EXAMPLES OF NON-THERMAL MOTIONS AS SEEN ON THE SUN

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SUMMARY

On the sun we can identify many of the motions derived from stellar spectral analysis. A summary is given of the observed solar velocity phenomena. Many of these (e.g. meridional flow, giant cells, solar differential rotation, supergranulation) are of great interest in astrophysics especially for interior structure and chromospheric and coronal structuring but contribute virtually nothing to the velocities derived from a solar irradiance spectrum analysis. Others (granulation, very small scale motions and to a lesser extent, oscillations) do contribute substantially to the integrated sun velocity analysis. Some of the properties of these motion fields are described.

1. INTRODUCTION

The word "turbulence" in astrophysics is used generally to decribe motions which cause line broadening and changes in line saturation (curve of growth effects) but which are otherwise intangible as a specific kind of motion because of the absence of additional observational information like spatial resolution, characteristic line profiles, line shifts, etc. Turbulence in astrophysics may therefore have nothing or little to do with hydrodynamic turbulence except for the fact that statistical techniques are used also in astrophysics to define the magnitude of the associated non-thermal motions because of the lack of sufficient observations. Astrophysical "turbulence" can include convection, waves, stellar winds, large scale flow patterns and even stellar rotation if the spectral resolution is insufficient to identify the characteristics of any of these non-thermal motions. Even "microturbulence," or the quasi-thermal motions derived from line saturation changes, can result from e.g. systematic velocity gradients along the line of sight say in stellar winds, in convection, or in acoustic waves propagating along the line of sight. Observations on the sun, where the abundance of precise observations allows the identification of many, although not all, of these "turbulent" motions, substantiate the

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[†] Operated by the Association of Universities for Research in Astronomy, Inc. under contract AST 78-17292 with the National Science Foundation.

above. Rather than talking about "turbulence" I therefore will use the term "non-thermal motions" to refer to the kind of motions discussed in this colloquium and the terms "micro-" and "macro-velocities" as introduced by Canfield and Beckers (1976) for what is often referred to as "micro-" and "macroturbulence." As a statistical measure of the non-thermal motions I will use rms velocities which are √2 x less than the usual turbulent velocities in the case of a gaussian velocity distribution.

In this review I will first summarize the non-thermal motions derived from observations of the sun as a star. Then I will describe the resolved and unresolved solar velocity fields as known today and compare these with the sun as a star results. Solar observations thus serve to identify the astrophysical mechanisms responsible for the stellar non-thermal motion observations. I refer to other recent reviews for a more detailed description (Beckers and Canfield, 1976; Canfield and Beckers, 1976; Deubner, 1977; Zirker, 1979; Beckers, 1980).

2. RESULTS OF SOLAR IRRADIANCE SPECTROSCOPY

High resolution, good photometric precision spectra of the integrated sun radiation obtained by Beckers _et al_. (1976) were analyzed by Gray (1977) and Stenholm (1977). Figure 1 shows part of this spectrum atlas. Stenholm (1977) derives a total

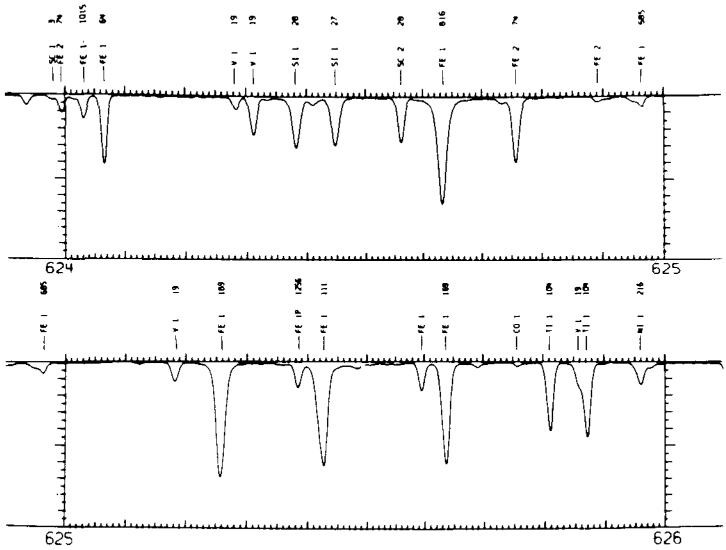

Figure 1. Portion of the spectrum atlas of integrated sunlight by Beckers _et al_. (1976).

non-thermal rms velocity field of 1.0, 0.6 and 0.3 km/sec for continuum optical depths of 10^{-1}, 10^{-2} and 10^{-3} respectively using Goldberg's (1958) multiplet method. These values are impossibly small considering that the solar rotation alone should result in rms velocities in excess of 1 km/sec.

