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AUTHOR(S): W. C. Feldman, B. Abraham-Shrauner, J. R. Asbridge,
and S. J. Bame

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THE INTERNAL PLASMA STATE OF THE HIGH SPEED SOLAR WIND AT 1 AU

W. C. Feldman, B. Abraham-Shrauner, J. R. Asbridge, and S. J. Bame
University of California, Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

The character of particle velocity distributions in the high speed solar wind is presented. It is found that electron distribution shapes differ from simple bi-Maxwellians in that a hot, strongly beamed, high energy electron component is always present and is observed to move relative to a distinct low energy electron component along the magnetic field direction, $\hat{B}$, away from the sun. The velocity difference between hot and cold electron components appears, at times, to be strongly correlated with the local Alfvén speed. This correlation suggests that the solar wind heat flux is being limited some of the time in the neighborhood of 1 AU. Proton velocity distributions are also best described in terms of two relatively convecting, unresolved components. The velocity of the lower density proton beam component is generally larger than that of the main component and the temperature of the main component perpendicular to $\hat{B}$ is typically 2 to 3 times larger than its parallel temperature. Alpha particles as a whole generally move faster than the protons along $\hat{B}$ and have a temperature which is, on the average, 6 times higher than the temperature of the total proton population. Evidence is presented which supports the idea that the two-component proton structure observed in high speed regions is intimately related to fine scale velocity variations at 1 AU, and hence by inference, to prominent spatial and/or temporal structures present throughout that part of the corona from which the solar wind evolves.

1) Introduction

An accurate determination and understanding of the internal plasma state of the solar wind is useful for several reasons. Although at 1 AU the energy of the solar wind is dominated by its bulk convection, the internal state provides diagnostic information of importance for determining the thermal state of the lower corona. Furthermore energy and momentum transport coefficients depend sensitively on the magnitude of electron and proton mean scattering lengths. These coefficients determine the plasma conductivity and viscosity which in turn may be important for estimating the electron heat flux and solar wind angular momentum flux at 1 AU.

Much is presently known about the average internal state of the interplanetary plasma at 1 AU as well as its variations with time. Most of the work on this subject prior to 1974 has been reviewed by Hundhausen (1970,1972) and Feldman et al. (1974a). The purpose of this paper is to summarize those analyses of Los Alamos IMP solar wind measurements which have been carried out since 1974. In particular we will concentrate on the character of particle velocity distributions in the high speed solar wind. Measured deviations from bi-Maxwellian velocity configurations of solar wind electrons and ions are presented in sections 2 and 3 respectively. These results are discussed in section 4 with particular emphasis placed on the origin of local proton heating inferred from proton distribution shapes observed during high speed flow conditions.

2) Solar Wind Electron Velocity Distributions

A cut along the magnetic field direction, $\hat{B}$, through a typical solar wind electron velocity distribution, f_e , is shown in Figure 1. The measured distribution is plotted using solid dots and the lines represent two essentially bi-Maxwellian functions, f_c and f_h , which fit the data best at low and high electron energies respectively. For this particular example (see Feldman et al., 1974b) a bi-Maxwellian function was fit to the measured velocity distribution of electrons with energies, $E < 79$ eV (Velocity, $V < 5270$ km s⁻¹). It is readily seen that although the fit is good for energies less than 79 eV, it seriously underestimates the measured velocity distribution at higher energies (see also Montgomery et al., 1968; Montgomery, 1972; Feldman et al., 1975). This effect is a general feature of solar wind electron distributions.

Figure 1. A cut through a solar wind electron velocity distribution along the magnetic field direction. The two solid parabolas are the two bi-Maxwellian functions which best fit the low and high energy electrons respectively. The vertical lines through the data points indicate the statistical plus digitization errors where they are larger than the plotting symbols.

