OVERSHOOTING MOTIONS FROM THE CONVECTION ZONE AND THEIR ROLE IN ATMOSPHERIC HEATING

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1. INTRODUCTION

Chromospheres and coronae in stars appear to require vigorous convection zones just below the surface. If we wish to understand how various dynamical instabilities contribute to the mechanical heating that is required to produce chromospheres, then we must be concerned both with fluid motions in the atmosphere and with the nature of their driving below the surface. One cannot really separate these two subjects. In order to emphasize this link, we will raise some basic questions about convective flows in a stellar envelope and of their penetration into the atmosphere. The significant puzzles between what is observed and what can be theoretically explained should serve to indicate some of the issues that need to be pursued. We will concentrate on the Sun in our discussions: the observations here are sufficiently detailed to provide the explicit challenges to theory unavailable in most other stars. However, we will also turn to A-type stars to illustrate a theoretical procedure for describing convection that may do better than the mixing-length approach in predicting the vertical structure in these flows.

2. DYNAMIC COUPLING OF THE CONVECTION ZONE WITH THE ATMOSPHERE

The solar atmosphere and the convection zone are linked by a number of dynamic and magnetic processes that have the potential for depositing energy in the chromosphere. The principal couplings are provided by: a) Some sort of magnetic dynamo action deep within the convection zone must be responsible for producing and shaping the observed magnetic fields near the surface. A variety of associated magnetic instabilities and magnetohydrodynamic waves have a major role in locally heating the atmosphere. Yet we are unable to predict theoretically how magnetic features on the solar surface really come about or what controls them, largely because detailed solar dynamo models are still beyond our grasp. b) The five-minute oscillations which now have been identified as standing acoustic waves in the envelope and largely evanescent waves in the atmosphere provide another strong link between these two regions.

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Although the dissipation of these waves by nonlinear processes in the photosphere and chromosphere is becoming clarified, the manner of driving these waves is still a matter of debate. Possibly a κ-mechanism may serve to excite these waves, though phase must be maintained over thousands of cycles within the highly turbulent medium of the convection zone before a given mode can attain an appreciable amplitude. Alternatively, the turbulence itself may lead to stochastic excitation of the many waves that are admissible in the cavity, though the efficiency of such a process is not well established. The choice of mechanism will require more detailed knowledge of the spectrum of the turbulence in the convection zone and of its interaction with the oscillatory modes. c) The long-period solar pulsations of global scale may provide links to even deeper into the interior. Although there is some dispute about their detection, these modes have the potential for transporting energy to the outer layers. d) The overshooting of convective motions into the photosphere and chromosphere perhaps yields the most immediate coupling between the vigorous turbulence below the surface and the atmosphere. The motions in the stable atmosphere are controlled by the structure of the flows in the subphotosphere and thus can serve as an immediate probe of the convection there. These overshooting motions of granulation and supergranulation may lead to a substantial deposition of mechanical energy as they are braked to a halt in the atmosphere.

We will concentrate most of our attention here on the overshooting motions, for they may be the most effective in revealing details of the structure of the convection zone. Such structure is seen to influence most of the coupling mechanisms between the inside of the Sun and the atmosphere, and thus plays a vital role in all attempts to understand how chromospheres and coronae are maintained.

3. DISCRETE SCALES OF SOLAR CONVECTION

One of the striking properties of the observed convective motions on the Sun is that the spectrum of their horizontal scales is discrete. The granules have scales of order 1 Mm (or 10^3 km), the supergranules have an average scale of 30 Mm, and the giant cells may be of order 150 Mm or greater. Although there is a range of sizes to the cellular patterns of both granulation and supergranulation, these motion fields basically differ by a factor of 30 in scale with apparently little in the way of convective flows in between. The existence of the giant cells is much less certain, for they are largely suggested by magnetic field patterns and by possible variations in the differential rotation. Thus the observed spectrum of the overshooting motions is not at all like that of fully developed turbulence with a continuum of scales extending from the large energy containing eddies down to the dissipation scales. Rather, a series of broad but discrete peaks appears in the spatial Fourier transforms of the velocity fields once the oscillatory components are removed. The spectrum must take on the character of fully developed turbulence at some very small scales, but these probably are well below the resolution limits of existing instruments.

