CORONAL ALFVÉN WAVES AND THE SOLAR WIND *J. W. Belcher*

ABSTRACT The observed properties of coronal Alfvén waves in the solar wind at 1 AU are briefly reviewed, with some theoretical discussion of their probable effects on the dynamics of the expanding solar corona. It is concluded that coronal Alfvén waves can have a major influence on both the small- and large-scale properties of the solar wind at 1 AU.

The interplanetary medium is a highly conducting, essentially collisionless plasma with approximate equipartition between thermal and magnetic field energy densities. Spacecraft measurements of the fine scale structure of the medium (scale lengths on the order of 0.01 AU and less) offer a unique opportunity to study the physics of such plasmas observationally. Of particular astrophysical interest are their wave and turbulence properties. When interplanetary field data were first obtained more than 8 years ago, the microscale structure (scale lengths on the order of 0.01 AU and less) was found to be quite irregular, and it seemed plausible [*Davis,* 1966] that many of the observed features were propagating as Alfvén or magnetoacoustic waves. *Coleman* [1967, 1968] carried out an extensive spectral and cross-spectral analysis of the Mariner 2 plasma and field data, and concluded that Alfvén waves propagating away from the sun in the rest frame of the wind could account for a substantial fraction of the fluctuations. This statistical analysis did not give patterns of occurrence of the waves or explicit examples of the wave forms. *Unti and Neugebauer* [1968] were the first to isolate a specific example of a quasi-periodic Alfvénic wave form. *Belcher et al.* [1969], in a preliminary analysis of Mariner 5 plasma and magnetometer data, identified outwardly propagating Alfvénic wave trains as frequently occurring phenomena, although for the most part they are nonsinusoidal and aperiodic.

Figure 1 is an example [*Belcher and Davis,* 1971] of one such wave train, with a length of about 0.25 AU. As in the preliminary analysis, a fluctuation is identified as an Alfvén wave if it satisfies

$$\mathbf{b} = \pm(4\pi\rho)^{1/2}\ \mathbf{v} \qquad (1)$$

where $\mathbf{b}$ is the vector perturbation in the magnetic field (the deviation from the average), $\mathbf{v}$ is the perturbation in the velocity, and ρ is the mass density of the plasma. Fluctuations in the field strength B and the density during such periods are relatively small, as would be expected for the transverse Alfvén mode. Figure 2 is a very high time resolution plot of three 10-min periods at times indicated on figure 1. At this resolution, the waves can appear either abrupt (2i, 2iii) or more gradual (2ii). The gradual changes predominate, with the more sharply crested waves occurring on the order of once per hour. The best examples of such waves (as in fig. 1) are found in high-velocity, high proton temperature, solar wind streams (fig. 3). *Belcher and Davis* [1971] have argued that the waves are generated at or near the sun, and are closely related to the dynamical processes that produce the hot, high velocity streams. Of course there are many other structures which contribute to the interplanetary microscale fluctuations (such as shocks, tangential discontinuities, and polarity reversals), but a careful study of 130 days of good field and plasma data from Mariner 5 indicates that Alfvén waves dominate the microscale fluctuations on the order of 50 percent of the time [*Belcher and Davis,* 1971]. They are thus a major source of fluctuations in the solar wind at scale lengths on the order of 0.01 AU and less.

The author is at the Center for Space Research, M.I.T., Cambridge, Massachusetts.