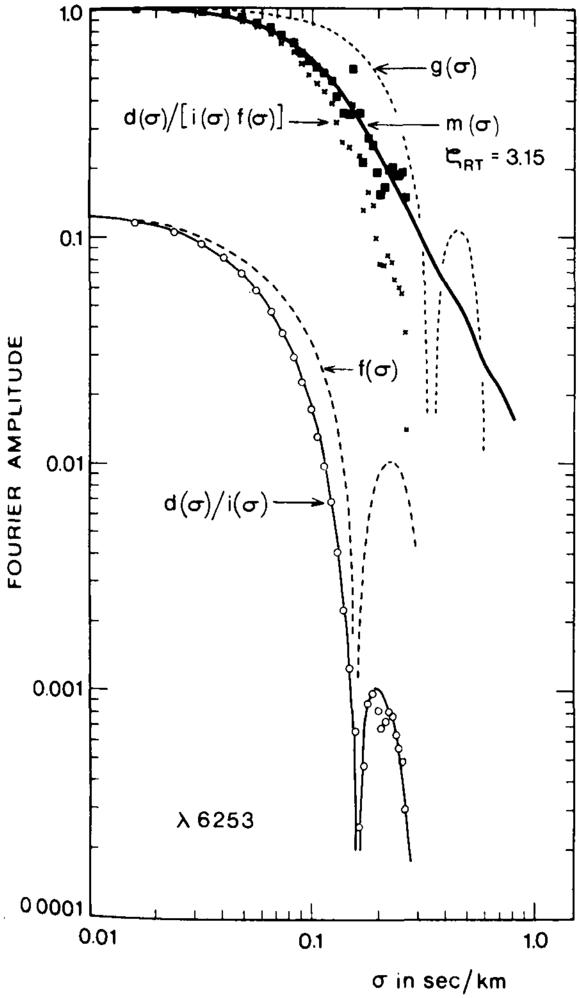

Figure 2. Analysis by Gray (1977) of the integrated sun λ6252.6 profile in the Fourier transform domain. σ = frequency in spectral domain (in cycles/Å); d(σ) = line profile; i(σ) = instrument profile; g(σ) = solar rotation; m(σ) = macrovelocities (from Gray, 1977).

Gray's (1977) analysis of solar line profiles in the Fourier transform domain gives results which look more reasonable. Figure 2 is from his publication and shows the separation (in the Fourier transform domain) of the Fe I λ6252.6 solar profile, after correction for instrumental smoothing (d(σ)/i(σ)), in solar rotation g(σ), macrovelocities m(σ) and the inherent line profile (including microvelocities), f(σ). The solar rotation velocity derived from g equals 1.92 km/sec which compares well with the solar synodic equatorial rotation rate of 1.80 km/sec. The rms microvelocity derived from the zero(s) in f(σ) (0.35 km/sec ± 0.1 km/sec) is somewhat less than the 0.5 and 0.7 km/sec vertical and horizontal microvelocities determined from "resolved" disk observations at $\tau \approx 0.01$ (Canfield and Beckers, 1976). The rms macrovelocities range from 2.1 to 1.6 km/sec when derived from weak to medium strong (≈150 mÅ) lines. These exceed the vertical (horizontal) macrovelocities derived from "resolved" disk observations (insufficiently resolved however to resolve the macrovelocity contributors) of 1.2 (1.6) km/sec and 0.7 (1.3) km/sec for $\tau_0 = 0.1$ and 0.01 respectively by almost a factor of two. An analysis of integrated sun spectra by Smith (1978) leads to similarly high values for the solar macrovelocities. The differences are probably the result of the different methods used in analyzing line profiles. It would be of interest to analyze the same set of solar spectral lines for macro- and microvelocities in both integrated sunlight and "resolved" disk spectra using the same analysis technique The result of such an analysis should remove the integrated sun - "resolved" solar disk discrepancies thus establishing a firmer link between solar and stellar velocity observations.

3. RESOLVED SOLAR MOTIONS

Figure 3 and Table 1 summarize the kinds of motions which have been resolved in the solar atmosphere. The important contributors to the total non-thermal velocity field are the solar rotation, the 5-minute oscillations and the solar granulation. The interesting solar motions associated with the supergranulation, non-radial pulsations and meridional flows would entirely escape detection in line profile analysis of the sun as a star but may show up in other ways. For example, the reversals in the integrated sun Ca^+ H and K profiles result to a large extent from the brightening in the chromospheric network which in turn originates in the supergranulation. I will restrict myself here to a short discussion of the three main known contributors to the macrovelocity field.