In order to quantify measured distributions at high energies, two of many possible models have been adopted. The first fits a bi-Maxwellian function to the high energy electrons (for the example in Figure 1, $E > 167$ eV or $V > 7660 \text{ km s}^{-1}$) in order to characterize the lower velocity moments (density, velocity and temperature) of this part of the velocity distribution. The second model uses the above bi-Maxwellian function times a low energy cutoff function (see Feldman et al., 1975) to analytically interpolate the measured high energy velocity distribution to electron energies lower than that at which $f_c > \frac{1}{2}f_e$. The composite high energy distribution, f_H is then numerically integrated to determine its four lowest velocity moments (density, N_H , velocity $\bar{V}_H$, temperature, T_H and heat flux, Q_H).

An extended survey of many electron distributions measured using the Los Alamos IMP analyzers showed that a bi-Maxwellian representation of high energy electrons is good during times of low solar wind bulk speed but poor during high speed flow conditions (Feldman et al., 1976a). It should be noted that even though a bi-Maxwellian is adequate during times of low bulk speed, it is not a unique representation. A power law in energy, exponential in speed or some other analytic form may equally well describe the velocity distribution of high energy electrons. During times of high bulk speeds, measured electron distributions are more strongly beamed (the high energy electrons develop a large thermal anisotropy) along the magnetic field direction, B , than can be accommodated by a bi-Maxwellian function. However, it turns out that even when a bi-Maxwellian function does not represent the shapes of measured high energy electron distributions accurately, the lower velocity moments of the model are still reasonably good representations of the true moments. In particular, estimates of the flux of high energy electrons, $N_H \bar{V}_H$, are not significantly different using either of the above adopted models.

Although the above two models for separating solar wind electron velocity distributions into two components ($f_e = f_c + f_H$) are not unique, they allow a quantitative discussion of how measured distributions deviate from simple bi-Maxwellian functions. We therefore proceed with a quantitative description of the salient features of observed electron velocity distributions within the context of the above two-component models. The high energy electron component is generally observed to be hotter than the low energy component. We can therefore unambiguously label them as the hot (f_H) and cold (f_c) electron components respectively. If the bi-Maxwellian model for f_H is adopted then $T_H \sim 6 T_c$ (Feldman et al., 1975). Hot and cold electron components are generally observed to move relative to one another along B in such a way that the net electron particle flux is zero in the frame of reference moving with the protons; i.e. $N_c \Delta \bar{V}_c + N_H \Delta \bar{V}_H = 0$ within experimental errors. Here and in the following, subscripts H and c refer to hot and cold electron parameters respectively and $\Delta \bar{V}_c$ ($\Delta \bar{V}_H$) is the difference in velocity between the cold (hot) component and the total electron population. The electron bulk velocity is observed to be equal to the solar wind proton bulk velocity to within about 50 km s^{-1} .

The velocity offset between hot and cold electron components (as defined above) is convincingly seen if that part of the measured electron distribution function along B pointing in the solar direction is folded over and plotted on top of that part measured along B but pointing in the antisolar direction. This operation has been performed for an electron distribution measured using the Los Alamos IMP 8 analyzer and the result is

Figure 2. A cut through an electron velocity distribution folded over onto the magnetic field direction but away from the sun. The dot (triangle) symbols represent the part of the measured distribution in the direction away from (toward) the sun. The dip in the center of the hot component velocity distribution shows the form of the cutoff function used to analytically interpolate the hot component distribution at low energy in the analytical-numerical hybrid model.

plotted in Figure 2 (see also discussion around Fig. 14 of Feldman et al., 1975). Using this type of presentation, the bulk speeds of hot and cold components can readily be evaluated graphically by determining the velocity interval, ΔV , through which one side of each component of the distribution needs to be translated to bring it into coincidence with its respective other side. In particular, for the example plotted in Figure 2, $V_c = \frac{1}{2}\Delta V_c \approx 380 \text{ km s}^{-1}$, $V_H = \frac{1}{2}\Delta V_H \approx 1330 \text{ km s}^{-1}$, whereas the total electron (and also proton) bulk speed, $V_s \approx 500 \text{ km s}^{-1}$. Therefore since $\hat{B}$ was nearly radial, $\Delta \bar{V}_c = \bar{V}_c - \bar{V}_s \sim -120 \text{ km s}^{-1}$ and $\Delta \bar{V}_H = \bar{V}_H - \bar{V}_s \sim 830 \text{ km s}^{-1}$. On the average $\Delta V_c \approx 50 \text{ km s}^{-1}$ and if the bi-Maxwellian hot component model is adopted, $\Delta V_H \approx 700 \text{ km s}^{-1}$ and $N_H/N_p = 0.065$ (Feldman et al., 1975). All three of these parameters are typically larger in the high speed solar wind.

