D simulations of compressible turbulent convection utilize the Anelastic Spherical Harmonic (ASH) code (Miesch et al. 2002) on massively parallel supercomputers. For simplicity we adopt the radial stratification of the present-day sun and examine global scale convection in a spherical shell extending from 0.72 to 0.97 solar radii. Such a configuration parallels the simulations discussed in Brun & Toomre (2002), where many other aspects of the modelling are presented in detail. Here we expand upon case AB studied in that paper. This configuration excludes the near-surface zone and a region of penetrative overshooting beneath the convection zone.

We have explored two paths through the parameter space of our simulations. In the first path, the rotation rate has been increased in a succession of models from the current mean solar rate Ω_s, maintaining the eddy diffusivities and viscosities at a constant level. Along this path, the turbulent nature of the simulation decreases with increased rotation rates as rotational effects begin to constrain the nature of the convection. In following our second path, rotation rates were again increased but now eddy diffusivities and viscosities were adjusted to maintain a similar level of supercriticality for each rotation state. Along this second path, the turbulent nature of the flows realized in the simulations remains roughly comparable.

3. RESULTS

We have examined the structure of the convective patterns and the differential rotation contrast achieved in a variety of cases rotating from one to two times the current solar rotation rate. This has required extended simulations in time to achieve statistically equilibrated conditions for the vigorously time-dependent convection that is realized.

Fig. 1 presents the main results from simulations at three different rotation rates ($\Omega_\circ = 1.0\ \Omega_s$, $1.6\ \Omega_s$ and $2.0\ \Omega_s$). We examine the resulting differential rotation (on the left) both as contours of angular velocity Ω with radius and latitude and with radial cuts of Ω at four specified latitudes. In defining such angular velocities within the highly time-dependent convection, we have formed very long time