3.1 SOLAR ROTATION

There are many different ways of measuring solar rotation using both spectroscopic techniques and the proper motions of tracers such as sunspots, coronal and chromospheric structures, standing 5-minute acoustic waves, etc. Recent reviews of methods and results are given by Howard (1978) and Paternó (1978). Of special interest are:

a. A systematic difference between the rotation rates of the photospheric

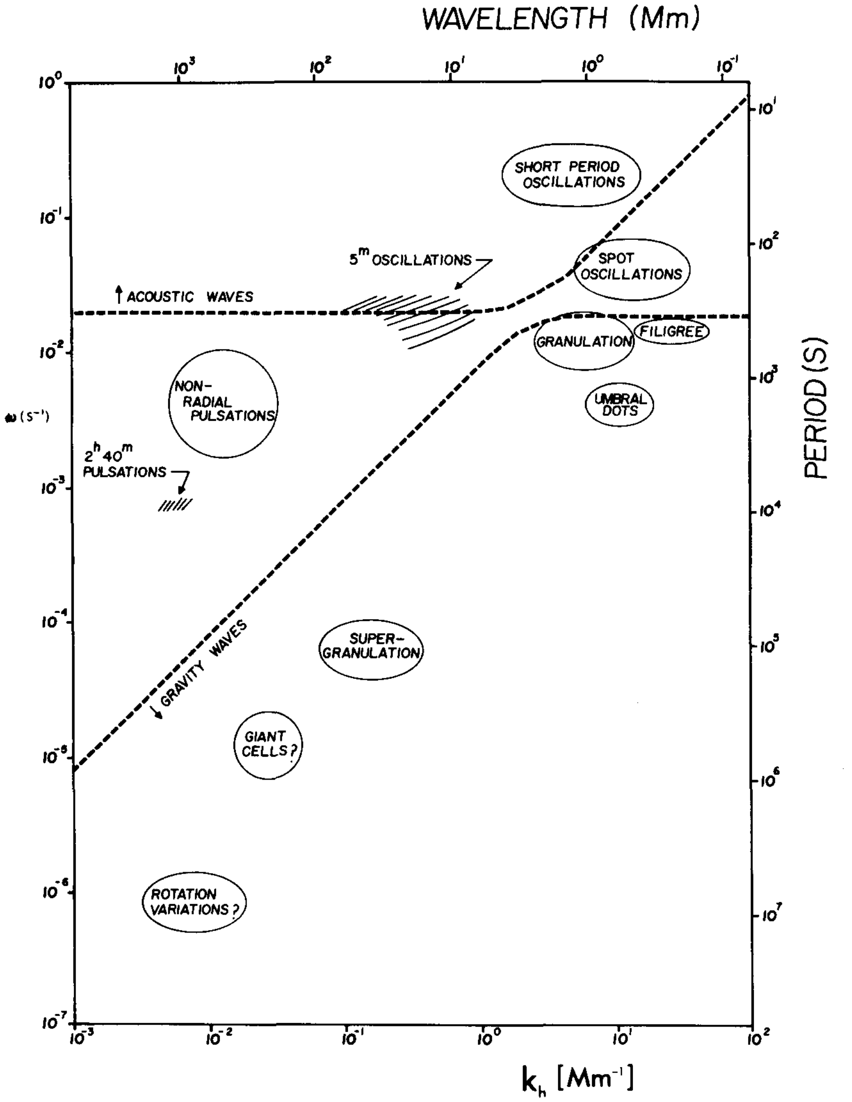

Figure 3. Location on the (k_h,ω) diagram of different types of solar velocity phenomena.

plasma as determined from Doppler shifts and that of longer-lived magnetic phenomena like sunspots, and other active region phenomena (Figure 4). The latter rotate ∿ 4% faster than the plasma or the short-lived magnetic phenomena. This difference is generally interpreted as the result of an increase of