The presence of such discrete scales in the overshooting motions must reflect an important property of the underlying convection. Of course this is an inference, but probably not an unreasonable one. Why the convection there should possess only a few preferred scales is still not clear, although it has been a matter of concern for over 15 years (cf. Joint Discussion D, Proc. 12th General Assembly, IAU, 1964). An early and continuing suggestion (e.g. Simon and Leighton 1964) is that the discrete scales may be a consequence of the specific depths at which H and He are ionized. Thus granulation is a scale of convection most efficiently driven by the H^+ zone at 2 Mm (based on 50% level of ionization), while supergranulation with its much larger 30 Mm horizontal scale would experience its primary driving as a result of the He^{++} ionization zone at a depth of 20 Mm. The giant cells in turn would respond to the overall depth of the convection zone of 150 Mm. What is however missing from this scenario is some observed scale of convection corresponding to the 7 Mm depth of the He^+ zone. Another suggestion is that the granulation scale arises from the transition boundary-layer formed at the top of the convection zone and that of supergranulation from the one at the bottom (Spiegel 1966). Yet a further suggestion is that a limited tier of convection cells can suffice to carry the heat outward, with giant cells being replaced by supergranules at a depth where the former become inefficient transporters of heat, and the supergranules in turn being replaced by granules near the surface (Simon and Weiss 1968). Many other variations have been proposed (e.g. Savchenko and Kozhevnikov 1978), but all involve some geometrical arguments about how a hypothetical cellular flow should behave. So far no theoretical models for the convection zone have been able to self-consistently obtain the discrete scales as the preferred ones without essentially imposing them from the outset.

Some recent observations of the height variation in supergranular flows strongly suggest that yet a further scale of convection is present (November, Toomre, Gebbie and Simon 1979a,b). The scale detected is about 7 Mm, and thus intermediate between granulation and supergranulation. We have chosen to label these flows mesogranulation. An example of such persistent flows is shown in Figure 1, which presents time-averaged intensity and Doppler velocity images taken at disc center with the diode array at Sacramento Peak Observatory. These averages span 60 min in time of data rasters obtained every 40 s in several spectral lines simultaneously. The dynamic range of the steady vertical velocities seen in the Mg I λ5173 line is ±110 ms^{-1}, with light areas depicting downflow and dark areas upflow. The upper image displays intensity variations as seen in the Ca II λ8542 line, with the familiar network of enhanced emission shown as bright regions. Comparison of the two images reveals that sites of general downflow (bright) in supergranulation tend to coincide with the network of emission, while regions of upflow (dark) are concentrated in the cell centers. We have sought to aid this comparison by outlining the emission network on the velocity image with faint dashes; the supergranules have an average scale of 40". The Mg I velocity image also shows that superposed on these large-scale motions is a pattern of steady flow that alternates in sign on a spatial scale of about 10" (or 7 Mm). Such a distinct substructure of both up and down