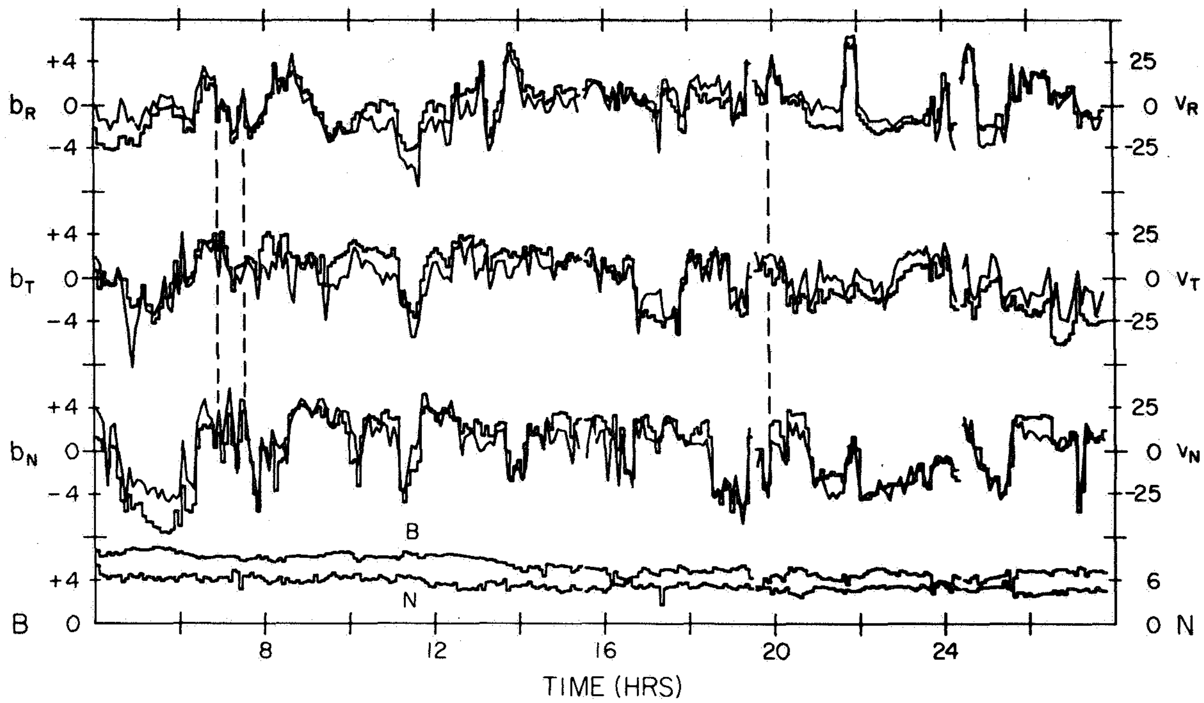

Figure 1. *Twenty-four hours of magnetic field and plasma data demonstrating the presence of nearly pure Alfvén waves. The upper six curves are 5.04-min velocity components in km/sec (diagonal lines) and magnetic field components in gamma (horizontal and vertical lines), with a scale ratio of approximately* $(4\pi N m_p)^{1/2}$. *Twenty-four hour averages have been subtracted. The polarity during this period is negative and the correlation positive, indicating outward propagation. The lower two curves are field strength and proton number density. RTN components are solar polar coordinates.*