A virtue of both two-component models of electron velocity distributions described above is that they account for the solar wind heat flux in a particularly simple way. In general, the electron heat flux, $\bar{Q}_e$, can be well approximated by (Feldman et al., 1975).

$$\bar{Q}_e \approx (N_H \Delta \bar{V}_H) \frac{5}{2} k T_H \left(1 - \frac{T_c}{T_H}\right) + \bar{Q}_H \quad (1)$$

The term, $\bar{Q}_H$ in equation (1) is the intrinsic third moment of the hot electron component and is identically zero if the bi-Maxwellian approximation to f_H is adopted. However, if the hybrid cutoff bi-Maxwellian and numerical approximation to f_H is adopted, the magnitude of $\bar{Q}_H$ is a substantial fraction of $\bar{Q}_e$ but oppositely directed; on the average, $\bar{Q}_H \approx -0.6 \bar{Q}_e$. Therefore, the heat flux according to both adopted models is carried primarily by the convection of the hot electrons relative to the bulk velocity along $\hat{B}$. In order to insure zero electron flux in the plasma rest frame, the hot component particle flux, $N_H \Delta \bar{V}_H$, must be matched by an oppositely directed flux of cold electrons, $N_c \Delta \bar{V}_c$, as is observed. Therefore, using the above parameterization, the electron heat flux is proportional to ΔV_c (and also to ΔV_H), the velocity difference between the cold (hot) component and the entire electron population. The relative cold component drift is readily and most accurately evaluated from measurements of f_H using either of the above models since $\Delta V_c = N_H \Delta V_H / N_c$.

Theoretical analyses of possible heat flux regulating mechanisms active in interplanetary space have shown (Forslund, 1970; Schulz and Eviatar, 1972; Perkins, 1973; Gary et al., 1975a,b) that if ΔV_c becomes larger than about the Alfvén speed, one of several microinstabilities may develop depending on the values of various plasma parameters. The net effect of the oscillating electric and magnetic fields associated with a particular unstable mode would be to alter the electron velocity distribution in such a way as to establish a stationary state of the plasma with respect to that mode. Therefore, a possible signature of the local regulation of the interplanetary heat flux may be an observable relationship between ΔV_c and V_A .

Such reasoning led to an experimental search for a correlation between ΔV_c and V_A . Indeed such correlations were observed on both short and long time scales at 1 AU. One remarkably clean example of a fine time scale correlation is shown in Figure 3. The importance of the Alfvén speed in causing the variation of ΔV_c evident in the figure is strengthened by the fact that the large decrease in V_A centered at 0800 UT (associated with a similar decrease in ΔV_c) was caused primarily by a decrease in the magnetic field strength and not an increase in the ion density. An example of a longer time scale correlation between ΔV_c and V_A is reproduced in Figure 4. This correlation is seen to be quite good throughout the entire high speed region although the large increase in V_A early on April 9 is not followed immediately by a corresponding increase in ΔV_c . These particular examples, as well as others, were interpreted (Feldman et al., 1976b) to suggest that the Alfvén speed is at times, a prime regulating factor of the solar wind heat flux through the relation $Q_e \propto \Delta V_c = \alpha V_A$. Here α is a dimensionless parameter of order unity which depends for its value on the local plasma configuration.

Figure 3. A plot of the Alfvén speed, V_A , relative cold component to total electron population bulk speed difference, ΔV_c , and solar wind speed, V_{sw} , during a 12 hour period centered on the maximum speed gradient region at the front edge of a high speed stream.

Figure 4. Hourly averages of the same parameters plotted in Figure 3 showing their variation through a clean example of a high speed stream.

