

## MODEL FOR ENERGY TRANSFER IN THE SOLAR WIND: MODEL RESULTS

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We describe the results of calculations of solar-wind flow in which the heating is due to (1) propagation and dissipation of hydromagnetic waves generated near the base of the wind, and (2) thermal conduction. A series of models is generated for fixed values of density, electron and proton temperature, and magnetic field at the base by varying the wave intensity at the base of the model. This series of models predicts the observed correlation between flow speed and proton temperature for a large range of velocities. The wave heating takes place in a shell about the sun  $\gtrsim 10 R_{\odot}$  thick. We conclude that large-scale variations observed in the solar wind are probably due mainly to variation in the hydromagnetic wave flux near the sun.

### ABSTRACT

Hartle and Barnes (p. 248) describe the formulation of solar-wind models in which hydromagnetic-wave dissipation is part of the energy transport. Here we review the results of these calculations and their implications [Barnes *et al.*, 1971].

The base radius was chosen to be  $2 R_{\odot}$ , as in the investigation by Hartle and Barnes [1970] of the effects of artificially specified heat sources. The base number density, electron temperature, proton temperature, and magnetic field were chosen to be, respectively,  $n_0 = 1.46 \times 10^6 \text{ cm}^{-3}$ ,  $T_{e0} = 1.3 \times 10^6 \text{ }^{\circ}\text{K}$ ,  $T_{p0} = 1.7 \times 10^6 \text{ }^{\circ}\text{K}$ , and  $B_0 = 0.18$  gauss. These values are somewhat different from those used in the earlier work [Hartle and Barnes, 1970] with artificial heat sources, but are still consistent with coronal observations. The choice of proton temperature greater than electron temperature implies preferential heating of the protons below  $r = 2R_{\odot}$ ; this effect is consistent with coronal observation [Newkirk, 1967] and is predicted by D'Angelo's [1968, 1969] model of heating the inner corona. The circular frequency of the hydromagnetic waves was

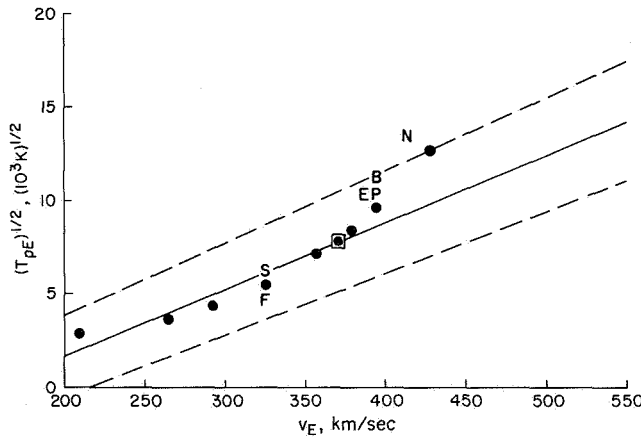
chosen as  $\omega_0 = 2 \times 10^{-2} \text{ sec}^{-1}$ , which corresponds to the maximum noise in the chromosphere and photosphere [Leighton *et al.*, 1962; Tanenbaum *et al.*, 1969]. The results of these computations ( $n$ ,  $v$ ,  $T_e$ ,  $T_p$  and  $B$  at

Table 1. Number density, flow speed, electron and proton temperatures, and magnetic field strength at 1 AU

$F_0$ , erg cm <sup>-2</sup> sec <sup>-1</sup>	$n_E$ , cm <sup>-3</sup>	$v_E$ , km/ sec	$T_{eE}$ , °K	$T_{pE}$ , °K	$B_E$ , $\gamma = 10^{-5}$ gauss
0	20	210	$2.4 \times 10^5$	$8.5 \times 10^3$	3.5
$1.4 \times 10^3$	18	270	$2.3 \times 10^5$	$1.3 \times 10^4$	2.9
$2.2 \times 10^3$	16	290	$2.3 \times 10^5$	$2.0 \times 10^4$	2.8
$3.4 \times 10^3$	15	330	$2.2 \times 10^5$	$3.2 \times 10^4$	2.6
$4.5 \times 10^3$	14	360	$2.2 \times 10^5$	$5.0 \times 10^4$	2.4
$5.2 \times 10^3$	14	370	$2.2 \times 10^5$	$6.2 \times 10^4$	2.4
$5.8 \times 10^3$	14	380	$2.1 \times 10^5$	$7.9 \times 10^4$	2.4
$6.5 \times 10^3$	14	390	$2.1 \times 10^5$	$9.6 \times 10^4$	2.3
$1.2 \times 10^4$	13	430	$2.1 \times 10^5$	$1.7 \times 10^5$	2.2