TABLE 1

Summary of Resolved Velocity Structures on the Quiet Sun

Structure	Size (km)	Lifetime	Velocity (rms*) ($\tau_0 = 0.1$) Vertical	Velocity (rms*) ($\tau_0 = 0.1$) Horizontal	Comments
Rotation	700000	10^{10} yr	0	1.8 km/sec	- 1.8 km/sec is the synodic rotation velocity - Varies with latitude (differential rotation) - 4% faster for "magnetic phenomena" (spots, faculae, etc.) - Differential rotation absent for coronal holes and large scale magnetic patterns - (Apparent) temporal variation of ∿ 2%
Meridional Flows	700000	?	---	30 m/s	- Towards poles
$20\text{-}60^m$ Non-radial Pulsations	10^5?	?	.5 m/s	---	- Detected as solar diameter variations and maybe in Doppler shifts
160^m Pulsations	700000	?	.5 m/s	---	- Detected by Doppler shifts
Large Scale Flows	200000?	?	---	30 m/s?	- Probably responsible for apparent rotation variations - May be identical to so-called giant cells
Supergranulation	32000	1 day	30 m/s?	150 m/s	- Packed pattern of large convection cells - Perhaps driven by He ionization zone - Causes a structuring of the photospheric magnetic field which in turn causes the chromospheric network
5^m Oscillations	20000	$\geq 100^m$	400 m/s	---	- Standing acoustic waves in upper convection zone

TABLE 1 (continued)

Structure	Size (km)	Lifetime	Velocity (rms*) ($\tau_0 = 0.1$)		Comments
			Vertical	Horizontal	
5^m Oscillations (continued)					- Show interference patterns both in temporal and spatial domain
Granulation	1500	500^s	460 m/s	890 m/s	- Associated with large intensity fluctuations (11% at 5000 Å) - Is convective overshoot phenomenon - Larger velocity amplitudes have been claimed
Short Period Oscillations	500?	?	250 m/s?	200 m/s?	- Periods < 100^s - Presence and magnitude under debate
Filigree	150km	500^s?	(500 m/s)	---	- Small scale magnetic regions of ∿ 1500 gs strength - Cover only very small fraction of sun and therefore do not contribute to total velocity field
TOTAL RESOLVED MOTIONS EXCLUDING ROTATION:			660 m/s	920 m/s	

*rms except for solar rotation and meridional flows for which actual velocities are given.

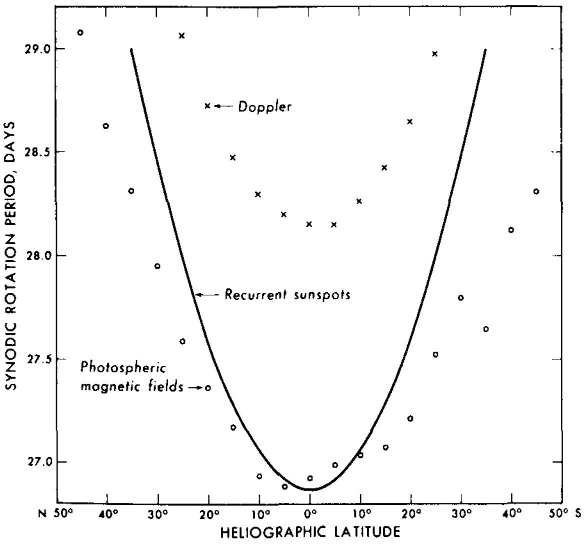

Figure 4. Solar rotation as a function of heliographic latitude for magnetic phenomena (sunspots) and photospheric plasma (Doppler) (from Wilcox and Howard, 1970).

rotation rates inwards into the sun in maybe the first ∿ 25000 km, this increase being reflected by deep-seated tracers like sunspots. This view has recently received additional support by the observation of the increase of solar rotation rates with depth using the standard 5^m period acoustic waves (Deubner et al., 1979). For stellar observations this may mean that rotation rates determined from line profiles and from e.g. periodic fluctuations of Ca^+ H and K profiles need not be the same.

b. A major variation of the differential rotation with latitude depending on the type of tracers used. Some, especially the long-lived coronal holes and general quiet sun magnetic field patterns show almost no differential rotation. This is believed to be due to a more rigid rotation of the solar interior probably in the deeper convection zone (∿ 100000 km?).

c. Temporal variations of the solar rotation of the order of a few percent. Short term changes (1-1000 days) are probably due to the passage of large scale velocity cells on the solar surface. Longer term changes like solar cycle-related changes of ∿ 3% (Howard, 1976; Livingston and Duvall, 1979) and secular changes (∿ 100 years) of ∿ 2% (Schröter and Wöhl, 1978) cannot be due to solar angular momentum changes on these time scales but must be the result of a redistribution of this momentum in the convection zone.