3) Solar Wind Ion Velocity Distributions at High Bulk Speeds

A previous survey of Los Alamos IMP 6 plasma data has revealed a wide variety of shapes of solar wind proton velocity distributions. These distributions range from isotropic Maxwellians to resolved double streaming configurations (Feldman et al., 1973, 1974a). Most of the time, and especially during high speed flow conditions, measured proton distributions are not well represented by a simple extension of a bi-Maxwellian shape which includes a third velocity moment (Whang, 1971; Feldman et al., 1973). In general, high energy extensions of solar wind proton distributions exceed extrapolations of the bi-Maxwellian functions which best fit the distribution peaks, by more than can be accommodated by Whang's multiplicative factor (Whang, 1971). In fact a visual survey of measured proton distributions strongly suggests that during high bulk speed flow conditions, solar wind protons are best described in terms of two unresolved, relatively drifting components, $f_p = f_M + f_B$. Here the subscripts M and B refer to main and beam proton components respectively.

In order to test this hypothesis two computer codes were written to reanalyze IMP 6 and 7 solar wind proton data in terms of two relatively convecting bi-Maxwellian and Lorentzian components. The numerical method employed for the bi-Maxwellian fits has been outlined previously (Feldman et al., 1976a). The method used for the Lorentzian fits was similar but slightly more complicated because it had to supply one extra free parameter, the power law high energy shape parameter, p . More details will be given in a later paper. For the present though, it is only necessary to note the difference in functional forms; the two-dimensional bi-Maxwellian

representation is given by

$$N \left(\frac{m}{2\pi k} \right) (T_{\parallel} T_{\perp})^{-1/2} \exp \left\{ - \left(\frac{m}{2k} \right) \left[\frac{(\bar{v} - \bar{v}_0)_{\parallel}^2}{T_{\parallel}} + \frac{(\bar{v} - \bar{v}_0)_{\perp}^2}{T_{\perp}} \right] \right\} \quad (2)$$

and the two-dimensional Lorentzian representation is given by

$$\frac{N(p-1)}{(p-2)} \left(\frac{m}{2\pi k} \right) (T_{\parallel} T_{\perp})^{-1/2} \left\{ - \frac{m}{2(p-2)k} \left[\frac{(\bar{v} - \bar{v}_0)_{\parallel}^2}{T_{\parallel}} + \frac{(\bar{v} - \bar{v}_0)_{\perp}^2}{T_{\perp}} \right] + 1 \right\}^{-p} \quad (3)$$

In both cases m is the proton mass, k is Boltzmann's constant, N is the density, $T_{\parallel}$ ($T_{\perp}$) is the temperature parallel (perpendicular) to the entire distribution symmetry axis (or effectively the magnetic field direction, $\hat{B}$), $\bar{v}_0$ is the bulk velocity, and for the Lorentzian form, p is the power law parameter which is assumed to be the same for main and beam components.

Before proceeding to the results it is first useful to note the limitations of the above analysis. Most important, the problem of analyzing two unresolved velocity distributions whose shapes and velocities are not known a priori, has no unique solution. For this reason IMP proton data were analyzed using two different functional forms in order to estimate the magnitudes of parameter uncertainties. Another limitation is that in order to make the analysis feasible for a large number of measured proton spectra we have used an iterated linear technique to solve a non linear problem. As a result the "converged" parameters obtained here are, to some extent, procedure dependent and may differ from those determined using a fully non linear analysis. In particular, although for some spectra a good fit looked possible, the computer code converged on a bad fit. It was therefore necessary to edit the results both according to the value of the goodness of fit parameter, χ^2 , and by visual inspection of the fidelity of the fits. Roughly 1/2 of all analyses were deemed visually acceptable and had a reduced χ^2 less than 5. Typical two-component fits had 50 to 60 degrees of freedom. It is therefore not possible to say whether convecting Lorentzians represent measured distributions better than do convecting bi-Maxwellians or perhaps some other functional form. However, because a substantial number of fits were exceedingly good and reproducible, it is possible to give a rough quantitative account of typical solar wind proton velocity distributions observed during high speed flow conditions at 1 AU.