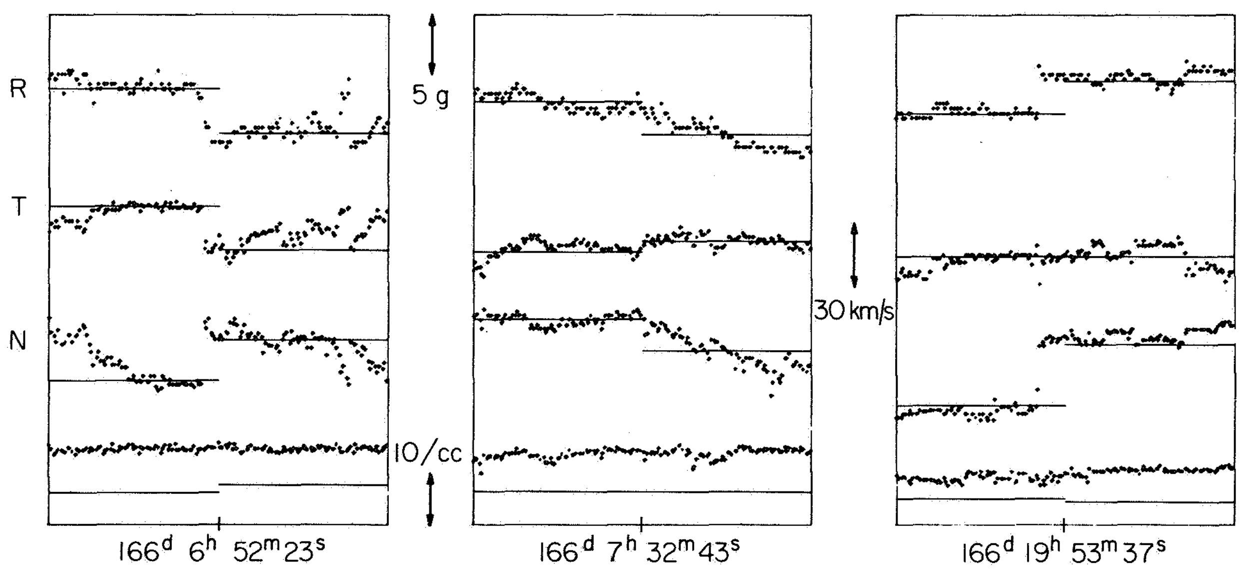

Figure 2. *Expanded plots of three 10-min periods of figure 1 at the times indicated by vertical dotted lines there. The points are high rate field data, the bars are 5.04 min plasma readings with the same scale ratio as in figure 1 and arbitrary zeroes. The lower set of bars are density readings, and the lowest points are field strengths.*

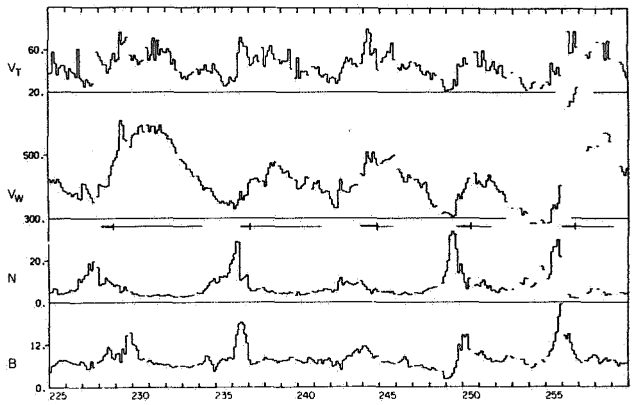

Figure 3. *Thirty-five days of Mariner 5 data plotted using 3-hr averages and showing the large scale stream structure of the solar wind. B is the magnetic field strength (γ), N is the proton number density (cm^{-3}), V_W is the radial proton bulk velocity (km/sec), and V_T is the most probable proton thermal speed (km/sec). The best examples of the outwardly propagating Alfvén waves (light bars) are found in high velocity streams and on their trailing edges. The largest amplitude waves (heavy bars) are found at the leading edges of high velocity streams.*

Assuming that the outwardly propagating waves observed at 1 AU are in fact generated at or near the sun (and this seems almost certain), we would like to point out some of the more obvious effects they will have on the dynamics of the expanding solar corona, assuming no wave damping. The waves contribute to the efflux of energy away from the sun, and they will do work on the wind as they propagate and are convected outward into interplanetary space [*Parker,* 1965]. Consider a one-fluid polytrope model of the solar wind for a non-rotating sun (radial field lines). With the assumption that the Alfvénic wavelengths are small compared to scale heights, we can write an expression for the transverse Alfvénic fluctuations as a function of r

$$\left.\begin{aligned} \delta \mathbf{B}(r,t) &= \mathbf{e}_t \delta B(r) \exp[i(\omega t - kr)] \\ \delta \mathbf{V}(r,t) &= \pm \frac{\delta \mathbf{B}(r,t)}{(4\pi\rho)^{1/2}} \\ \omega &= k(V + V_A) \end{aligned}\right\} \qquad (2)$$

with the WKB amplitude [*Parker,* 1965] given by

$$\delta B(r) = \delta B_o \left(\frac{\rho}{\rho_o}\right)^{3/4} \frac{(1 + V_A{}^o/V_o)}{(1 + V_A/V)} \qquad (3)$$

where the subscript o refers to an arbitrary reference level. This expression is for outwardly propagating Alfvén waves with no damping (dissipation of wave energy directly into thermal energy); V is the radial solar wind speed, V_A is the Alfvén velocity, and ρ is the solar wind density.

The total energy flux across a sphere of radius r, including Alfvén waves, is given by

$$F = 4\pi r^2 \left[V\left(\frac{1}{2}\rho V^2 + \frac{\alpha}{\alpha - 1} p + \rho\Phi\right) + \frac{1}{2}\left(\frac{1}{2}\rho\delta V^2\right) V + \frac{1}{2}\frac{\delta B^2}{4\pi}(V + V_A)\right] \qquad (4)$$

where Φ is the gravitational potential and p is the thermal pressure. The first term in parentheses contains the familiar terms evaluating the kinetic energy density associated with the radial motion, the sum of the enthalpy and the energy transported by thermal conduction, and the gravitational energy. The terms in the second and third parentheses are due entirely to the presence of the waves. The second is the wave kinetic energy density convected by the bulk velocity and the third is the radial component of the Poynting vector. Using the WKB wave amplitudes given above, we can write an expression for the wave energy flux as a function of r:

$$\left.\begin{aligned} F_{\mathrm{wave}}(r) &= 4\pi r_o{}^2 \frac{\delta B_o{}^2}{8\pi} V_A{}^o \left(1 + \frac{V_o}{V_A^o}\right)^2 \frac{1 + \frac{3}{2} M_A}{(1 + M_A)^2} \\ M_A &= \frac{V}{V_A} = \frac{V_o}{V_A{}^o}\left(\frac{\rho_o}{\rho}\right)^{1/2} \end{aligned}\right\} \qquad (5)$$

where M_A is the solar wind Alfvén mach number and is a monotonically increasing function of r. It can easily be shown that $F_{wave}(r)$ is a monotonically decreasing function of r, approaching 0 as $r \to \infty$. Since the total energy flux F must remain constant, there is thus a continual transfer of energy flux from the waves to the wind.

We can heuristically understand the mechanism which produces this energy transfer by considering the $1/c$ $\mathbf{J} \times \mathbf{B}$ term in the equation of motion. In the Parker radial field model, this term is identically zero. With Alfvén waves, however, it is proportional to

$(\mathbf{k} \times \delta\mathbf{B}) \times (\mathbf{B}_O + \delta\mathbf{B})$, where $\mathbf{B}_O$ is the radial background field, $\mathbf{k}$ is the radial propagation vector, and $\delta\mathbf{B}$ is the Alfvénic perturbation (transverse to the radial). The $(\mathbf{k} \times \delta\mathbf{B}) \times \mathbf{B}_O$ term in this expression is also transverse to the radial, and produces the $\delta\mathbf{V}$ perturbation. The $(\mathbf{k} \times \delta\mathbf{B}) \times \delta\mathbf{B}$ term, however, is in the radial direction. If the wave amplitude were not a function of r, this second order term would average to zero over one cycle of the waves. However, since the wave amplitude is a function of r, there is a small nonzero average over one wave cycle, and thus a net acceleration of the plasma in the radial direction. The radial equation of motion becomes

$$\rho V \frac{\partial V}{\partial r} = -\rho \frac{\partial \Phi}{\partial r} - \frac{\partial}{\partial r}\left(p + \frac{\delta B^2}{8\pi}\right) \qquad (6)$$

The waves exert an effective pressure on the wind (analogous to a radiation pressure), which serves to increase the streaming velocity. Thus the energy flux in the waves decreases as r increases away from the sun, with a corresponding increase in the plasma streaming motion.

Having determined that outwardly propagating Alfvén waves can do work on the solar wind, we turn to the question of the importance of this effect on the large-scale solar wind dynamics. Consider a reference level $r_O = 10^6$ km. At this level, $V_A^O \gg V_O$, so that the wave energy flux here is given by

$$F_{wave}(r_O) = 2.2 \times 10^{33} \frac{\epsilon B_O^{\ 3}}{(N_O)^{1/2}} \text{ ergs/sec} \qquad (7)$$

where $\epsilon = 1/2\ (\delta B_O / B_O)$, and N_O is the proton particle density. If we take representative values of B_O and N_O of 1 gauss and 2×10^7 cm^{-3}, respectively, we find that

$$F_{wave}(r_O) = \epsilon (5 \times 10^{29}) \text{ ergs/sec} \qquad (8)$$

This flux estimate is to be compared to estimates of the energy flux due to thermal conduction from the lower corona on the order of 2×10^{27} ergs/sec, and of the energy flux in the solar wind at 1 AU on the order of 10^{27} ergs/sec. Even small amplitude waves at 10^6 km ($\epsilon \ll 1$) are associated with large energy fluxes because of the high Alfvén velocity. Note the strong dependence of $F_{wave}(r_O)$ on B_O; small changes in B_O at 10^6 km cause large variations in the wave energy flux for fixed values of ϵ and N_O. In this simplified model, all of the wave energy flux is eventually transferred to increased plasma streaming motion, so that the effect of the waves on the large scale solar wind dynamics can be quite large.