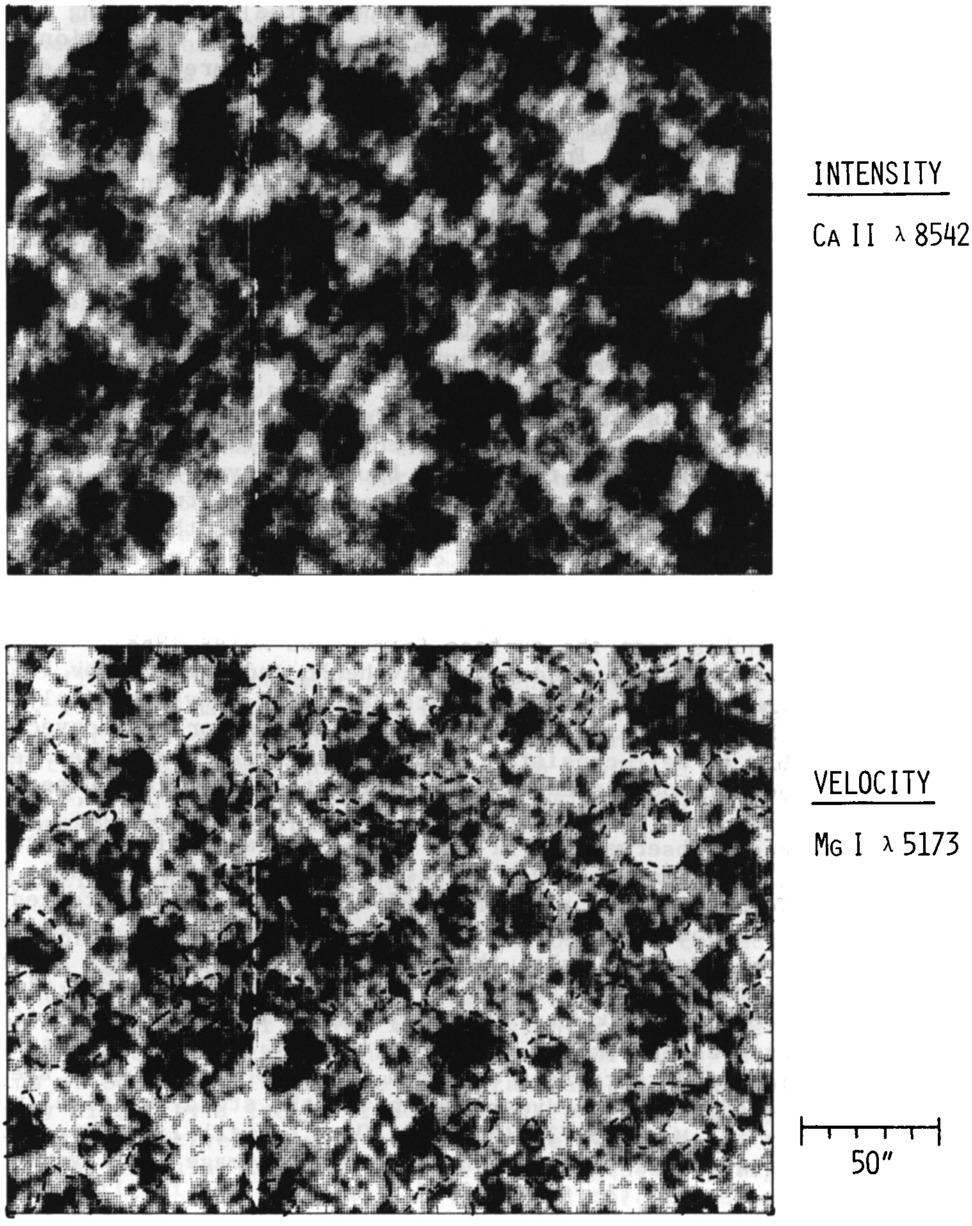

Figure 1. Supergranulation and mesogranulation as seen in time-averaged intensity and Doppler velocity images at disc center on the quiet Sun. The network of enhanced emission in the Ca II line is displayed as bright regions in the upper image. The accompanying steady vertical velocities obtained in the Mg I line have a dynamic range of $\pm 110\ ms^{-1}$, light areas being ones of relative downflow, dark of upflow. Mesogranulation appears as the 10" (7 Mm) scale of persistent cellular flows.

flow is present fairly uniformly over the image. These cellular flows are the mesogranulation and appear to persist over several hours in time. Observations in the photospheric Fe I λ5576 line and in the Mg I line formed just above the temperature minimum show that the mesogranulation structures are quite well correlated. Further, simultaneous observations carried out in the Si II λ1817 line using the University of Colorado Ultraviolet Spectrometer on the OSO-8 satellite reveal that such scales of persistent flow are also present in the middle chromosphere.

The mesogranulation may be the missing scale of convection if the sequence of ionization depths and associated scale heights does serve to determine the preferred scales. It may also be that these flows represent higher spatial harmonics of the primary supergranule cell resulting from nonlinear excitation of the horizontal overtones. In either case the mesogranules may be expected to exhibit time variations shorter than those of supergranules. Observations to determine their lifetimes are presently under way, and will be accompanied by studies to be coordinated with the SMM satellite to examine further their height dependence. The detection of mesogranulation requires stable and sensitive spectrographs, combined with careful filtering out of the strong five-minute oscillation and granulation velocities. This may explain why these motions have not been previously reported. The task however remains to try to explain the presence of any of these discrete scales of convection, each differing roughly by a factor of 5 from the next.

4. ENERGY TRANSPORT BY OVERSHOOTING CONVECTION

The variation with height in the atmosphere of granulation, mesogranulation and supergranulation can provide estimates of the mechanical energy transported by these flows and of its possible conversion into wave modes through instabilities. The vertical structure in these overshooting motions can also be used to place some constaints on the flows just below the surface.