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$r = 1$  AU) are summarized in table 1 [from *Barnes et al.*, 1971]. The subscript  $E$  denotes the value of a quantity at 1 AU. This series of models implies a correlation between  $T_{pE}$  and  $v_E$  that may be compared against the observed correlation. This comparison is indicated in figure 1 [Barnes et al., 1971] where we plot  $T_{pE}^{1/2}$  against  $v_E$  to facilitate comparison with the empirical formula of *Burlaga and Ogilvie* [1970a]. The predicted and observed correlations agree for  $v_E \lesssim 430$  km/sec; most (about 70 percent) solar-wind observations lie in this velocity range [Hundhausen et al., 1970]. The range of agreement can probably be extended to about  $v_E = 450$  km/sec by adjusting the base conditions.



**Figure 1.** Correlation of  $T_{pE}^{1/2}$  and  $v_E$ . The units of  $T_{pE}$  are  $10^3$  °K. Solid and dashed lines are, respectively, the average and variances of the Burlaga-Ogilvie empirical formula. Filled circles (including the boxed one) correspond to models listed in table 1. Letters N, E, P, B correspond to models in which one (and only one) of the boundary conditions is modified from the main series, with  $F_0 \approx 5.2 \times 10^3$  ergs  $\text{cm}^{-2} \text{sec}^{-1}$  (the corresponding main-series point is boxed): for N,  $n_0 = 1.2 \times 10^6 \text{ cm}^{-3}$ ; for E,  $T_{e0} = 1.2 \times 10^6$  °K; for P,  $T_{p0} = 1.6 \times 10^6$  °K; for B,  $B_0 = 0.2$  gauss. Letters S and F correspond to models with the same boundary conditions as the main series, but different wave frequencies; for S,  $\omega_0 = 10^{-2} \text{ sec}^{-1}$  and  $F_0 = 2.9 \times 10^3$  ergs  $\text{cm}^{-2} \text{sec}^{-1}$ ; for F,  $\omega_0 = 4 \times 10^{-2} \text{ sec}^{-1}$  and  $F_0 = 3.9 \times 10^3$  ergs  $\text{cm}^{-2} \text{sec}^{-1}$ . Reprinted courtesy University of Chicago Press © 1971.

Therefore, for the velocity range corresponding to most solar-wind observations, the observed temperature-velocity correlation is obtained for fixed base conditions by varying the single parameter  $F_0$  (the base hydro-magnetic wave energy flux). On the other hand, extension of the computed correlation curve indicates that

the predicted correlation will no longer agree with observation for velocities above 450 km/sec. One reason for this discrepancy may be that high-velocity winds come from coronal regions where the base conditions are different. However, it is also possible that the discrepancy is due to the large wave amplitudes associated with high fluxes ( $F_0 \gtrsim 10^4$  ergs  $\text{cm}^{-2} \text{sec}^{-1}$ ), for at large amplitudes the dissipation rate probably increases, and hence moves the heat source inward; furthermore, at large amplitudes the momentum transfer by wave dissipation can be significant. Both processes will probably increase  $v_E$  more than  $T_{pE}$ , which would improve the agreement between the models and observation.

Table 1 also predicts correlations among the other flow parameters. For example, it indicates an inverse correlation between density and flow speed, which is observed, although the computed densities are systematically higher than what is observed by about a factor 2. The predicted electron temperature does not vary much with flow speed, consistent with observation [Burlaga and Ogilvie, 1970a]; the values of  $T_{eE}$  given in the table are 30 to 40 percent higher than reported measurements, but considerably lower than the values obtained in previous two-fluid calculations [Hartle and Sturrock, 1968; Hartle and Barnes, 1970]. Finally, the calculations predict an inverse correlation between the magnetic field  $B_E$  and the flow velocity; observational studies are not conclusive on this point [Burlaga and Ogilvie, 1970b]. The computed values of  $B_E$  are systematically smaller than observed by about a factor 2.

