

PRESENT DEVELOPMENTS IN THEORY OF THE SOLAR WIND *E. N. Parker*
An invited review

Current problems and developments in the theory of the large-scale expansion of the solar corona are reviewed. The outstanding question is whether the energy supply to the quiet corona is mainly thermal conduction outward from a region of active heating at its base, or mainly wave propagation outward from the base. It is suggested that the question can be settled only when the properties of the wind can be sampled over a wide range of radial distance from the sun, from far inside the orbit of earth to well beyond. It has been suggested that hydromagnetic waves may drive the expansion of the active corona by direct transfer of momentum as well as energy.

ABSTRACT

INTRODUCTION

This paper presents some of the current theoretical work, and outstanding problems, posed by the observations in understanding the quiet solar wind. For a comprehensive coverage of the entire subject the reader is referred to the collected proceedings of this meeting, as well as to the many excellent reviews already in the published literature [Dessler, 1967; Lüst, 1967; Ness, 1968; Axford, 1968; Wilcox, 1968; Hundhausen, 1968, 1970; Holzer and Axford, 1970; see also Parker 1965b, 1967, 1969].

THE BASIC PROBLEM

A consideration of the energy supply provides the most direct confrontation with the theoretical questions posed by the solar wind. The energy is believed to be supplied by sound, gravity, and hydromagnetic waves generated in or beneath the photosphere by the convection. The question is where, and in what way, the waves are dissipated and the energy transferred to the expanding corona.

For simplicity suppose that the coronal gas is pure hydrogen, neglecting helium and heavier elements. Denote the mass of the hydrogen atom by M . Denote by $N(r)$ and $T(r)$ the number of hydrogen atoms per unit

volume and the temperature, respectively, at a distance r from the center of the sun. The gas is fully ionized, so the pressure is $p = 2 NkT$ and the thermal energy density is $3 NkT$. Hence, the thermal energy in a volume V is $U = 3 NkTV$. The thermal energy is available, upon expansion of the volume V , to lift the gas out of the gravitational field of the sun. The gas in the volume V is bound to the sun by the gravitational potential $\Phi = -GM_{\odot}MN/r$. Of course, if the gas expands outward from the sun, more gas crowds in behind to replace it, doing the work pV on the volume V . Thus the total energy directly available for escape is the enthalpy

$$E = U + pV = 5 NkTV$$

The ratio of the available energy E to the gravitational binding energy Φ is

$$\frac{E}{|\Phi|} = \frac{5kT(r)r}{GM_{\odot}M}$$

For a coronal temperature of 2×10^6 °K this ratio is about 0.5. The thermal energy is only half the amount needed to lift the gas out of the solar gravitational field. Hence, the solar corona expands continually to form the solar wind only because thermal energy Q is supplied to

The author is with the Department of Physics, University of Chicago, Chicago, Illinois.

the gas while it is expanding away from the sun [Parker, 1958]. The total energy available is then $E + Q$. For the quiet corona and solar wind $E + Q$ is evidently about 25 percent larger than Φ , because it leads to a solar wind at large radial distance with a velocity equal to about half the 600 km/sec escape velocity from the base of the corona.

The addition of energy can be represented in a very simple mathematical way using the conventional polytrope relation $p = p_0 (N/N_0)^\alpha$ where α is chosen to be less than the adiabatic value of 5/3. This artifice permits integration of the momentum equations, leading to winds of the general character of the observed solar wind for α between the isothermal value of 1.0 and about 1.3 [Parker, 1960b]. The effective enthalpy, which now includes the addition of heat Q , can be written

$$E_{\text{eff}} = \frac{2\alpha}{\alpha-1} NkTV$$

in terms of α . The polytrope law, however, is only a convenient, and often used, mathematical device for representing the addition of heat. It tells us nothing about the actual mechanisms responsible for the addition.

The total energy flux F carried by the wind is then the convection of kinetic energy, gravitational potential energy, and the effective enthalpy,

$$F = 4\pi r^2 N\nu \left(\frac{1}{2} M\nu^2 - \frac{GM_\odot M}{r} + \frac{2\alpha kT}{\alpha-1} \right)$$

where ν is the wind velocity at r and $4\pi r^2 N\nu$ is the number of atoms streaming away per unit time, a quantity independent of r .