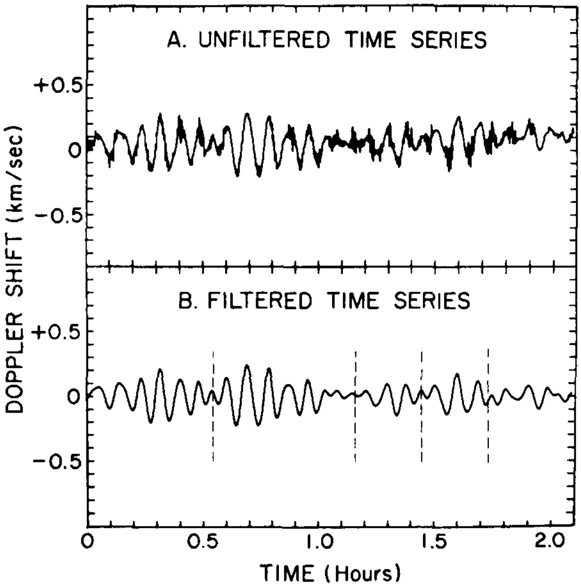

Figure 5. Typical velocity curve for individual oscillation (averaged over 10 x 10 arc sec) (from White and Cha, 1973).

3.2 FIVE MINUTE OSCILLATIONS

Figure 5 shows the time variation of the Doppler shift at one point on the solar disk. The velocity oscillations with 5 minute periods increase in amplitude with height. The rms velocity amplitude is given by Canfield (1976) as

$$V_{rms} = 0.35 \exp(h/1100) \text{ km/sec} \qquad (1)$$

where h equals the height above τ_{5000} (= τ_0) = 1 in km. The 5 minute oscillations in the photosphere are evanescent waves but just below the solar surface they can be identified with propagating acoustic waves (or p-mode waves) which propagate inward into the sun to some depth at which they are reflected upward again to be reflected again near the solar surface. The trapping of the waves results in an interference pattern which shows up at the solar surface as a ridge structure in the (k_h,ω) diagram as predicted by Ulrich (1970) and Ando and Osaki (1975) and as observed by Deubner (1975, 1978) and Rhodes _et al_. (1977, see Figure 6). The 5 minute oscillations are therefore an important tool for the study of the solar interior and have so far led to somewhat improved models of the solar convection zone (Rhodes _et al_., 1977), an estimate of the mixing length parameter ℓ/H of 2-3 (Rhodes _et al_., 1977)

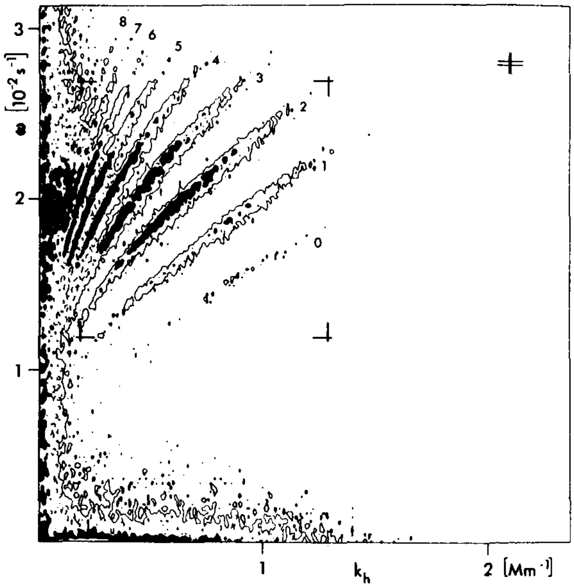

Figure 6. (k_h,ω) diagram of solar 5^m oscillation showing the resolved interference patterns (from Deubner, 1978).

and a measure of the depth variation of the solar rotation rate (Deubner et al., 1979).

3.3 SOLAR GRANULATION

The solar granulation is the result of the convective overshoot of the motions in the superadiabatic convection zone below the visible solar surface into the subadiabatic photosphere. Although in deeper layers convection carries most of the energy flux, at the layers we observe the granulation, only a small percentage of the energy is carried as convective energy flux. The solar granulation is close enough in size to the resolution limits of solar telescopes and of the atmosphere that corrections for finite resolution are major. This is especially true for velocity observations where longer exposure times, and more complex instruments, are needed. There is therefore disagreement among investigators as to the velocity fluctuations associated with the granulation. The values used in Table 1 were taken from Canfield (1976) who gives the rapidly decreasing (with height) vertical rms velocity associated with the solar granulation as

$$V_{rms} = 1.27 \exp(-h/160) \text{ km/sec} \tag{2}$$

a result which has been substantially confirmed by Keil (1979) by a better separation of granular and oscillatory velocities.