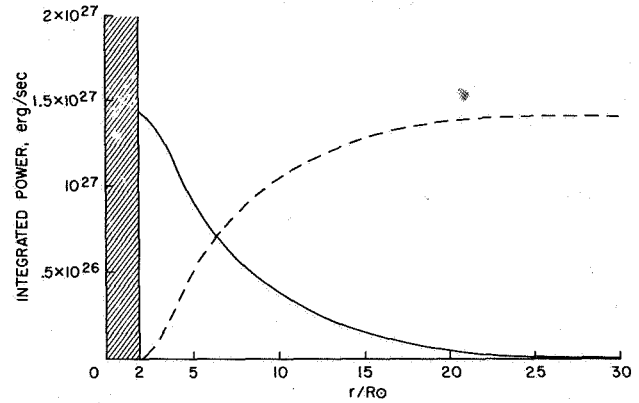
In summary, the correlations between velocity, density, and proton and electron temperatures are qualitatively consistent with observation, the electron temperature is somewhat higher than reported observations, and the density is high and the magnetic field low by about a factor 2. It may be that modifications in the model, such as the inclusion of nonradial flow and magnetic stresses, will be necessary to improve agreement between the predicted and observed values of density and magnetic field. On the other hand, it is possible that some improvement can be achieved by suitably changing the boundary conditions. We cannot at present make any conclusive remarks about the effects of varying the base conditions, because the large amount of computing time necessary for each model has limited the number of models that we have run. Such an investigation is planned. Some preliminary results on the effects of varying base conditions are indicated in figure 1, where we indicate the effects on the  $(T_{pE}, v_E)$  correlation. The effect of varying the wave spectrum

seems to be moving the  $(T, v)$  pair approximately along the observed correlation line, suggesting that this correlation is not very sensitive to the spectrum. Varying each of the base quantities  $n_0, T_{p0}, T_{e0}, B_0$  tends to move the  $(T, v)$  pair away from the observed correlation, although certainly some variation in these quantities is consistent with observation.

It is established that the observed correlation between proton temperature and flow speed in the solar wind at the orbit of earth can be explained by models in which an efflux of fast-mode hydromagnetic waves is dissipated beyond  $2 R_\odot$ . From this viewpoint, the large-scale variability in the observed  $v_E$  (and corresponding  $T_{pE}$ ) is due primarily to the variability of this efflux (and possibly of its frequency spectrum) rather than variability of density and temperature at the base of the outer corona. The order of magnitude of the postulated efflux ( $10^{27}$  ergs/sec) is quite reasonable when compared with estimates of the power required to heat the inner corona ( $5 \times 10^{27}$  ergs/sec) and the chromosphere ( $5 \times 10^{29}$  ergs/sec) [Osterbrock, 1961]. Since the power that heats the outer corona and solar wind by wave dissipation is fairly small compared with the power required to maintain the inner corona, it seems plausible that the relative large-scale inhomogeneity in the wave flux at  $2 R_\odot$  is greater than the relative inhomogeneities in large-area averages of density and temperature, which would mean that the flow properties of the wind are mainly determined by the wave flux  $F_0$ . Finally, the wave periods chosen in these models (2.5 to 10 min) correspond to maximum photospheric and chromospheric disturbance [Leighton et al., 1962; Tanenbaum et al., 1969]. Altogether, then, the assumptions about the wave flux and spectrum are consistent with what is known about the solar chromosphere and corona.

The proton heating takes place over a very extensive region, 10–20  $R_\odot$  in radius, as may be seen from figure 2, in which wave efflux and proton heating are plotted against  $r$  for one of the higher velocity models. In this case, half the proton heating takes place beyond  $r = 6.2 R_\odot$ , and the last 10 percent of the proton heating occurs beyond  $r = 14 R_\odot$  (the subsonic-supersonic transition in these models occurs at  $r \sim 6 R_\odot$ ). Half the wave efflux is dissipated inside  $r = 6 R_\odot$ , but 5 percent survives beyond  $r = 15 R_\odot$ . Thus it appears that a (small) fraction of the noise generated by the convective envelope of a late-type star should play a significant role in driving a stellar wind, and, in part, this noise would survive as turbulence many stellar radii from the star.