Thermal conduction outward from the base of the solar corona is obviously one source of heat supply from the inner to the outer corona [van de Hulst, 1953, Chapman, 1957] and was the first explicit mechanism considered in connection with the expansion to form the solar wind [Noble and Scarf, 1963].

In this case, the thermal conduction term must be added to F :

$$F = 4\pi r^2 N\nu \left(\frac{1}{2} M\nu^2 - \frac{GM_\odot M}{r} + \frac{2\alpha kT}{\alpha-1} \right) - 4\pi r^2 \kappa(T) \frac{dT}{dr}$$

where the thermal conductivity $\kappa(T)$ is $6 \times 10^{-7} T^{5/2}$ ergs/cm sec $^\circ\text{K}$ [Chapman, 1954]. Noble and Scarf [1963] constructed the first solar wind models using this energy flux. They obtained wind velocities of 300 km/sec and densities of $7/\text{cm}^3$ at the orbit of earth for a

temperature $T_0 = 2 \times 10^6$ K in the low corona, in general agreement with observation. However, it was necessary to assume a rather low density $N_0 = 1-3 \times 10^7/\text{cm}^3$ at the base of the corona. If N_0 is chosen to be as large as observed, $N_0 \cong 1-2 \times 10^8/\text{cm}^3$, then much lower wind velocities and higher densities at the orbit of earth result, because the thermal conductivity (which is essentially independent of the gas density) is unable to supply enough energy to maintain the temperature of the expanding coronal gas. The reduced temperature in the outer corona then gives a small wind velocity at large r , which leads to an increased N through $r^2 \nu N = \text{constant}$ [see discussion in Parker, 1965a, b].

If one wishes the model to fit the observed coronal density at the sun, the temperature must be reduced somewhat near the sun, to give a more rapid decline of density with radial distance, and the temperature must be increased somewhat beyond several solar radii, to give the observed 300 km/sec wind velocity. This would require heating the expanding corona with waves from the sun [Noble and Scarf, 1963; Parker, 1964a; Barnes, 1968, 1969].

The wind velocity can be enhanced and the density reduced somewhat if the thermal conduction from the sun is obstructed at large r [Parker, 1964a, 1965b]. Then the thermal energy piles up behind the obstruction, raising the temperature and increasing the velocity of the expanding wind gases (whereupon the energy passes the obstruction in the form of enhanced wind velocity). Transverse magnetic fields are the most obvious obstruction to thermal conduction. Beyond the orbit of earth the interplanetary magnetic field is largely transverse and therefore may be expected to furnish an obstruction. The angle θ which the spiral field makes with the radial direction is $\tan \theta = \Omega r/\nu$ where Ω is the angular velocity of the sun ($\Omega \sim 3 \times 10^{-6}$ rad/sec), so that $\theta = 45^\circ$ at 0.7 AU (for quiet day wind velocities of the order of 300 km/sec) and is larger than 45° beyond. Thermal conduction is reduced by the factor $\cos^2 \theta$, which is already below 0.5 at the orbit of earth. At Mars $\cos^2 \theta$ is 0.2 or 0.3.

Forslund [1970] has pointed out another effect: that the high thermal conduction flux in the wind leads to skewed electron distributions, producing plasma instabilities and thereby reducing the effective thermal conduction coefficient. The heat from viscous dissipation is a further contributing factor. Recently several authors [Brandt et al., 1969; Gentry and Hundhausen, 1969; Urch, 1969; Cuperman and Harten, 1970] have worked out the effects quantitatively. Unfortunately, the reduction of κ at large r does not appear to have a sufficiently