Durrant et al. (1979) however strongly disagree with the Canfield and Keil results. They derive a much slower height variation of

$$V_{rms} = 0.98 \exp(-h/1700) \text{ km/sec} \qquad (3)$$

which leads to much larger velocities at the heights where lines are observed. This implies much more convective overshoot and lends some support to granule models by Nordlund (1976, 1977, 1978, 1979). These models have much larger velocities than those listed in Table 1, so large in fact that the almost entire macrovelocity field is contained in solar granular motions.

The observations by Keil and Canfield (1978) are the basis for the theoretical model of the solar granulation by Nelson (1979) shown in Figure 7. This model shows

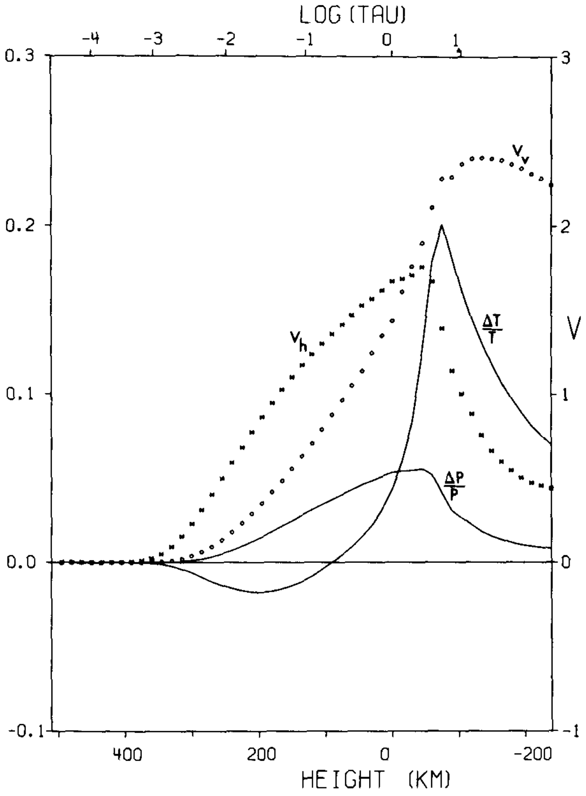

Figure 7. Model for solar granulation ΔT/T and ΔP/P and the horizontal and vertical velocities refer to amplitudes of sinusoidal variations (from Nelson, 1979).

substantial horizontal motions and a temperature inversion at $\tau_0 = 0.23$ (as indeed has been observed in the wings of the Ca^+ H and K lines). This model has a cell size of 1060 km, somewhat below the observed value of 1500 km and it does not, of course, include the wide distribution of convective cell sizes actually observed on the sun.

Solar granulation, although mostly constant across the solar disk, does show some decrease in both contrast and size in active regions and perhaps at supergranule boundaries.

4. UNRESOLVED SOLAR MOTIONS

Depending on whether one accepts the results and models by Canfield (1976), Keil (1979) and Nelson (1979) or those by Durrant et al. (1979) and Nordlund (1976, 1977, 1978, 1979) there is or there is not a significant amount of unresolved solar motions (at scales $\leq$ 500 km). This is an unresolved question but I tend towards the Canfield and Keil results. That leaves most of the solar motion field at small scales. There are some clues as to the nature of this small scale velocity field:

4.1 SHORT PERIOD OSCILLATIONS

Deubner (1976a, b) suggests that the remaining line broadening and the microvelocities are due to short period ($\leq$ 1 minute) propagating acoustic waves with spatial wavelengths along the line of sight comparable to or smaller than the width of the velocity weighting function. He supports the suggestion by observations of the temporal power spectrum of solar velocities which show small high frequency peaks (periods $30\text{-}100^s$) which he contends are the result of the peculiarities of spatial filtering along the line of sight by the velocity weighting function. After a large correction for this filtering he derives $\sim$ 1 km/sec rms velocities at $\tau_0 \approx 0.1$ for these oscillations which comes close to explaining the entire line broadening. Cram et al. (1979), on the basis of a full dynamic model for a 30-second period oscillation, find that these rms velocities could be as small as 0.1-0.2 km/sec which is insufficient to explain the line broadening but sufficient for coronal heating.