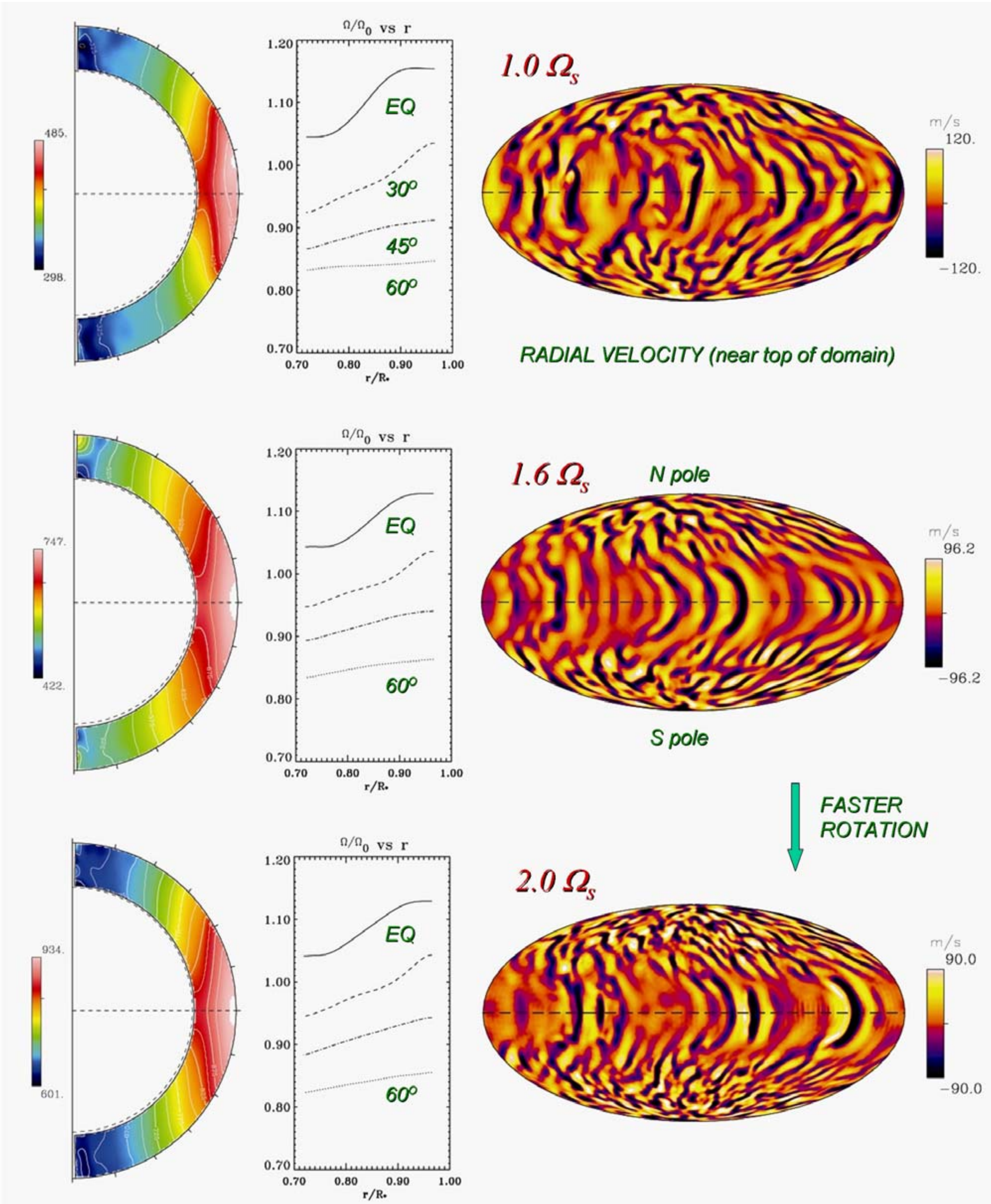

Figure 1. Results of three nonlinear simulations at increasingly rapid mean rotation rates (sampling 1, 1.6, and 2 times the solar rate Ω_s). Shown on the left (color contours, ranges indicated in nHz) are time-averaged angular velocity profiles with radius and latitude, accompanied by radial cuts at indicated latitudes. A strong differential rotation is achieved in all cases. On the right are global Mollweide projections of radial velocity v_r near the top of the domain, showing snapshots of the intricate and evolving convective structures (downflows are dark). At low latitudes, the flow patterns exhibit some alignment with the rotation axis (columnar convection or "banana cells"). The patterns at higher latitudes are more isotropic and cyclonic. The convection becomes spatially intermittent near the equator at the highest rotation rates.

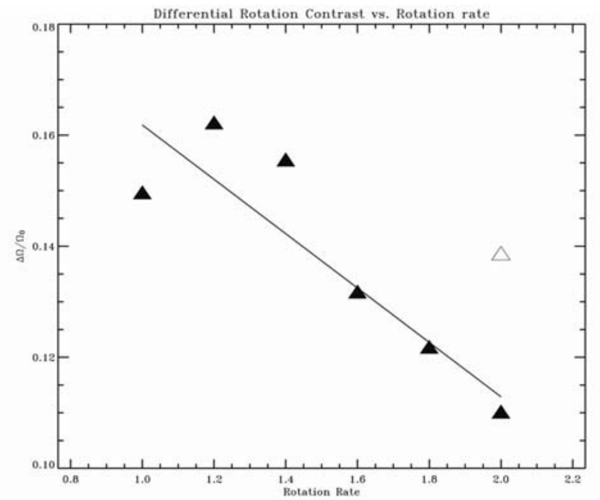

Figure 2. Proportional angular velocity contrast $\Delta\Omega/\Omega_\circ$ between equator and high latitudes realized at different mean rotation rates $\Omega_\circ/\Omega_s$, showing a systematic decrease with increasing $\Omega_\circ$. The hollow triangle is a state of more turbulent convection achieved by reducing the eddy diffusivity and viscosity.