large effect to make up the entire difference. The theoretical models fit the density of the wind at the orbit of earth and in the outer corona only with a density as small as $3-5 \times 10^7/\text{cm}^3$ at the base of the corona, better than the $1-3 \times 10^7/\text{cm}^3$ required by the simpler models, but still well below the $1-2 \times 10^8/\text{cm}^3$ observed. The models also predict a thermal conduction flux at the orbit of earth which is several times larger than observed. Consequently, *Hartle and Barnes* [1970] have taken up the formal calculation of models of the corona with energy deposition from the dissipation of hydromagnetic waves from the sun. They show that the wind velocity is increased, and/or the density decreased, if heat is added by wave dissipation in the broad region containing the sonic transition point, where the expansion velocity crosses the speed of sound. The sensitive region is roughly $2-25 R_\odot$. With their model it is a simple matter to bring the density at the base of the corona and at the orbit of earth both into line with the observations. They point out that their theoretical model fits the empirical relation

$$T^{1/2} = (0.036 \pm 0.003)v - (5.54 \pm 1.50)$$

between the proton temperature T (in units of 10^3°K) at the orbit of earth and the wind velocity v (in km/sec) proposed by *Burlaga and Ogilvie* [1970a]. The empirical relation is remarkable in that it applies to both quiet and disturbed times. Hence, from the work of *Hartle and Barnes* [1970] we have a strong case that in quiet times the coronal heating extends out from the sun for several solar radii.

Needless to say, the active corona and solar wind, with velocities two or more times the quiet day values, and densities half or less the quiet values, implies very active heating of the corona, presumably by wave dissipation, out to 0.1 AU or more. The models of *Hartle and Barnes* show what can be done in this respect.

Burlaga and Ogilvie [1970b] make the interesting point, too, that the total pressure in the wind $p + B^2/8\pi$ is generally uncorrelated with wind velocity. And they note that the sum $p + B^2/8\pi$ varies much less over periods of hours than either p or $B^2/8\pi$ separately, suggesting local hydrostatic equilibrium in the wind.

When one goes beyond the gross properties of density and velocity of the wind, considering the individual temperatures and anisotropies of the electrons and protons at the orbit of earth, more detailed models are needed. Treating the ionized hydrogen of the wind as a single gas overlooks the fact that it is mainly the electrons that are responsible for thermal conduction, and they are but weakly coupled by collisions to the

protons. For this reason, the two-fluid models of the solar wind have been developed [*Sturrock and Hartle*, 1966; *Hartle and Sturrock*, 1968; *Hartle and Barnes*, 1970] in which the electron and proton gases are treated separately, with an energy exchange between the two depending on the temperature difference $T_e - T_p$ and the collision rate ν . Thus the total energy flux F is independent of r , but the energy fluxes F_e and F_p for the electron and proton gases separately satisfy

$$\frac{dF_e}{dr} = -\frac{3}{2} \nu Nk (T_e - T_p) 4\pi r^2$$

$$\frac{dF_p}{dr} = +\frac{3}{2} \nu Nk (T_e - T_p) 4\pi r^2$$

There is little effect on the wind velocity and density. But the temperature is profoundly affected. With the one-fluid model, the theoretical temperature of the wind at the orbit of earth is of the order of $2 \times 10^5^\circ\text{K}$ (for $2 \times 10^6^\circ\text{K}$ at the base of the corona). With the two-fluid model, the calculated electron temperature is $3 \times 10^5^\circ\text{K}$ and the proton temperature is quite low, $4 \times 10^3^\circ\text{K}$. The observed electron temperatures are generally around $1.5 \times 10^5^\circ\text{K}$ and do not vary much with the level of solar activity. The observed quiet-day proton temperatures are typically $4 \times 10^4^\circ\text{K}$, with values as low as 10^4°K only rarely observed. The proton temperatures increase to 10^5°K , and more, with the advent of solar activity.

Altogether, then, the one-fluid model gives temperatures that at the orbit of earth are close to the observed electron temperatures. The two-fluid model gives too low a proton temperature and too high an electron temperature. That is to say, T_e and T_p are actually tied together more closely than can be accounted for by the Coulomb collisions assumed to couple the two gases in the simple two-fluid theory. *Wolff et al.* [1971] show that inclusion of viscosity can raise the proton temperature to $4 \times 10^4^\circ\text{K}$, which agrees with typical quiet-day observations. And, of course, introducing wave dissipation into the two-fluid model near the sun can be made to bring T_e and T_p closer together and into rough agreement with the observed values [*Hartle and Barnes*, 1970; *Cuperman and Harten*, 1971].