There is evidence for the existence of a turbulent region about the sun. It has been proposed that observed solar cosmic-ray anisotropies can be understood in terms



**Figure 2** Profile of the net wave efflux  $4\pi r^2 F_T(r)$  (solid line) and net integrated heating  $4\pi \int_0^r P_p(r') r'^2 dr$  for the protons (dashed line). These curves pertain to the model of table 1 defined by  $F_0 = 5.8 \times 10^3 \text{ ergs cm}^{-2} \text{ sec}^{-1}$ .

of scattering in a turbulent region ( $\sim 20 R_\odot$  characteristic dimension; see Burlaga, 1969). Radio observations suggest that the corona and solar wind are turbulent throughout the region  $r \lesssim 1 \text{ AU}$  [Hewish and Dennison, 1967; Cohen et al., 1967; Jokipii and Hollweg, 1970; Hollweg, 1970a]. Finally, Belcher and Davis [1971] have shown that much of the power in solar wind fluctuations directly observed at 1 AU is due to outwardly propagating Alfvén waves. They argued that these waves (net efflux  $\sim 3 \times 10^{24}$  ergs/sec, periods 10–10<sup>4</sup> sec) are very likely the signature of noise generated near the sun.

Assuming that the collisionless heating mechanism of these models is significant in stars other than the sun, it follows that the magnetic field of the star is crucial in determining whether a stellar wind flows. In one sense this is not surprising, since it is generally recognized that a suitably oriented strong magnetic field, through its stresses, might effectively inhibit the expansion of a stellar corona. But it turns out that even a radially oriented magnetic field can play a crucial role. If the energy transport in a stellar corona is purely conductive, then even a rather strong, but radially oriented magnetic field, would not restrict coronal expansion. On the other hand, if the magnetic pressure is substantially higher than particle pressure at the coronal base, dissipation of a sufficiently intense hydromagnetic-wave flux will choke off the flow. This occurs because if  $\beta_p = 8\pi n_0 k T_{p0} / B^2$  is small (about 0.3 or less), the damping rate  $\gamma \propto \exp(-1/\beta_p)$ , so that the damping rate can be very sensitive to  $B_0$ . Hence the heating may be

negligible at the base. But since  $\beta_p$  increases fairly rapidly with distance from the star, dissipation can become strong somewhere beyond the distance at which a purely conductive flow becomes supersonic. There will be strong heating in the region of supersonic flow, which will reduce the flow speed and possibly drive the expansion subsonic. Thus the magnetic field can act as a valve on a supersonic stellar wind.

Finally, we discuss briefly the relationship between the models reported in this paper and some other ideas about energy transport in the solar wind. It has been argued that typically observed values of  $v_E$  and  $T_{pE}$  can be understood without invoking an extended heat source, provided one assumes some collisionless mechanism for proton-electron energy exchange [Cuperman and Harten, 1970b; Hundhausen, 1969; Nishida, 1969]. There are two main difficulties with that view: first, there is no reason to believe that such energy exchange can account for the observed correlation between  $T_{pE}$  and  $v_E$ ; and second, it is not clear what sort of mechanism could produce such energy exchange, although some interesting possibilities have been discussed by Forsslund [1970]. It has also been proposed that an external heat source is not required if thermal conduction is inhibited by some mechanism [Hundhausen, 1969; Forsslund, 1970]. Again, it seems unlikely that the  $T_{pE}$ - $v_E$  correlation could be explained by such a cutoff of conduction. Furthermore, inhibition of thermal conduction in the region of supersonic flow does not affect the flow very strongly [Cuperman and Harten, 1970a; Holzer and Axford, 1970], its main effect being to reduce the conduction flux and (possibly) the electron temperature at 1 AU. In this connection, it may be noted again that the latter quantities are somewhat higher than their observed values in the present models, so that agreement with observation of these quantities might be improved by allowing for inhibition of thermal conduction. Also, due to our choice of base conditions, the thermal conduction flux at 1 AU is considerably smaller in the present models than in those of Hartle and Sturrock [1968] and Hartle and Barnes [1970]. In the present models, this flux is of order 10 to 30 percent of the flow energy flux at 1 AU.