The flow properties in granulation are presented in Table I, drawing largely on the observations of Keil and Canfield (1978) and Canfield (1976). Both the vertical velocity and momentum in granulation decrease rapidly with height, yielding a scale height for the vertical momentum of $\ell_m \simeq 70$ km in the lowest 400 km of the photosphere. The mechanical energy flux associated with these granular flows decreases rapidly with height, from a value that we can roughly estimate from Table 1 to be 6×10^8 ergs $cm^{-2}s^{-1}$ at the base of the photosphere to a value of 10^4 at the height of 400 km. This decrease in the mechanical flux is not the result of buoyancy braking in the stable atmosphere, judging from the results of dynamical models by Nordlund (1976) and particularly by Nelson and Musman (1977, 1978) for granular flows in the photosphere. These models can be tuned to reproduce the observed decrease of velocity with height only by invoking a significant turbulent drag on the motions. We may view such a drag as a rough parametrization of the production of turbulence and internal gravity waves by dynamical instabilities in these shearing flows. The production of internal

Table 1. Solar granulation: Variation with height in the observed rms vertical velocity and momentum, yielding momentum scale heights ℓ_m.

HEIGHT (km)	DENSITY (g/cm^3)	ℓ_ρ	VERTICAL VELOCITY (m/s)	VERTICAL MOMENTUM (g/cm^2 s)	ℓ_m
0	3. 10^{-7}		1300	3.9 10^{-2}	
		150 km			75 km
200	8. 10^{-8}		350	2.8 10^{-3}	
		110 km			65
400	1.3 10^{-8}		90	1.2 10^{-4}	

gravity waves at heights of 200 km and upward is of interest, for at these height such waves would not be dissipated by the cooling effects of the H^- ion lower in the photosphere. The production of these waves by shear instabilities is likely, and their wave flux should bear some relation to the rapid decrease of the mechanical flux with height in granular flows. Chromospheric radiative losses appear to require a mechanical flux of order 4×10^6 ergs $cm^{-2}s^{-1}$. The internal gravity waves produced over a range of heights by instabilities in the overshooting motions of both granulation and supergranulation may provide a mechanism for transporting energy to the upper chromosphere that has been largely overlooked. Estimates of nonlinear wave breaking heights for such internal gravity waves by Mihalas (1979) suggest that energy deposition can occur at heights not accessible to acoustic waves.

The flow properties for supergranulation and mesogranulation are summarized together in Table 2, since it has not yet been possible to clearly separate out the contributions from these two components. The data are based on the coordinated ground-based and satellite observations of November, Toomre, Gebbie and Simon (1979a,b) using the Fe I, Mg I and Si II spectral lines to determine the persistent velocities. The heights of formation of these spectral lines span about 1400 km or nearly 11 density scale heights. The most striking result is that these flows are able to penetrate into the middle chromosphere, and that the velocity fields observed there correlate well with regions of approaching and receding motion in the photosphere. The dynamic range of the steady Doppler velocities observed at radius vector 0.8 increases from 800 ms^{-1} in the photosphere (Fe I) to over 3000 km s^{-1} in the middle chromosphere, (Si II). At disc center the corresponding vertical velocity increase is from about 100 ms^{-1} to again of order 3000 ms^{-1}; the associated rms velocities are listed in Table 2. Despite this increase in the velocities, the vertical momentum associated with the flow decreases by a factor of 10^3, owing to the decrease in gas density. Judging from the three spectral lines studied, the scale height ℓ_m for the decrease in this momentum component is about 135 km in the first 400 km above the photosphere, changing to 260 km in the subsequent 1000 km. A distinct change appears to have occurred in the flow structure: in the low photosphere, the horizontal component of velocity predominates, whereas

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Table 2. Solar supergranulation and mesogranulation: Height variation of the vertical rms velocity and the associated momentum as observed at disc center, and the more nearly horizontal velocity at radius vector 0.8.

	HEIGHT (km)	DENSITY (g/cm^3)	ℓ_ρ	VERTICAL VELOCITY (m/s)	'HORIZONTAL' VELOCITY (m/s)	VERTICAL MOMENTUM ($g/cm^2\,s$)	ℓ_m
Fe I	200	$8, 10^{-8}$		30	200	$2, 10^{-4}$	
			110 km				135 km
Mg I	600	$2, 10^{-9}$		50	70	$1, 10^{-5}$	
			145				260
Si II	1600	$2, 10^{-12}$		800	800	$2, 10^{-7}$	

higher in the atmosphere, the motions appear to become increasingly isotropic.