Typical fits of two convecting bi-Maxwellians to proton distributions measured in high speed bulk flow regions using the IMP 7 analyzer are plotted in the top half of Figure 5. Two dimensional contours of corresponding velocity distributions measured using the IMP 6 analyzer are presented in the bottom half of the figure. Special note should be taken of two facts readily observable in the figure which are generally valid during high speed flow conditions. 1) The two-dimensional contour diagrams indicate an enhanced extension at higher energies. Radial projections of the velocity distributions show that these extensions are well characterized by distinct but unresolved secondary proton beams convecting relative to main proton components. Typical velocity differences in the high speed solar wind range between 40 and 60 km s⁻¹. 2) Inspection of the 2-D contours shows that the perpendicular temperature of the main component, $T_{\perp M}$, is larger than the parallel

Figure 5. A plot of two typical proton velocity distributions measured during high speed solar wind flow conditions. The lower panels show the two dimensional contour diagrams of the measured distributions and the upper panels compare the best fit relatively convecting two component bi-Maxwellian model with the radially projected data. The beam fits are represented by the solid circles, the main component fits are given by the solid triangles, the open triangles give the sum of beam and main component fits, and the measured distribution is plotted by the open squares.

temperature, $T_{\parallel M}$. A previous analysis has shown that typically, $T_{\perp M} \sim 2.4 T_{\parallel M}$ (Bame et al., 1975).

An overview of two months of IMP 7 data (February and March 1973) shows that $T_{\parallel M}$ in the high speed solar wind is comparable to T_c , the temperature of the cold component electrons. During the 19 high speed regions tabulated by Feldman et al. (1976c) the average value of T_c was $8.5 \times 10^4 K$. This value is close to a typical value of $T_{\parallel M}$ in high speed regions and is a factor of 2.7 times less than the simultaneously measured average total proton temperature which is close to a typical value of $T_{\perp M}$. Other general characteristics of the bi-Maxwellian fits are: 1) The beam is generally hotter than the main component; typically T_B is 2 to 3 times T_M . 2) The beam contains a substantial fraction of the total number of protons; typically N_B is 20 to 40% of N_M . 3) The beam is anisotropic in the sense that $T_{\parallel B} > T_{\perp B}$; typically $T_{\parallel B}$ is 1.2 to 1.8 times $T_{\perp B}$.

Even though $(T_{\parallel}/T_{\perp})_B$ and $(T_{\perp}/T_{\parallel})_M$ are generally larger than one in the high speed solar wind, conspicuous and believable examples can be found for which $T_{\perp}/T_{\parallel} > 1$ for both main and beam components simultaneously. It should be noted that although most Lorentzian or bi-Maxwellian fits yield $T_{\parallel B} > T_{\perp B}$, most two-dimensional contour diagrams show evidence that the beam is being heated perpendicular to B . For example, although both bi-Maxwellian fits in Figure 5 give $T_{\parallel B} > T_{\perp B}$, the outer contours of the distribution functions show a pronounced perpendicular bowing at high proton energies. This fact probably indicates that neither of the above adopted models is fully adequate to represent measured proton distributions although they are a definite improvement over single component models.

In general, the Lorentzian fits yield results which are qualitatively similar to those obtained using bi-Maxwellian functions. Although particular examples can be found for which the two-convecting Lorentzian model provides

fits which represent the data better than do those of the two-convecting bi-Maxwellian model, the reverse is also true. On balance we are unable to judge which is the better model on the average. For example, during a typical one day period within a high speed stream, a comparison between Lorentzian and bi-Maxwellian models showed that the Lorentzians provided superior fits 22% of the time, were clearly inferior 15% of the time, were indistinguishable from the bi-Maxwellian fits 12% of the time, and both models provided unacceptable fits 51% of the time.

The velocity moments of alpha particle distributions are also observed to vary characteristically across solar wind high speed streams. Previous analyses have shown that in the high speed solar wind, alpha particles 1) are a 4 to 5% constituent (Hirshberg et al., 1974; Feldman et al., 1976d), 2) travel faster than the protons along $\hat{B}$ with a typical relative speed of about 25 to 30 km s⁻¹ (Asbridge et al., 1976), and 3) are about 6 times hotter than the protons (Feldman et al., 1976d). It should be noted that the drift speed of the alpha particles is such that they lie roughly, but slightly more than midway between the proton main and beam components in velocity space.