Being spherically symmetric, the present models do not allow for heating due to collision of fast and slow streams, as proposed by Jokipii and Davis [1969]. Current observational evidence suggests that the main effect of this heating is to produce local "hot spots," rather than large-scale heating, for  $r = 1$  AU. [Burlaga and Ogilvie, 1970a; Belcher and Davis, 1971], although it is quite possible that this effect produces larger scale

heating beyond 1 AU. Hollweg [1970b] has suggested that electron heating may be important in driving the solar wind. The calculations reported here suggest that this is probably not the case, because essentially all the wave energy is dissipated in the proton component. Nevertheless, a certain amount of electron heating might occur; it is possible that this heat would simply be conducted away, but it might also be converted to flow energy. The effects of varying electron heating have not yet been investigated. Further discussion of the relationship between models with external heating and other models may be found in Hartle and Barnes [1970].

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## COMMENTS

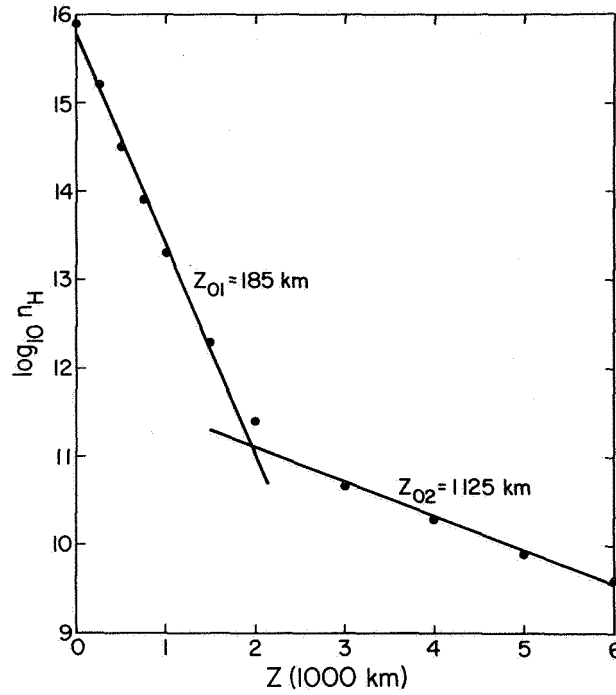
*J. V. Hollweg* I would like to comment on two points that have been mentioned so far this morning. The question of the energy supply to the solar wind, and the observation of Alfvén waves in the solar wind. Along the way I will also comment briefly on the sources of high velocity streams, a possible explanation for the latitude dependence if it exists, a possible explanation for the lack of a solar cycle dependency, and on the paper just presented by Dr. Barnes.

Belcher, Davis, and Smith have recently reported a fairly positive identification of large amplitude Alfvén waves in the solar wind a large fraction of the time. The salient feature of these Alfvén waves is that they are almost always propagating outward from the sun in the frame of reference moving with the plasma. This suggests that their source is below the Alfvénic critical point, and I want to discuss here a particular solar source. That is, the generation of Alfvén waves by the supergranular motions at the solar surface.

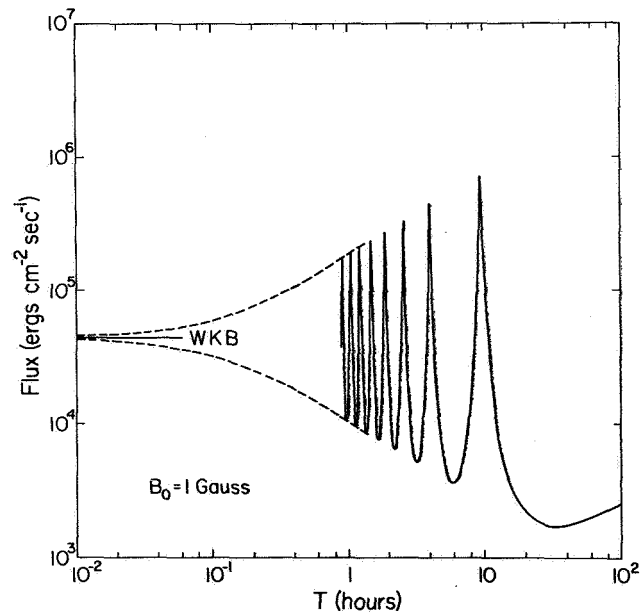
The basic idea is fairly simple. The supergranulation is a large scale convective cellular motion at the surface. The motion is mainly horizontal with a time period of 20 to 40 hr, and velocities of the order of 0.5 km/sec. Field lines will be rooted into the solar surface and moved around horizontally by the supergranulation. It's like wiggling the end of a string and you thereby send Alfvén waves up the vertical magnetic field line.