Consider the thermal anisotropy of the electron and proton gases. The observations at the orbit of earth show 92 percent of the energy flux convected in the form of kinetic energy of the wind and only 4 percent in thermal conduction, whereas the two-fluid model gives over 50 percent in thermal conduction at the orbit of earth [see

discussion in *Hundhausen*, 1970]. The observed anisotropies in the proton temperatures are only 2 to 1, whereas Coulomb collisions alone give 50 to 1.

Thus again the theoretical model can be brought more into line with the observations with liberal doses of wave dissipation toward the sun. Plasma waves may be called on to suppress thermal conduction and thermal anisotropy, and the dissipation of hydromagnetic waves can be called on to supply whatever energy is needed to give the observed velocity and density at the orbit of earth. But the theoretical models that produce quantitative agreement with all presently observable properties of the wind are complicated. Postulating wave dissipation introduces enough arbitrary parameters that the present quiet-day observations can be fitted—probably in more ways than one. It is not evident that a unique theoretical model can be constructed, showing the general quantitative characteristics of the wind at the orbit of earth, without direct observation of the wind over much of the distance between earth and the sun, and beyond the orbit of earth, to establish (1) whether the observed electron anisotropies are, or are not, compatible with the anisotropy deduced from $\kappa dT/dr$ and the observed dT/dr ; (2) whether the electron and proton anisotropies at any given position are compatible with the waves observed there; (3) what plasma waves and plasma instabilities are actually present; or (4) what hydromagnetic waves are present. It is likely that quantitative observation of the wind over the regions inside and outside the orbit of earth will show novel features (and inconsistencies in some of our present ideas) that could not possibly have been anticipated from theory and from analysis of observations near the orbit of earth.

One of the fundamental questions that has been a subject of curiosity for a long time is whether the solar corona and wind expand radially outward from the sun, or whether the low latitude corona contributes most of the wind, so that the wind near the equatorial plane is expanding rapidly toward high solar latitudes. If the wind is expanding away from the equatorial plane, the gas density drops more rapidly than the $1/r^2$ for radial flow. The temperature, density, and velocity of the wind at the orbit of earth could be seriously affected by nonradial expansion.

Another question is the inhomogeneity of the corona near the sun. The structure of the small-scale filaments near the sun is not known with precision, nor is it known to what extent the solar wind arises from filaments, or interfilament regions. Expansion limited to filaments appears to be a necessary part of any pure conduction models that are to fit the high coronal densities near the sun. The filaments expand faster than

r^2 with increasing radial distance, thereby reducing the wind density relative to that of the corona. (Dynamical studies of filaments are noted in the last section.)

THE ROLE OF WAVES

Hydromagnetic waves generated at the sun are a source of heat for the solar corona and solar wind. The degree to which waves heat the quiet-day corona and solar wind is a subject of some discussion, as noted above. Waves generated by wind velocities that vary around the sun—that is, colliding streams—and by wind velocities that vary with time in the rotating frame of the sun, have also been studied by many authors [*Parker*, 1963; *Jokipii and Davis*, 1969; *Carovillano and Siscoe*, 1969; *Siscoe and Finley*, 1970; *Burlaga et al.*, 1971]. These studies consider the waves both as a phenomenon to be observed directly and as a source of heat for the wind. *Belcher* [1971] has recently pointed out another role of waves—namely, supplying momentum directly to the wind.

The expanding corona and wind are stable to small perturbations [*Parker*, 1966; *Carovillano and King*, 1966; *Jockers*, 1968], and the propagation of hydromagnetic waves outward from the sun proceeds in a straightforward manner subject to the damping of thermal conductivity, Landau damping [*Barnes*, 1966, 1967], and stochastic fields [*Jokipii and Parker*, 1969; *Valley*, 1971].