The rapid decrease of momentum in supergranular flows with height implies that substantial braking has occurred, as may be expected of motions penetrating into a very stable, stratified atmosphere. The velocities in such overshooting convection can, in regions of large density variation, display large amplitude changes with height, and these need not be monotonic. Further, conservation of mass in such cellular flows requires that the horizontal momentum be proportional to the rate of change of vertical momentum with height. This implies that the horizontal velocities will dominate near regions of strong braking, such as in the low photosphere and probably in the underlying subphotosphere. Conversely, the absence of dominant horizontal velocities suggests less braking of vertical momentum, as now appears to be the situation in the middle chromosphere. If the braking continues at the same rate even higher into the atmosphere, supergranulation velocities should be evident in the transition region.

The extensive penetration of supergranulation and mesogranulation into the atmosphere raises the possibility that these motions have associated with them a mechanical energy flux that could help resolve some of the dilemmas of chromospheric heating. We have obtained rough estimates for this flux and find it to be of the order of 10^5 ergs cm^{-2} s^{-1} in the low photosphere and of order 10^3 ergs $cm^{-2} s^{-1}$ in the middle chromosphere. Thus the energy flux is too small to have a direct effect on the heating, and granulation may play the bigger role. The apparent decrease in the mechanical flux with height must be accounted for by the production of turbulence and internal gravity waves: both of these small scales of motion can be expected to result from dynamical instabilities of the strong horizontal shear layers present in the supergranular motions in the photosphere. The Reynolds numbers and Richardson numbers associated with these flows favor the production of geostrophic turbulence. Although the efficiency of generation of internal gravity waves is generally less well understood, these waves could explain some of the observed nonthermal spectral line broadening seen over a range of heights.

5. THE FLOWS BELOW THE SURFACE

Theoretical models of convection in the Sun are still in an unsatisfactory state. Existing mixing-length models have not been able to explain most of the observed features on the Sun: the discrete scales of motion of granulation and supergranulation fall in this category, as does differential rotation with both latitude and depth, and so too magnetic dynamo action. Progress on any of these issues requires the use of far more detailed dynamical descriptions; however all the approaches tend to be very difficult to implement. We have been working on an approach that has shown considerable promise for answering basic dynamical questions about solar convection and suggesting observations that should be carried out. This description involves the use of anelastic modal equations that can be applied to the entire convection zone.

Our theoretical procedure (Latour, Spiegel, Toomre and Zahn 1976) evolves from two simplifications to the full dynamical equations: Acoustic waves are filtered out with the anelastic approximation, and the horizontal structure of the flow is expanded in a finite number of horizontal planforms or modes. The resulting anelastic modal equations are capable of describing compressible convection over multiple scale heights and with all the complexities arising from realistic equations of state in a star. The order of the differential equations to be solved for the vertical structure is however high, since the order of the non-linear system varies as (6n+3), where n is the number of horizontal modes retained in the analysis. The procedure has been extensively tested within the context of laboratory convection for up to three modes and shown to be successful (Toomre, Gough and Spiegel 1977; Spiegel, Toomre and Gough 1979). The stellar applications have so far concentrated on the use of the single-mode equations. However, the results in analyzing the entire outer envelope of an A-type star have been quite significant. These stars have proven to be an extremely useful framework for developing and refining the single-mode anelastic procedure, for here, unlike in the Sun, the mean structure is not overly sensitive to the details of the convection.

We have demonstrated that the two convection zones in A stars are dynamically coupled by the convective motions penetrating through the intervening stable material (Toomre, Zahn, Latour and Spiegel 1976). A typical single-mode solution of large horizontal scale, much like that of supergranulation, is illustrated in Figure 2 (extracted from Zahn, Toomre and Latour 1979). These flows originating in the He^{++} zone are able to penetrate upward all the way to the surface of the star, in a manner contrary to mixing-length predictions. Thus convective motions are not simply confined to the unstable regions, and for A stars this means that diffusive gravitational separation of elements cannot be occurring in what previously was supposed to be a quiescent region between the H^+ and He^{++} convection zones. A more striking result concerns the nature of the supergranular scale flow in the shallow H^+ zone. Analysis of the buoyancy and pressure work terms in Figure 2d reveals that pressure effects dominate in the upper zone. The predominantly