averages (over about 400 simulation days) of the zonal velocities, averaged over all longitudes. Differential rotation is clearly present throughout the bulk of the convection zone in all three cases, capturing much of the flavor of the differential rotation deduced from helioseismology in the bulk of the solar convection zone (e.g., Thompson et al. 2003). Namely, the equators rotate rapidly, the high latitudes slowly, and there is a steady decrease of Ω with latitude. The radial profiles of $\Omega/\Omega_\circ$ (Fig. 1, middle) emphasize that the angular velocity here only decreases slowly with radius. The nature of the pattern of the convection is revealed in the snapshots of radial velocity v_r (Fig. 1, right) presented in global Mollweide projection of a full spherical surface. Extended lanes of downflow (dark tones) and upflow (bright tones) dominate convection at low latitudes, while more isotropic cyclonic patterns are evident at high latitudes. Such convection patterns are found to propagate prograde relative to the mean rotation rate at low latitudes and retrograde at high latitudes. In these simulations, all the time-dependent flows have been evolved to statistically mature states, typically involving about 2500 simulated days for each case, thus ranging from 100 to 200 rotation periods.

It is of significance that a strong differential rotation contrast is maintained at all rotation rates considered (Fig. 1), with a monotonic decrease of angular velocity from the equator to high latitudes. As shown in Fig. 2, the proportional angular velocity contrast between the equator and high latitudes ($\Delta\Omega/\Omega_\circ$) decreases gradually with more rapid rotation. Though that ratio decreases with increasing rotation rate, it remains substantial over the range considered here. This suggests that global dynamo action influenced by differential rotation in the bulk of the convection zone is likely to have been sustained during earlier times in the sun's evolution.

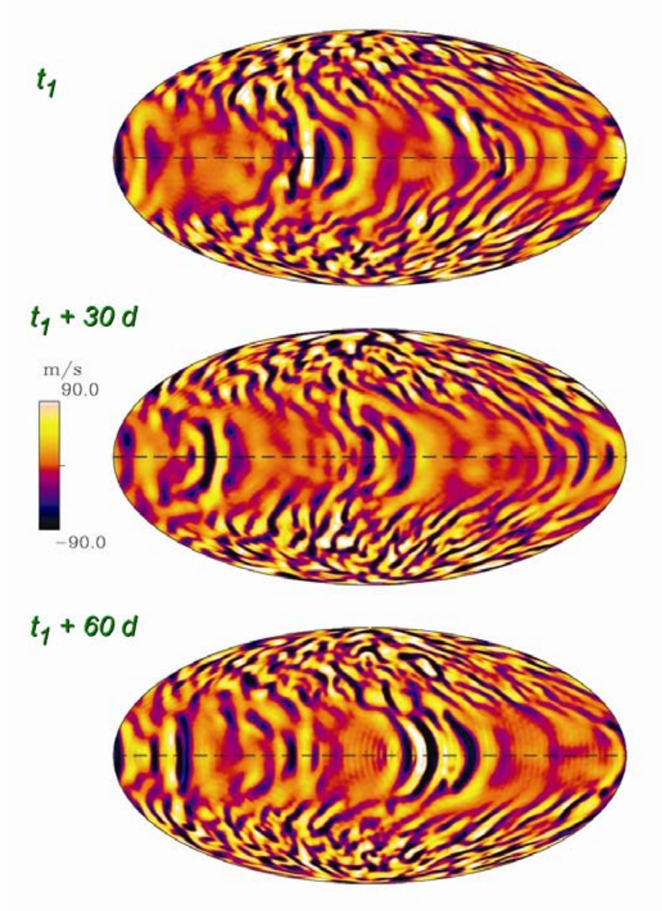

Figure 3. Global views of the evolution of radial velocity v_r for a simulation rotating at twice the solar rate, sampled at three intervals each separated by about 30 simulated days. At low latitudes, confined regions of strong convection (appearing as rather distinct pulses) largely maintain their identity as they propagate prograde relative to the rotating frame. At high latitudes, the propagation of the more isotropic convection is retrograde.

Maintaining the differential rotation contrast evident in Fig. 1 requires a continual redistribution of angular momentum. In our simulations, we find that this is achieved by Reynolds stresses, meridional circulations, and thermal baroclinic effects, much as in Brun & Toomre (2002).