Consider the idealized situation of a solar wind with spherical symmetry about a nonrotating sun. Then the wind velocity and density $v(r)$ and $N(r)$ are functions only of r . The magnetic field is radial and declines outward as $1/r^2$. Alfvén waves involving displacements in the ϕ direction are easily treated when the wavelength is small compared to the scale r of the wind, and it is readily shown [*Parker*, 1965b] that the amplitude of outward propagating waves varies as

$$\delta B(r, t) = \delta B_0 \left(\frac{N}{N_0} \right)^{1/4} \frac{v_0 / C_0 + 1}{v / C + 1} \exp i\omega \left(t - \int \frac{dr}{v + C} \right)$$

$$\delta v(r, t) = -\delta v_0 \left(\frac{N}{N_0} \right)^{1/4} \frac{v_0 / C_0 + 1}{v / C + 1} \exp i\omega \left(t - \int \frac{dr}{v + C} \right)$$

where C is the local Alfvén speed $B/(4\pi NM)^{1/2}$ and $r^2 v N = \text{constant}$. The subscript zero denotes the value at some specified reference level. The waves do work on the wind because of their centrifugal force $(\delta v)^2/r$ and

their magnetic pressure $\delta B^2/8\pi r$ exerted on the wind. The forces exerted by the waves are outward, in the same direction as the wind, so that they boost the wind along in its outward flow. The rate at which work is done is [Parker, 1965b]

$$P = \frac{NM\langle\delta v^2\rangle v}{r} + \frac{\langle\delta B^2\rangle}{8\pi} \frac{dv}{dr} \text{ erg/cm}^3 \text{ sec}$$

The new point that Belcher [1971] makes is that the work done by the waves directly on the wind can greatly enhance the velocity of the wind. The energy flux F has added to it the term $4\pi r^2 \times (1/2)NM\langle\delta v^2\rangle v$ representing convection of the kinetic energy, and the term $4\pi r^2 \times \langle\delta B^2\rangle/8\pi (v + C)$ representing the convection and propagation of magnetic energy.

If the wave amplitude δB is nearly as large as the radial field B , the waves may contribute as much as the pressure gradient to accelerating the wind. For with $\delta v = \delta B/(4\pi NM)^{1/2}$ it follows that the centrifugal force term $NM\langle\delta v^2\rangle/r$ is $\langle\delta B^2\rangle/4\pi r$, which may be comparable to $B^2/8\pi r$. Presumably $B^2/8\pi$ can be as large as the gas pressure $2NkT$, so the driving force of the waves may be as large as the driving force of the pressure gradient. Wave driving can have a large effect on the wind. Belcher suggests that such wave propulsion may contribute to the production of the fast, hot, tenuous winds that sometimes come from the active sun. Presumably the waves would both accelerate the wind, in the manner just described, and heat the wind on dissipation. Clearly, the effect must be included in any comprehensive model of the solar wind.

A final comment is in order concerning the propagation and damping of hydromagnetic waves in the solar wind. Not many years ago there was a general impression that long wavelength hydromagnetic waves (say $\lambda \sim 10^{11} - 10^{12}$ cm) propagate in the solar wind with but little damping. All the stability calculations mentioned above are based on this idea, using the simple field equations without damping. Then Barnes [1966, 1967] showed that Landau damping dissipates all such waves in distances of 1 AU or less, except for Alfvén waves, which propagate exactly along the field, and magnetosonic waves propagating exactly across the field. Then Jokipii [1967; Jokipii and Parker, 1969] pointed out that the lines of force of the interplanetary magnetic field are stochastic. The mean field follows the usual Archimedes spiral (or radial pattern in the idealized case above), but the individual neighboring lines of force wander (random walk) apart if one follows along the lines. The random walk is the result of turbulence on the sun (granules, supergranules) as well as turbulence in

interplanetary space. In any case, Valley [1971] has shown that Alfvén waves and magnetosonic waves are dispersed in distances of 1 AU by the stochastic nature of the large-scale field. Valley points out, then, that *no hydromagnetic waves escape damping* in distances of 1 AU. This does not entirely exclude waves generated near the sun from reaching the orbit of earth, because such waves are largely convected, rather than propagated, in the solar wind. The Alfvén speed is 0.1–0.2 the wind speed. But the dissipation is a significant effect and must be considered in any model involving waves as a source of either heat or momentum for the wind.

