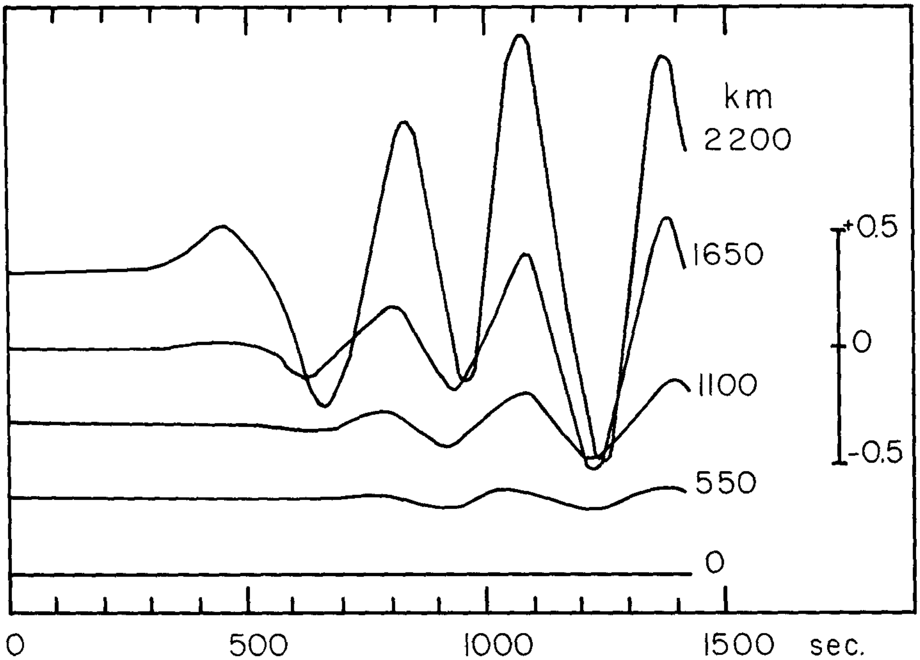

Fig. 1. Vertical velocity as a function of time at different levels, 4000 km from the center. The scale at the right gives the velocity in units of the maximum velocity at the origin.

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10. WAVE MOTION AND THE STRUCTURE OF THE SOLAR CHROMOSPHERE

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Although the structure of the solar atmosphere depends to some extent on the magnetic field, it cannot be said to be highly sensitive to this field. This fact indicates that the nonthermal energy flux responsible for heating the chromosphere and corona is predominantly acoustic rather than magnetohydrodynamic.

If one considers that the energy propagation is in the form of acoustic waves, and takes note of the fact that the propagation characteristics of acoustic waves in a gravitating atmosphere

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differ from those of acoustic waves in a uniform gas, one obtains a good fit to observational data for the middle and upper chromosphere and the corona.

The dispersion relation for the propagation of acoustic waves vertically in a gravitating atmosphere is

$$\omega^2 = \omega_0^2 + a^2k^2 \tag{1}$$

where a is the speed of sound and ω_0 is the resonance frequency $a/2H$, where H is the scale height. Frequencies below ω_0 (which corresponds to a resonance period of about 5 minutes) are not propagated but are instead evanescent. Waves of this character may be responsible for the heating of the low chromosphere. Photospheric disturbances of frequency ω_0 give rise to a resonant excitation of the chromosphere, which is observationally detectable (**1**).

Waves of frequencies greater than ω_0 may propagate, but the nature of the dispersion relation (1) has two interesting effects. One is that waves launched with frequency close to ω_0 will be refracted *towards* the vertical as they propagate through the solar atmosphere. The second is that waves which are harmonically related in frequency are not harmonically related in wave number: this has the important effect of inhibiting the build-up of harmonics of a small-amplitude wave, thereby inhibiting the formation of shock waves.