The difficulty with the calculation is that with a 20 to 40 hr wave period you get wavelengths very much longer than the scale heights, so you actually have to solve the wave equation. To simplify things I have taken a biexponential solar chromosphere. In figure 1 the points are taken from observations; I have calculated the model for the biexponential atmosphere shown by the straight line.

Figure 2 shows the calculated Poynting flux you get when you solve the wave equation. This is for a magnetic field of 1 gauss. The horizontal scale is the period of the motion at



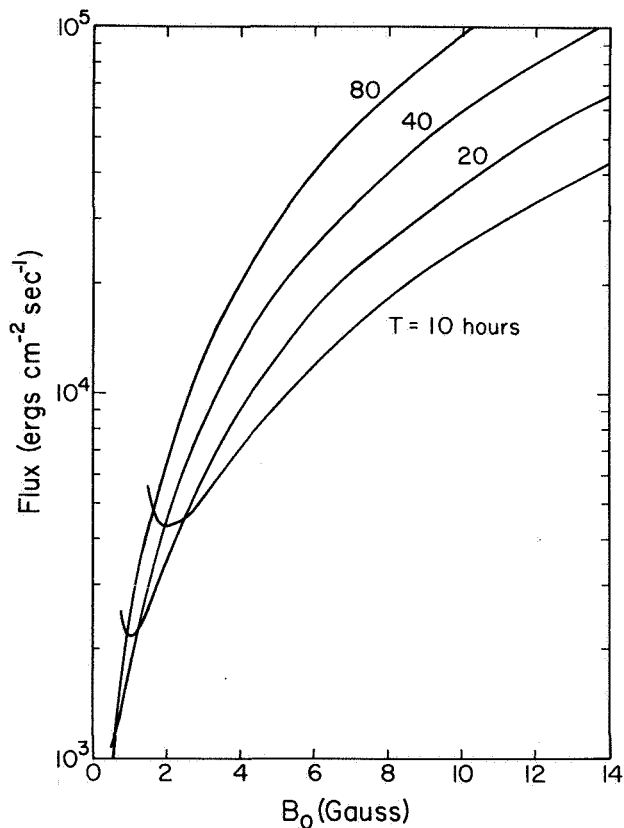
**Figure 1.** The proton concentration in the solar atmosphere as a function of height above the visible edge of the sun. Circles are data points, and the solid lines are the idealized model used in this work.



**Figure 2.** The Poynting flux in supergranulation-driven Alfvén waves as function of wave period, for a magnetic field strength of 1 gauss.

the surface in hours. If you are looking at periods of the order of 20 to 40 hr, for a magnetic field of 1 gauss you get energy fluxes of several times  $10^3$  ergs  $\text{cm}^{-2}$   $\text{sec}^{-1}$ .

Figure 3 shows more specifically how this varies with magnetic field. The interesting point is that the energy flux is a very strong function of magnetic field. So if the magnetic field were 2 gauss you would get something like  $5 \times 10^3$  ergs  $\text{cm}^{-2} \text{sec}^{-1}$ . These energy fluxes are of the order of what one would like to have to explain the discrepancy between the original two fluid solar wind model and the observations. With a slightly stronger magnetic field you can get energy fluxes of the order that Dr. Barnes has just presented. This has several consequences. The first is that if there are very subtle variations in the magnetic field strength or in the amplitude of the supergranular motions at the solar surface, you can get a very significant change in the energy flux in these waves, and if these waves should dissipate in the solar wind, high velocity streams would result. Furthermore, if there were a subtle increase in the motion, or in the magnetic field away from the solar equator, one might explain the apparent fact that there are at times more high velocity streams away from the equator.