MISCELLANEOUS TOPICS

Those interested in exospheric models of the solar corona, in which magnetic irregularities are ignored and the outer corona and wind are treated as an aggregate of noninteracting particles (except for the charge-separation electric field), are referred to the recent papers of Jockers [1969] and Hollweg [1970] [see also the discussion and references in Hundhausen, 1970]. It is well known that the moments of the collisionless Boltzmann equation give the ordinary hydrodynamic equations, so that the fluid and free-particle treatments cannot be wholly different [Parker, 1960a]. But the free-particle approach is much more involved, particularly in the question of boundary conditions at the sun, so that only with the recent work, beginning with Brandt and Cassinelli [1966], has it been possible to carry through the exospheric model correctly, obtaining wind velocities of a few hundred km/sec at the orbit of earth. Needless to say the exospheric models lack the mixing of thermal velocities between different directions, and between electrons and protons, that is indicated by observations of the thermal anisotropy and proton temperatures at the orbit of earth.

Siscoe [1970; Parker, 1964b; Carovillano and Siscoe, 1969] has recently looked further into the dynamics of coronal streamers, treating fast and slow streams with solar rotation included. Interest has also arisen recently in solar wind filaments because of the east-west asymmetries that may develop between slow and fast streams [Siscoe et al., 1969], and several theoretical papers treating that aspect have appeared [Carovillano and Siscoe, 1969; Siscoe, 1970; Siscoe and Finley, 1970]. Siscoe and Finley [1969] have shown that the observed $1^\circ - 3^\circ$ north-south deflections sometimes observed in the wind direction can be explained by 10 to 20 percent pressure variations with solar latitude. The calculations suggest that coronal gas from $\pm 12^\circ$ solar latitude may arrive at the orbit of earth. Pneuman and Kopp [1970] consider the nonradial expansion in streamers, showing

that it leads to reduced wind densities at the orbit of earth.

It will be recalled that several years ago a number of authors became interested in the decelerating torque exerted by the wind on the rotating sun and on the azimuthal velocity v_ϕ of the wind at the orbit of earth [see review and list of references in *Parker*, 1969; *Wolff et al.*, 1971]. The torque is approximately the 10^{30} to 10^{31} dyne-cm exerted by the spiral magnetic field [*Parker*, 1958]. The calculations of the azimuthal velocity in the wind predict $v_\phi = 1$ to 2 km/sec, whereas observations [*Belton and Brandt*, 1966; *Brandt*, 1967; *Hundhausen et al.*, 1968] indicate 5 to 10 km/sec. The error could lie in the difficult analysis of the observations. But if the observational analysis is correct, it suggests perhaps a systematic forward tilt of the magnetic fields in the rotating sun [*Schubert and Coleman*, 1968]. This puzzle remains unsolved after several years of serious consideration.

This is perhaps the place to note recent research pertaining to some of the fine points in the theory of the solar wind. Questions of unique and convergent solutions including thermal conductivity and/or viscosity have been explored by *Eisler* [1969a, b], *Weber* [1970] and *Wolff et al.* [1971]. See also the paper by *Whang et al.* [1966]. Explicit solutions of the polytrope equations have been given by *Tyan* [1970] and by *Holzer and Axford* [1970].

Tan and Abraham-Shrauner [1971] have worked out the equations of motion including the pressure anisotropy in the gas and have given numerical solutions that compare well with observations.

Another point of recent interest is the transition from a supersonic to a subsonic wind that occurs if the coronal density is slowly increased while the temperature remains fixed [*Parker* 1965a]. Calculations show analytic solutions with the temperature declining asymptotically as $T \sim 1/r^{2.7}$ in the supersonic regime (low-density corona) and $T \sim 1/r$ in the subsonic regime (high-density corona) with a special isolated supersonic solution $T \sim 1/r^{2.5}$ [*Whang and Chang*, 1965] in the transition region between the regular supersonic and subsonic regions. *Durney* [1971] has recently carried out numerical calculations indicating a range of supersonic solutions with $T \sim 1/r^{4.3}$ in the transition region. If his conclusion is in fact correct, it indicates a richer field of solutions than previously imagined, and suggests that further investigation may be rewarding.