An important consequence of the second point is that waves will form shocks, and hence dissipate, only if the amplitude of velocity oscillations is comparable with the speed of sound. The condition that waves should form weak shocks, and thereby dissipate a small fraction of their energy, is in this way found to be approximately.

$$n^2T^3 = 10^{24}s^2 \tag{2}$$

where s is the energy flux (in cgs units). If, for a given energy flux and density, the temperature were lower than given by equation (2), shock waves would be formed, some of the energy would be dissipated, and the temperature would rise. If, on the other hand, the temperature were higher than indicated by equation (2), the acoustic waves would not form shocks, there would be no dissipation, and radiation would reduce the temperature. We see, in this way, that the heating mechanism is *self-stabilizing*.

If one compares relation (2) with data for the chromosphere (**2**), one finds that there is good agreement if one adopts for the energy flux s the value 10^5 erg cm^{-2} sec^{-1}. This is indeed the value deduced by Osterbrock (**3**) for the energy flux which must be delivered to the corona.

One may understand the transition from the chromosphere to the corona by considering the influence of thermal conductivity upon propagation of acoustic waves (**4**). In the chromosphere, thermal conductivity is sufficiently low that the equation of state is adiabatic and the acoustic waves are not dissipated. In the corona, thermal conductivity is sufficiently high that the gas is isothermal and again there is no dissipation. Dissipation of acoustic energy by thermal conductivity is highest where the conductivity is not so low that the gas is adiabatic and not so high that it is isothermal. For a given frequency spectrum of acoustic waves, one may determine a relationship between density and temperature which expresses this critical condition. One then finds that this condition enables one to understand why, at a certain height, the temperature of the solar atmosphere ceases to increase. The acoustic energy flux which arrives at the upper chromosphere is dissipated in the transition region between the chromosphere and corona. The energy injected in this region is dissipated partly by conduction out into the corona and partly by conduction back down into the chromosphere.

These ideas are described at greater length in Reference (**5**).

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DISCUSSION

P. A. Sturrock. (answering a question by E. A. Spiegel). Radiative losses should be taken into account, and the n, T relationship should then ensure that the energy input from acoustic waves is just sufficient to balance radiative loss. Since the energy loss from acoustic waves is very sensitive to M, this should not effect the n-T profile greatly.

C. de Jager. If shockwave dissipation is only important for $M \gg 1$, how should one then explain that the temperature in the upper photosphere (for $\tau_0 \lesssim 0{\cdot}1$) deviates already considerably from the value computed for radiative equilibrium, whereas at these levels $M < 0{\cdot}5$?

P. A. Sturrock. This model was developed for application to the middle and upper chromosphere. The low chromosphere is apparently heated by a different energy flux—possibly by acoustic waves of frequency less than the critical frequency, which are evanescent.

11. DÉFORMATION DU PROFIL DES RAIES LIÉES AUX ONDES SONORES DANS LE CAS SOLAIRE

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Nous supposons l'atmosphère solaire traversée par des ondes planes, telles que la vitesse verticale de la matière à l'altitude z et à l'instant t soit donnée par l'expression

$$v(z, t) = a\,\rho(z)^{-\frac{1}{2}} \cos 2\pi\left(\frac{t}{P} - \frac{z}{L}\right)$$

dans laquelle a est un coefficient arbitraire et $\rho(z)$ la densité à l'altitude z.

Nous étudions le profil d'une raie de Fraunhofer au centre du disque solaire. Soient A et B deux points du profil non perturbé, d'égale intensité et distants de $2\,\Delta\lambda$; A′ et B′ les points correspondants du profil à l'instant t (égale intensité, même distance $2\,\Delta\lambda$). Nous appelons $d(t)$ le déplacement Doppler entre AB et A′B′.

En supposant la température, la densité et la fonction source dans la raie indépendantes du temps en première approximation, nous calculons par des procédés numériques et pour diverses valeurs de a et L les premiers termes du développement de Fourier de $d(t)$.

La méthode est appliquée aux deux raies 8514 Fe I et 8542 Ca II, avec les valeurs de $\Delta\lambda$ utilisées dans les observations par J. Evans, R. Michard et R. Servajean (1). Nous utilisons le modèle solaire d'Utrecht (1964) et adoptons pour la raie 8542 Ca II une fonction source empirique déduite des observations de Zirker.

Dans les deux cas, $d(t)$ est bien représenté par le premier terme de son développement de Fourier, si l'on se limite à d'assez grandes longueurs d'ondes et à de faibles amplitudes: la