4) Summary and Discussion

The internal plasma state of the high speed solar wind at 1 AU is generally observed to deviate substantially from that expected for a simple fluid. The salient features of this state are as follows. 1) A distinct, high energy electron component exists and is observed to be strongly beamed along the magnetic field direction, $\hat{B}$, and moving relative to the plasma reference frame away from the sun. This motion is accompanied by a corresponding return flow of low energy electrons (relative to the plasma reference frame) back towards the sun in such a way that the net electrical current away from the sun is zero. 2) Proton velocity distributions are best described in terms of two relatively convecting components. The temperature anisotropy of the main proton component is large and in the sense that $T_{\perp M} > T_{\parallel M}$; on the average $T_{\perp M} \approx 2.4 T_{\parallel M}$. The beam component velocity is generally larger than that of the main component; relative speeds are typically 40 to 60 km s⁻¹. Beam densities are typically 20 to 40% of main component densities and beam anisotropies are moderate to small with parallel temperatures generally exceeding perpendicular temperatures. 3) The alpha particles travel away from the sun relative to the protons along $\hat{B}$ at speeds which are frequently 25 to 30 km s⁻¹. 4) Internal energy is not equally partitioned among all the particle components.

Some properties of the internal state of the high speed solar wind are difficult to understand unless local wave-particle interactions are important in the neighborhood of 1 AU. For example: 1) The bulk velocity of the cold electron component is generally less than that of the protons. Striking examples like those shown in Figures 3 and 4 strongly suggest that the magnitude of the speed difference between the cold electron component and the total electron population is close to and, in some way coupled to the local Alfvén speed. 2) A single bi-Maxwellian function accounts for the velocity distributions of interplanetary electrons out to about 6 times the cold component thermal energy. Although during high speed solar wind flow conditions the ratio of the coulomb electron self collision time to the time required for an electron with speed along $\hat{B}$ of $\sqrt{kT_c/m_e}$ to transit a density

scale height is comparable to, but slightly less than one, electrons with energies of $6kT_c$ are collisionless. Therefore the adequacy of a single bi-Maxwellian function for interplanetary electrons with energies $\lesssim 6kT_c$ cannot be explained as resulting from binary coulomb interactions alone. 3) The anisotropy of the peaks of proton distributions observed in the high speed solar wind is large and in the sense that $T_{IM} > T_{\parallel M}$. Such an anisotropy must be produced locally since in the absence of collisions, conservation of the proton magnetic moment would produce $T_{\parallel M} > T_{IM}$.

On the basis of the above evidence it is likely that wave-particle interactions are effective in reducing both electron and ion mean scattering lengths below their binary coulomb values in the high speed solar wind at 1 AU. Such a reduction should lead to a corresponding reduction in the conductivity and viscosity of the local plasma. This expectation is consistent with an interpretation of the ΔV_c , V_A correlation shown in Figure 4, as indicating that, at least some of the time, the electron heat flux is under local regulation in the high speed solar wind at 1 AU (Feldman et al., 1976b).

It is useful to try to identify the dominant source of energy flux which causes most of the local particle scattering and heating effects observed in the high speed solar wind. Although it is not possible to make a definitive determination from measurements made only at 1 AU, a likely choice is that agent which transports the most internal energy flux away from the sun. A previous analysis (Feldman et al., 1976c) showed that most of the internal energy transported during high speed flow conditions is carried as convected proton enthalpy and as Alfvén waves or other propagating bulk velocity variations such as small amplitude high speed stream disturbances. It is therefore likely that the energy flux necessary to produce the complex ion configurations observed at 1 AU is carried in the form of 1) proton internal energy, 2) Alfvén waves, 3) many small amplitude high speed streams or 4) a suitable combination of all three. The shapes of proton velocity distributions in the high speed solar wind strongly suggest that the dominant flux of proton internal energy is carried by a distinct secondary beam of protons.