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DISCUSSION *D. B. Beard* I have seen some recent interpretations by our group and others of observations of the *K* component of the solar corona in which the electron density was estimated to be more like 10^9 rather than 10^8 cm^{-3} . Can you reasonably accommodate the higher figure?

E. N. Parker Well, the 1 or 2×10^8 atoms/cm³ I gave is for the quiet corona, because I wanted to discuss the quiet solar wind. The active corona shows densities up to 10^9 atoms/cm³ and I think all one can say is that it is quite evident there is extensive wave heating, though how extensive nobody knows. Again, one can construct models with the wind expanding away from local regions. These fit the data at the orbit of earth, but they are by no means unique. There are several ways to handle the parameters.

K. Schatten I would like to comment on the amount of nonradial flow that Gene Parker discussed. In calculating the coronal magnetic field, for the years 1965 and 1966 we found approximately a 1 to 6 expansion by area or a 1 to 2-1/2 expansion in terms of linear dimension. So for models that include this expansion from local regions it might be worthwhile to use these numbers for the approximate expansion.

E. N. Parker What do those numbers mean, again?

K. Schatten For a unit solid angle on the sun we determine the magnetic flux and ask what solid angle this flux will extend over at 1 AU. It turns out that the solid angle will be about 6 times as large at 1.0 AU.

E. N. Parker How is this determined? It's very interesting.

K. Schatten Using the computed magnetic field, according to the coronal magnetic field models, one follows the field vectors from the sun's surface to a 'source' surface at about a solar radius and observes how much area on the sun maps out to how much area at the source surface. One then assumes a radial extension from the source surface to 1.0 AU. The 1 to 6 figure suggests that about 17 percent of the sun's surface is directly connected by field lines to 1 AU.

E. N. Parker You're saying that some spots on the sun are the dominant sources of the field at the orbit of earth?

K. Schatten Yes. The model of the coronal field does *not* suggest a complete 100 percent direct extension of flux from the sun to 1 AU.

J. V. Hollweg I have a question about the damping of Alfvén waves. Is it not reasonable to consider the stochastic nature of the magnetic field as actually due to random Alfvén waves, in which case you wouldn't describe scattering of Alfvén waves off the random field?

E. N. Parker It's possible to think of the stochastic nature of the field as due to Alfvén waves, in which case it is wave scattering rather than scattering from an equilibrium field. You get roughly the same answers.

E. J. Smith I have a related question. You mentioned the scattering of waves. Where would this become important?

E. N. Parker For waves of length 0.01 or 0.1 AU it is important at the orbit of earth. That is, given the estimates of the degree by which the field random walks, the scattering of Alfvén waves is an important effect inside the orbit of earth. Apparently, for waves of almost any dimension less than 1 AU, the scattering takes place as soon as they leave the sun. The distances which a wave will propagate is typically 1 AU, but in making numerical estimates, one must remember that when a wave arrives at the earth, it has not propagated 1 AU. It has been convected for about 4/5 AU, during which time it propagated only about 1/5 AU. So the damping is significant, but not excessive.

F. W. Perkins I would like to make a comment for those theorists working themselves out of a job doing solar wind calculations. There's another interesting problem concerning mass loss from stars. Red super giant stars are structured such that the combination of heat and ionization energy for regions just below the surface of these stars is above zero. It's difficult to determine how the flow will come off these stars.

A. Hewish I would just like to mention that the best available data on solar winds from radio scintillations indicate complete spherical symmetry up to ecliptic latitudes of 70° and over a range of radial distance of 0.3 to 1 AU. There is limited data on the acceleration of the wind closer to the sun.

E. N. Parker By spherical symmetry you mean the velocity of the wind is more or less independent of direction from the sun?

A. Hewish The velocity is radial and independent of latitude or distance from the sun in that range.

G. W. Pneuman An observation that might pertain to this high density problem is that corona observations of the inner corona during solar eclipse seem to indicate that many regions of very high density may not be taking part in the coronal expansion at all, but are confined in large closed loop structures.