4.2 UNRESOLVED CONVECTIVE MOTIONS FROM THE LIMB EFFECT

After correction for gravitational redshift solar lines show a blue shift with respect to their laboratory wavelength standard. Because of its peculiar center to limb variation this shift has been called the "limb effect." Of the three most likely causes for the limb effect, pressure shifts, wave shifts and convective shifts, only the latter remains as a possible one after Beckers and DeVegvar (1978) and Cram et al. (1979) showed that the former two are much too small and perhaps of the wrong sign. Convective wavelength shifts are caused by the correlation of intensity and velocities seen e.g. in the solar granulation. The different weighting of the out and in line-of-sight velocities by the intensities results in an apparent outward motion (blue shift) of solar lines even when there is no net mass flux. The origin of the limb effect as a convective line shift receives further support from the properties of the limb effect: (i) the decrease of the line shift with increasing line strength (e.g. Beckers and DeVegvar, 1978) as the consequence of the decrease of the convective overshoot with height, (ii) the absence of the line shift in sunspots (Beckers, 1977) as the consequence of the suppression of convection in sunspots, and (iii) the explanation of the center-to-limb variation as the consequence of the effect of both vertical and horizontal motions in convective elements (Beckers and Nelson, 1978).

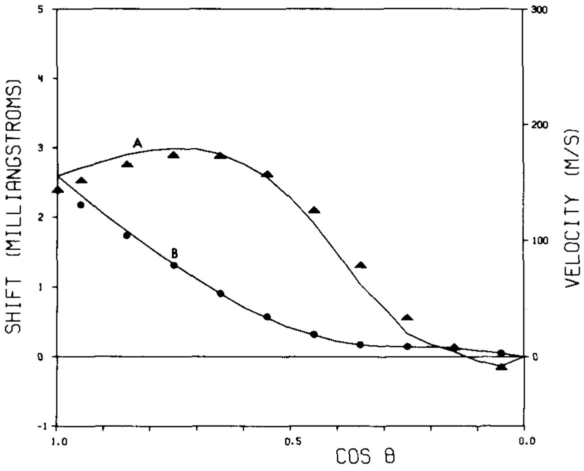

Figure 8. Calculation of the limb effect for a weak 2eV excitation potential line using the Nelson (1979, see also Figure 7) model of solar granulation. Curve B includes only vertical velocities in the granulation, curve A includes both vertical and horizontal velocities. Full lines are for line center Doppler shifts, dots and triangles are for line center of gravity displacements (from Beckers and Nelson, 1978).

Figure 8 shows the calculated center-to-limb variation for the Nelson (1979) model of solar granulation including both vertical and horizontal motions. The calculated wavelength variation is indeed very similar in shape to the observed limb shift but it is a factor of 2 to 3 smaller. If indeed the convective shift interpretation is correct, it implies that the Nelson model underestimates the velocities and/or temperature fluctuations by a factor of ∿ 2. This may be the result of insufficient resolution of the spectra used to calibrate the model. The Nordlund model, on the other hand, would give results quite consistent with the observed limb effect. As the most likely state of affairs I will assume that the Nelson model holds for convective cell sizes between 500 and 2000 km and I will postulate at $\tau_0 \approx 0.1$ to 0.01 a smaller convective cell regime with sizes between 50 and 500 km and with velocities twice that of the granulation (see Table 1). With the addition of the granular convective shift these cells produce a total convective shift comparable to the observed shift.

TABLE 2

Contributions to the Total Non-Thermal Velocity Field

Structure	rms Velocity (m/s) $\tau_0 = 0.1$ (h = 138 km)		rms Velocity (m/s) $\tau_0 = 0.01$ (h = 238 km)	
	Vertical	Horizontal	Vertical	Horizontal
Supergranulation	30?	150	30?	150
5^m Oscillations	400	0	450	0
Resolved Granules	460	890	90	450
Unresolved Convection from limb effect	920	1780	180	900
Short Period Oscillations	250	200?	280	220?
Total	1130	2000	570	1080
Total Macro- and Micro-velocities from Line Width*	1460	2060	910	1550
Residual	920	500	710	1110
Total Microvelocities*	1160	1770	730	1100

*From Canfield and Beckers (1976).

Table 2 completes Table 1 with this assumed motion and compares the total motion thus derived with the total non-thermal motions and the microvelocities as summarized by Canfield and Beckers (1976). Figures 9 and 10 show the same data in the form of the power contained in the different size regimes. The residual power at horizontal scales below 50 km is shown, rather arbitrarily, as a Kolmogoroffian distribution. Also shown is the total velocity power above a given horizontal size as well as the power contained in microvelocities (μ). Table 2 and Figures 9-10, crude as they are, give a reasonable summary of our current understanding on the size distribution and the physical nature of the solar photospheric velocities.