It has been known for some time that Alfvén waves are an important interplanetary phenomenon intimately associated with high speed solar wind flow conditions (Belcher et al., 1970; Belcher and Davis, 1971). The present summary has shown that unresolved proton beams are important in the high speed solar wind as well. Both effects must be ultimately caused by fine scale spatial and/or temporal structures present throughout that part of the corona from which the solar wind evolves. If Alfvén waves or small velocity amplitude solar wind streams damp in interplanetary space (see e.g. Hollweg, 1973; Hundhausen, private communication, 1976) a net heating of the ions may result. Ion heating may also result if the secondary proton beams in the solar wind dissipate as they propagate away from the sun. Such an effect is possible since it has been shown recently that for high speed solar wind conditions, three different ion beam driven instabilities have threshold values which depend, in part, on the ratio of the difference in speed between proton beam and main components to the local Alfvén speed (Montgomery et al., 1975, 1976). Because the Alfvén speed decreases monotonically with increasing distance from the sun, it is reasonable to expect that kinetic processes may effect the transfer of the directed kinetic energy carried by the proton beam to random thermal energy of the proton main component and alpha particles. In either case both mechanisms predict a correlation between the ion

temperatures at 1 AU and variations of the solar wind bulk velocity. Indeed it is well known that both the proton temperature (Burlaga and Ogilvie, 1970; Hundhausen et al., 1970) and the rms value of bulk velocity variations in 3-hour intervals (Hundhausen, 1970) increase with increasing bulk speed. The fact that both are directly correlated is shown explicitly in Figures 6 and 7 for protons and alpha particles respectively. Here $V_T = \sqrt{3kT/m}$ is a thermal speed defined such that $\frac{1}{2}mV_T^2 = \frac{3}{2}kT$, the average thermal energy carried by each ion species, and $\langle \delta V^2 \rangle^{1/2}$ is the average value of the rms variation in the bulk flow velocity during successive 3-hour time periods. The solid dots in Figures 6 and 7 correspond to averages over each of 61 time intervals between March 1971 and July 1974 during which the solar wind bulk speed was less than 350 km s^{-1} and not increasing with time. The triangles correspond to averages over each of 19 time intervals of "structure-free" high speed flows (see e.g. Feldman et al., 1976c, 1976d) observed during the same overall time period. An inspection of the figures shows that the correlation between V_T and $\langle \delta V^2 \rangle^{1/2}$ is quite good. This fact supports the idea that fine scale velocity variations are not only associated with, but may be the cause of local ion heating in interplanetary space.

It has been suggested previously that interplanetary Alfvén waves originate in the circulation pattern of supergranulation convection cells (Hollweg, 1972). Although this source may be responsible for all of the complex internal plasma structure observed in the high speed solar wind at 1

Figures 6 and 7. A plot of the proton (left) and alpha particle (right) thermal speed against the rms value of solar wind bulk velocity variations in successive 3-hour intervals averaged over 61 low speed and 19 high speed solar wind flow conditions selected from data measured between March, 1971 and July, 1974.

AU, it is not presently known in detail, whether transverse Alfvén waves, with a dominant period of about 10 to 20 hours, can produce as intense a secondary proton beam as is evident in Figure 5. Other possible sources of the large amplitude Alfvén waves and secondary proton beams observed in the high speed solar wind are the chromospheric spicules and macro-spicules. It is worth noting that the macro-spicules are jets of dense plasma with typical bulk velocities in the transition region between 50 and 150 km s⁻¹ (Bohlin et al., 1975; Withbroe et al., 1975). Furthermore these jets are only observed in coronal holes which are the most likely sources of high speed solar wind (Krüger et al., 1973, 1974; Nolte et al., 1976; Sheeley et al., 1976). It is possible that such intense jets produce both transverse and longitudinal velocity variations in the overlying coronal layers which eventually evolve into the large amplitude Alfvén waves and secondary proton beams observed so prominently in high speed solar wind regions at 1 AU. If correct, then the two-component proton structure of the high speed solar wind is the direct result of a two-component coronal structure composed of an ambient, steady state expansion upon which is superimposed prominent fine scale velocity variations which are either caused by an ensemble of transient jets of spicular plasma or by some, as yet unidentified, long time period coronal wave motion.