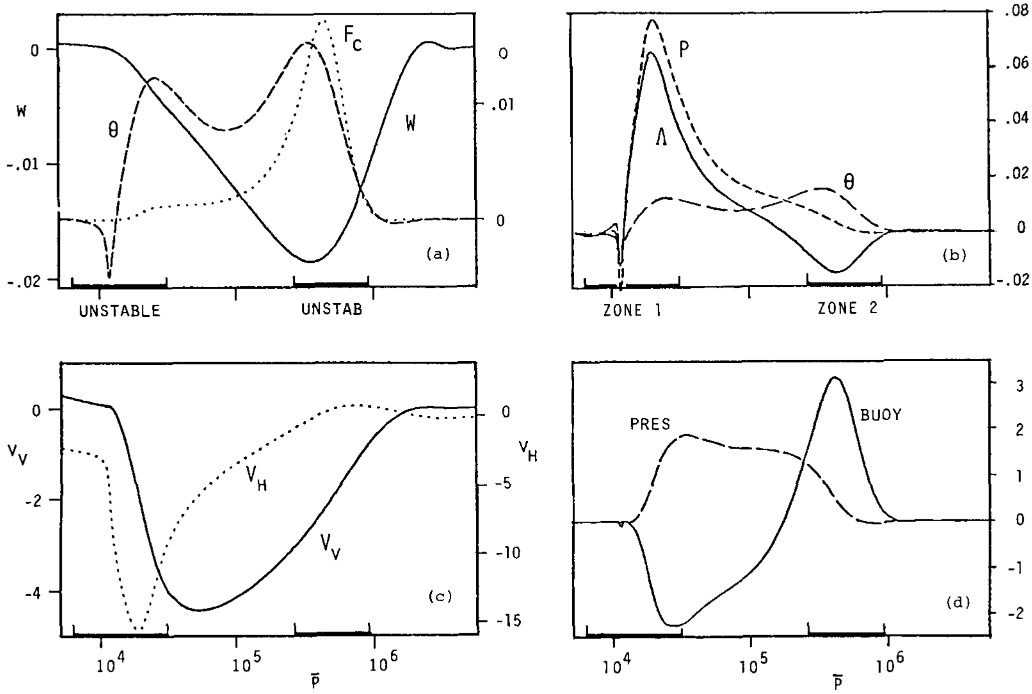

Figure 2. Properties of three-dimensional convection in the outer envelope of an A-type star as a function of depth (or log p). The domain extends over 30,000 km in the vertical, the surface of the star being on the left. Panel (a) displays the vertical momentum W, the relative temperature fluctuation θ and the convective heat flux F_c, revealing that convective motions driven mainly in the deeper unstable zone 2 (He^{++}) penetrate all the way to the surface of the star. The two convectively unstable zones (indicated by horizontal bars) are thus dynamically coupled. The proportion of the total flux carried by F_c at its maximum is 3.6%. Panel (b) presents both θ and the relative fluctuations in density Λ and in pressure P, all drawn to the same scale; this shows that Λ, and thus the buoyancy force, is controlled largely by θ in zone 2 and by P in zone 1. Panel (c) shows the vertical and horizontal velocities in km s^{-1}, with strong horizontal shear flows present in zone 1 (H^+). Panel (d) displays the work done on the motions by buoyancy and pressure forces, showing buoyancy driving in zone 2 and braking generally above.

vertical motions (as shown by V_V in Figure 2c) in the convection deeper down are turned into strong horizontal shear flows (V_H) in the upper zone, largely as a result of the strong braking of vertical momentum in this region. This serves to greatly diminish the vertical velocity amplitudes that are actually visible in the atmosphere. Such a result is quite remarkable: convection of small horizontal scale, like granulation, can experience buoyancy driving in the H^+ zone, while supergran-

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ular scales experience major pressure forces in that region, which serve to turn the flow. The deflection of the large-scale flows is partly a response to the rapidly decreasing scale height, for similar behavior is evident in models of compressible convection in polytropes (Graham 1975; Massaguer and Zahn 1979). Net work is extracted by both the small and large scales of convection from the H^+ unstable zone, though how this is accomplished is very different.

These results with A stars suggest that supergranulation in the Sun may well have the behavior depicted in Figure 2, thereby possessing strong horizontal flows in the H^+ zone just below the surface. Further, the shallow but highly unstable H^+ region can largely prevent large-scale cellular motions from getting through into the atmosphere with any significant portion of their original momentum. If this prediction is borne out by further work with anelastic modal equations applied explicitly to the Sun, then we may arrive at an explanation of why the observed velocity amplitudes in supergranular flows in the atmosphere are so small. This may also explain why the giant cells of global scale (manifestations of which appear in magnetic field patterns) are just below detection level for velocities in the atmosphere.

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