Figure 4 shows the results of numerical solutions of Equation 3. The reference level r_O is 10^6 km, with fixed values of N_O and B_O (2×10^7 cm^{-3} and 1 gauss) and variable T_O, with $\alpha = 1.228$. Shown are the wind velocity

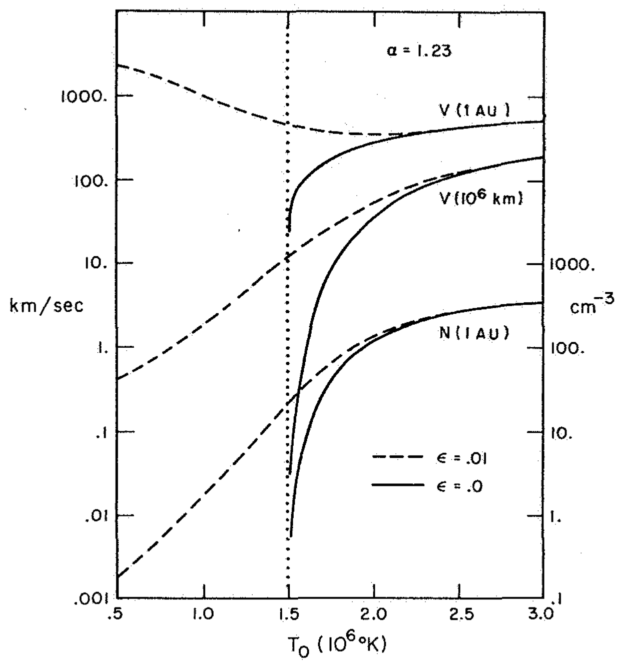

Figure 4. *The solar wind velocity V at 1 AU and 10^6 km, and the proton particle density N at 1 AU, as functions of the temperature T_O at 10^6 km, for two values of ϵ.*

at 10^6 km and at 1 AU, and the solar wind particle density N at 1 AU, as functions of T_O, for two values of ϵ(0. and 0.01). For $\epsilon = 0.$ and this value of α, the Parker wind solutions do not exist below $T_O = 1.5 \times 10^6$ °K. The inclusion of the wave energy flux ($\epsilon \neq 0.$) results in the existence of wind solutions for ranges of coronal reference temperatures T_O below 1.5×10^6 °K, as the Alfvén waves provide the additional energy needed to lift the coronal plasma out of the solar gravitational field. Note that the wave-dominated solutions can easily produce a combination of high velocities (~700 km/sec) and low densities (~2 cm^{-3}) at 1 AU for reasonable conditions at 10^6 km, something impossible to do in Parker polytrope models with no waves. There are some fairly important deficiencies in this model that should be mentioned. The observed wave length spectrum of the Alfvén waves at 1 AU (~5×10^6 km and less) implies that the WKB assumption is only approximately satisfied near the sun. Also, $\delta B/B$ typically increases by a factor of 20 to 50 between 10^6 km and 1 AU, so that even small-amplitude waves at 10^6 km will tend to become nonlinear ($\delta B/B \simeq 1$) by 1 AU. This will introduce nonlinear and wave damping effects not included in the model. With these deficiencies in mind, the model is a reasonable first attempt to determine the effects of coronal wave pressures on the dynamics of the wind.

In summary, it is clear from both the observations and the simplified model discussed above that coronal waves generated at or near the sun can have a major effect on both the small and large-scale structure of the interplanetary plasma at 1 AU. At the small scale they provide a major source for the interplanetary microscale fluctuations, and at the large scale they are almost certainly a dominant factor in the dynamics of the high-velocity streams, as has been suggested many times before.

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DISCUSSION

A. Barnes What was the total energy efflux at the base of the corona (fig. 4) of Belcher for $\epsilon = 0.01$?

J. Belcher For that value I think it's on the order of 2×10^{27} ergs/sec. The Alfvén velocity is very high there, so even small-amplitude waves can carry a tremendous amount of energy into the plasma at the Alfvén velocity.

Unidentified Speaker In connection with the identification of the source region for the Alfvén waves, is it necessary that the source be very close to the sun? From the comments this morning in the theoretical discussion, the decay times are e-folding times for these waves. As such that they can propagate only a relatively short distance, and it seems to me that the observations only require that the source be closer to the sun than the point of observation, but not that they be within the critical surface. Do you have a comment on that, John?