With increasingly rapid rotation, the convection at low latitudes begins to exhibit a prominent modulation with longitude in the strength of the convective flows. This is a significant finding. Namely, the relatively uniform pattern of "banana cells" (or columnar convection aligned with the rotation axis) at low latitudes realized at the solar rotation rate Ω_s in Fig. 1 is gradually replaced by spatially separated pulses in which the downflows are considerably stronger. Fig. 3 examines the evolution and prograde propagation of the low-latitude confined states of the columnar convection. Time-longitude maps (as shown in Fig. 4) reveal that these modulation patterns (pulses) persist over very long time intervals and maintain their identity even as individual convective features travel through the pattern. Such localized regions of strong convection are reminiscent of confined states of nonlinear traveling wave convection studied in double-diffusive systems (Spina et al., 1998).

We find here that the individual convection cells (forming our low-latitude convective background) translate in a prograde manner at a rate faster than the mean zonal velocity established by the convection (interpreted as differential rotation). Conversely, the pulses propagate in the same sense but more slowly. The striking modulation of the convection with longitude in our most rapidly rotating case is also evident, though more weakly, in our case rotating at the rate of the present sun. This may have some bearing on the formation of active magnetic longitudes, should such modulated and persistent convection pulses lead to stronger downflow plumes that impact and disturb toroidal magnetic fields in the tachocline.

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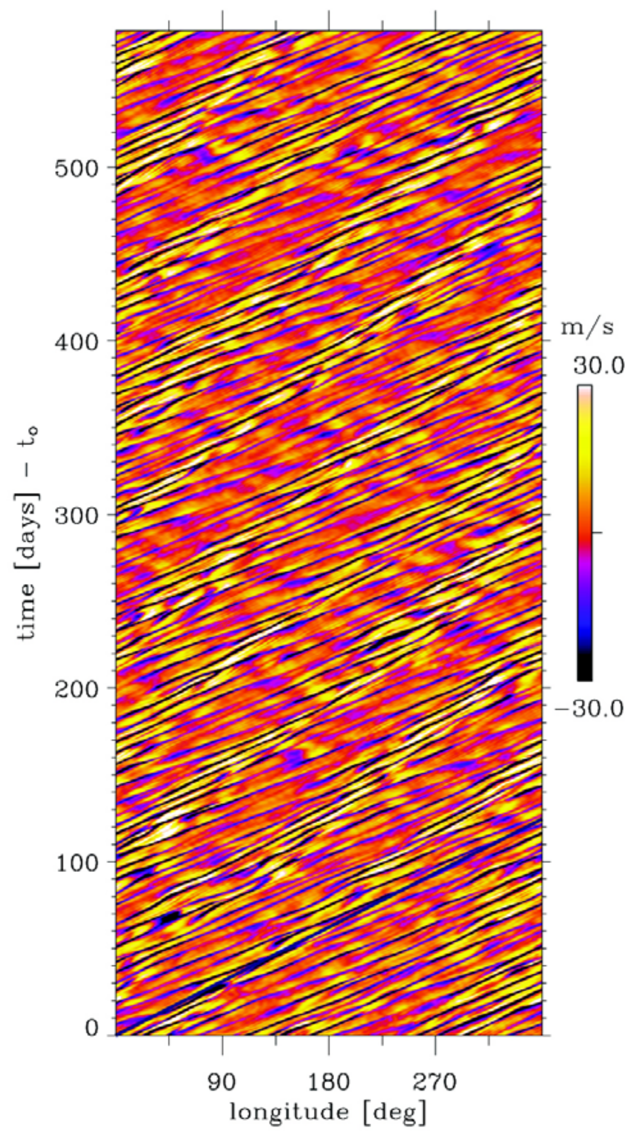

Figure 4. A time-longitude map of structure propagation for the case rotating at twice the solar rate. Cuts in longitude were made at a latitude of $15°$, sampling the radial velocity v_r near the top of the domain at all longitudes. Shown here are more than forty rotations after the simulation has reached a mature state. A distinctive pattern of three pulses is evident, propagating prograde in longitude. The individual banana cells propagate faster than the sustained zonal flows (indicated here by the blue line at the lower left of the map), whereas the pulses propagate slower.