5. CONCLUSION

Much, and probably most, of the solar non-thermal motions occur on scales smaller than the resolution limits of present observations. Although the sun teaches us something about the nature of velocity fields in stars of the solar type, it has

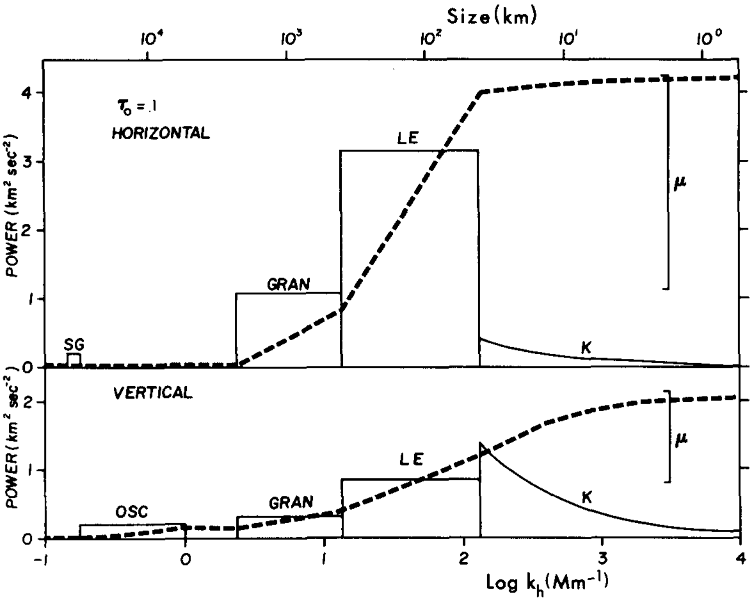

Figure 9. Power (rms velocities squared) associated with the different velocity regimes at τ_0 = 0.1. SG = supergranulation; OSC = oscillations; GRAN = resolved granulation according to Nelson (1979); LE = unresolved convective motion derived from limb effect and K = assumed Kolmogoroffian velocity distribution for spatial scales less than 50 km with an amplitude to give the total non-thermal velocity as observed from line width. μ = microvelocity according to Canfield and Beckers (1976); the upper limit of the bar associated with μ is the total micro and macro velocity field. The dashed line represents the total velocity power at scales above the scale in the abcissa.

not told us all. In this paper I have not discussed any of the numerous interesting chromospheric and coronal motions which have been observed on the sun. Neither did I discuss motions in strong magnetic field regions like sunspots which are similar in total magnitude to those on the quiet sun but totally different in nature. The study of motions in the quiet photosphere by itself is however a most interesting topic because of the interesting astrophysical processes involved which include both small scale convection, large scale circulation, pressure waves, rotation, etc. The sun allows us to make more detailed measurements of these motions and to compare these with astrophysical predictions.

Comments by Drs. Cram, Keil and Zirker helped me in the preparation of this paper.

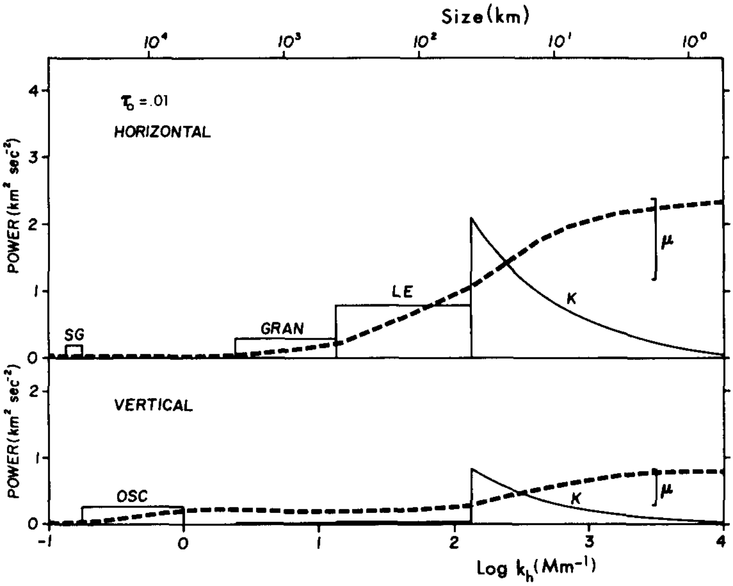

Figure 10. As Figure 9 but for τ_0 = 0.01.

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