J. Belcher Yes. Typically, any source of fluctuations, for example, stream-collisions, will generate waves propagating in all directions. If this source is outside the Alfvénic critical point, all the waves are swept out or convected, so you'll see waves going in both directions. However, if the source is inside the Alfvénic critical point you will only see the waves that propagate outward into the solar wind because the waves that propagate inward can propagate faster than they are being convected and they can move back toward the sun. Incidentally, the Alfvénic critical point, at which the solar wind velocity exceeds the local Alfvén velocity, is located at 10 to 20 $R_\odot$.

E. J. Smith I would like to make a couple of brief comments having to do with the identification of the different types of discontinuities in interplanetary space. Len

Burlaga (p. 315) mentioned an analysis of his that indicates that certain classes, namely, the rotational discontinuities, occur at most, say, 25 percent of the time, at least in the data samples taken. Now, I feel, rightly or wrongly, that I have been partly responsible for this controversy and I know that there is a fundamental legal principle in English law that silence is usually interpreted as assent. So I thought I would take a couple of minutes to indicate that I do not necessarily assent. The method of analysis I have used is different from the one Burlaga has used. I don't think we've heard the last word about this matter of discontinuities yet. I'm certainly not about to give it now. However, those of you who are interested in this controversy might be interested in both the technique I'm using and, more importantly, the results that have been obtained so far.

Figure 1 is just an attempt to remind those of you who haven't been through this

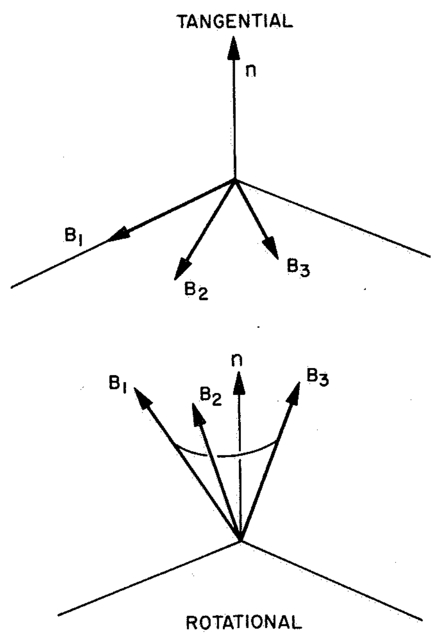

Figure 1. *Field changes across tangential and rotational discontinuities.*

recently of one way of viewing the distinction between the two types of discontinuities. The upper half of the figure shows how the field changes across a tangential discontinuity: It tends to rotate in the plane of the discontinuity, although it may change magnitude as well as direction. The fact that it rotates in the plane of discontinuity, as this drawing indicates, implies that there is no normal component to the magnetic field. At a rotational discontinuity, on the other hand, the field rotates in a cone about the normal to the plane of the discontinuity and consequently there is a normal component to the field. This distinction is borne out by the type of analysis discussed by, for example, Landau and Lifshitz. Using this rather simple approach I have analyzed the discontinuities from the Mariner 5 data as a basis for determining: (1) the direction of the normal to the plane of the discontinuity, and (2) whether there is a component of the magnetic field that is essentially constant and parallel to that direction.

Figure 2 is a histogram of the results obtained so far. The relative percentages of the number of cases for which the magnitude of the normal component relative to the total field has ratios indicated on the abscissa extend all the way up to one. As you can

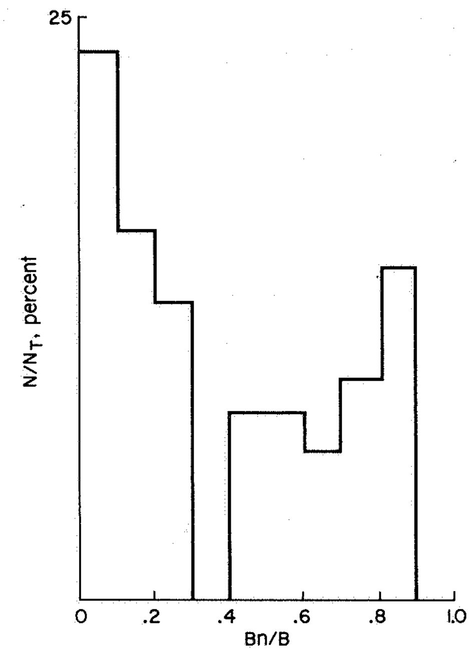

Figure 2. *Distribution of the normal components of the set of discontinuities analyzed.*