**Figure 3.** *The Poynting flux as a function of solar magnetic field strength, for a variety of wave periods.*

This large flux leads one to expect Alfvén waves to be found in the solar wind, and they are, in fact, observed. I believe that supergranular motions are the source of waves seen by Belcher, Davis, and Smith. However, they take the point of view that the Alfvén waves seen at the earth are the undamped remnant of something else that is going on at the sun, while I would take the point of view that the Alfvén waves are, in fact, primary. I calculate a very large energy flux compared to what is observed at the earth, and this implies that damping occurs in the solar wind.

As to the question of the solar cycle, although one sees variations in the corona with the solar cycle, there may be little or no variation of the supergranulation or of the

average magnetic field with solar cycle, and this would perhaps explain why one doesn't see a great variation in the solar wind energy flux at the earth with solar cycle.

There are a couple of problems. The biggest is that the supergranular periods are 20 to 40 hr and the dominant period that Belcher and Davis see is approximately 2 hr. There are two possible explanations for the discrepancy. One might be to assume that there is really a broad spectrum of motions at the solar surface, and since figure 2 shows an increase of flux toward lower periods one would thus tend to preferentially see the lower periods. The other possible explanation is the following: The supergranular motions at the solar surface are not coherent; each supergranule in a sense generates its own wave. Thus, the waves generated from separate but adjacent supergranules are going to have a tendency to "collide" with each other, and this is going to limit the amplitude of the wave. Since the amplitude can be related to the period, this is in effect a limitation on the wave period.

Another problem is that I predict very large fluxes, while only very small fluxes are seen at 1 AU. So I suggest that damping is going on. The question is, how does this damping occur. I can think of several explanations. One is that large-amplitude Alfvén waves coupled nonlinearly with ion sound waves can damp by Landau damping. This is a possible mechanism. Also, there might be an interaction of magnetic moments with fluctuations of the magnetic field strength and this is another type of Landau damping. Another possibility involves the motion of "colliding waves" again. If  $\delta B/B_0 = \delta v/v_A \gtrsim 0.5$ , then when these waves "collide" they are colliding super-Alfvénically. You would then expect shocks and nonlinear dissipation.

DISCUSSION *Unidentified Speaker* I would like to ask a question of Dr. Barnes. Does this model overcome the high density problem which Dr. Parker mentioned earlier.

*A. Barnes* We don't know. We started our calculations out at 2 solar radii, where there is no density problem.

*Unidentified Speaker* Can I ask a second question or make a second comment to Dr. Hollweg? We have observed oscillations in the intensity in the corona with a period of approximately 270 sec. Now, whether this is a characteristic of the entire corona or just a freak event we don't really know. Presumably they are associated with the macroscopic observations at the photospheric level.

*J. V. Hollweg* Two hundred seventy sec is 5 min, which is much shorter than the periods I'm talking about. I'm talking about several hours or more. I think that your oscillations may be connected with gravity wave propagation in the chromosphere and there is possibly some coupling. But that is an interesting observation in any case.

*A. J. Hundhausen* I feel compelled to rise and register my standard objection to Barnes's conclusion that his model really agrees well with the solar wind, particularly since he has neglected the difficulty with the density. His model predicts a density at 1 AU that is high by a factor of roughly 3 yet he chooses to emphasize only agreement with proton temperatures, despite the fact that the thermal energy is only a few percent of the energy in the solar wind. I must also object to his contention that those who construct steady models that do not explain dynamic phenomena such as the temperature-velocity relationship should bow their heads in shame. However, I've made these objections before, so I'll leave it at that.

But I would like to mention the model which will soon be published in the *Astrophysical Journal* by Wolfe, Brandt, and Southwick. Theirs is a two-fluid model including an artificial inhibition of the thermal conductivity of electrons. They predict most solar wind parameters that agree better with observations than does the model presented by Barnes, but without any assumption of additional nonthermal heating.