appreciate, in a 5 to 10γ field, when you get up to this end of the axis, the values of the normal components are very large. They can be 5 γ or larger. The important thing about this distribution function, the most obvious feature, is that it has a double hump. There is obviously no narrowly defined classification, for example, two δ functions, one at zero and the other for a finite, normal component. Nevertheless, you see very clearly that there appear to be two broad classes of discontinuities. There is some overlap where one ends and the other begins, and this introduces some uncertainty into the exact statistics that you end up with. The point is that I have chosen those discontinuities for which the normal component is 0.4 or more of the field magnitude on the two sides. Then it turns out that on the basis of this classification there is about an equal number of rotational and tangential discontinuities. That's been a consistent result which I've been obtaining with this method looking at different sets of data. There are other ways of checking this, which is what I'm doing now. Certainly the method Burlaga used, based on simultaneous plasma data, can be a very powerful one, and that is another way of now testing to see whether this classification is indeed the correct one or not.

There are other properties of discontinuities that should be mentioned. One of the important ones is that for a rotational discontinuity the magnitude of the field should remain constant at all times. The magnitude of the field may or may not be constant for tangential discontinuities. Now, based on this classification, all discontinuities selected as being rotational display a change in the magnitude of the field which is less than 0.1 of the total field.

J. R. Jokipii How do you determine the shock normal from one spacecraft?

E. J. Smith The normal to the discontinuity? I use a technique that a number of people have used for various purposes. It is the so-called "variance method." The distribution of the individual vectors is assumed to form an ellipsoid, which may degenerate into a plane. The variance analysis determines the principal axes of that ellipsoid, or equivalently, the eigenvalues and eigenvectors. The direction in which the variance is a minimum is taken to be the normal to the discontinuity. I then look at the individual discontinuities in the principal axis coordinate system and see the extent to which there is a nonnormal magnetic field component. This is a technique that Siscoe used to study discontinuities. Sonnerup also used it in studying the magnetopause, if you are familiar with those applications.

F. C. Michel Do you make this computation once for each discontinuity or do you select several and impose some consistency relation–for example, that successive discontinuities should tend to be parallel?

E. J. Smith I do this analysis on each individual discontinuity, and I use the vector fields on both sides as well as some vectors inside the current sheet. I do the analysis on that whole set, which is about 2 to 3 min of data.

F. C. Michel The field for rotational discontinuities should be the same on both sides unless the plasma pressure changes, and statistically such changes should average out. Thus, the average field before the discontinuity should equal that after it. Shock waves, for example, would not have that property.

E. J. Smith The classification really has nothing to do with the constancy of the magnetic field magnitude. I just use that as a test afterwards.

N. F. Ness I want to ask two specific questions: (1) How many discontinuities were in the sample you showed for the distribution of B_N/B, and (2) what was the average time interval of the data set used to define the discontinuity?

E. J. Smith The histogram that I showed contains a little over 60 discontinuities, and they are fairly large. I tried to pick examples where the field was relatively quiet both before and after the discontinuities, so there wouldn't be any large variations which might tend to obscure the identification of normal components. These occur on the average once every 6 hr. As I said earlier, the actual analysis interval is something like 3 min. The discontinuities, of course, are very abrupt, and consequently the transition occurs in less than 3 min.

K. Schindler It seems to me that your classification still might contain quite a number of weak shock waves, whereas Burlaga's doesn't.

E. J. Smith I suppose it's possible that some shocks have been included. However, in looking at the discontinuities I have always tried to be careful to avoid shocks and I have used the plasma data for that. I look at the plasma velocity and see whether it's changed and also look to see the extent of the change in the magnitude whenever there's been a change in the magnitude of the field.

A. Barnes If possible I would like to jump back to the question Norman Ness raised before about Alfvén waves propagating out from the sun. I think there may be a bit of confusion on this point. This morning I wrote down an equation (p. 337) that indicated the decay of Alfvén waves might be very significant. I should point out that the equation is based on an estimate for bounds that include the value zero. The only solid calculation on this point that I know of is the one Gene Parker mentioned yesterday, which was performed by George Valley. His conclusion is that many Alfvén waves originating at the sun could probably reach the earth but with considerable attenuation. There is one other point. For most of the distance between the earth and sun, or at least half the distance, $\Delta B/B$ will be smaller than at the earth even though the energy efflux in the Alfvén waves is larger than at 1 AU.