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References

- Asbridge, J. R., S. J. Bame, W. C. Feldman, and M. D. Montgomery (1976): Helium and hydrogen velocity differences in the solar wind. Accepted by J. Geophys. Res.
- Bame, S. J., J. R. Asbridge, W. C. Feldman, S. P. Gary, and M. D. Montgomery (1975): Evidence for local ion heating in solar wind high speed streams. Geophys. Res. Lett., 2:373.
- Belcher, J. W., L. Davis, Jr., and E. J. Smith (1969): Large amplitude Alfvén waves in the interplanetary medium: Mariner 5. J. Geophys. Res., 74:2302.
- Belcher, J. W., and L. Davis, Jr. (1971): Large amplitude Alfvén waves in the interplanetary medium, 2. J. Geophys. Res., 76:3534.
- Bohlin, J. D., S. N. Vogel, J. D. Purcell, N. R. Sheeley, Jr., R. Tousey, and M. E. Van Hoosier (1975): A newly observed solar feature: macro-spicules in He II 304 Å. Astrophys. J., 197:L133.

- Burlaga, L. F., and K. W. Ogilvie (1970): Heating of the solar wind. Astrophys. J., 159:659.
- Feldman, W. C., J. R. Asbridge, S. J. Bame, and M. D. Montgomery (1973): On the origin of solar wind proton thermal anisotropy. J. Geophys. Res., 78:6451.
- Feldman, W. C., J. R. Asbridge, S. J. Bame and M. D. Montgomery (1974a): Interpenetrating solar wind streams. Rev. of Geophys. and Space Phys., 12:715.
- Feldman, W. C., M. D. Montgomery, J. R. Asbridge, S. J. Bame and H. R. Lewis (1974b): Interplanetary heat conduction - IMP-7 results. In: Solar Wind Three, C. T. Russell, ed., Inst. of Geophys. and Planet. Phys., UCLA, CA, p. 334.
- Feldman, W. C., J. R. Asbridge, S. J. Bame, M. D. Montgomery and S. P. Gary (1975): Solar wind electrons. J. Geophys. Res., 80:4181.
- Feldman, W. C., J. R. Asbridge, S. J. Bame, S. P. Gary, and M. D. Montgomery (1976a): Electron parameter correlations in high speed streams and heat flux instabilities. Accepted by J. Geophys. Res.
- Feldman, W. C., J. R. Asbridge, S. J. Bame, S. P. Gary, M. D. Montgomery and S. M. Zink (1976b): Evidence for the regulation of solar wind heat flux at 1 AU. Accepted by J. Geophys. Res.
- Feldman, W. C., J. R. Asbridge, S. J. Bame, and J. T. Gosling (1976c): High speed solar wind flow parameters at 1 AU. Accepted by J. Geophys. Res.
- Feldman, W. C., J. R. Asbridge, S. J. Bame, and J. T. Gosling (1976d): Plasma and magnetic fields from the sun, in The Physical Output of the Sun and its Variation with Time, O. R. White, J. A. Eddy and D. Heath, eds., University of Colorado Press, to be published.
- Forslund, D. W. (1970): Instabilities associated with heat conduction in the solar wind and their consequences, J. Geophys. Res., 75:17.
- Gary, S. P., W. C. Feldman, D. W. Forslund, and M. D. Montgomery (1975a): Electron heat flux instabilities in the solar wind. Geophys. Res. Lett., 2:79.
- Gary, S. P., W. C. Feldman, D. W. Forslund, and M. D. Montgomery (1975b): Heat flux instabilities in the solar wind. J. Geophys. Res. 80:4197.
- Hirshberg, J., J. R. Asbridge, and D. E. Robbins (1974): The helium component of solar wind velocity streams. J. Geophys. Res., 79:934.
- Hollweg, J. V. (1972): Supergranulation-driven Alfvén waves in the solar chromosphere and related phenomena. Cosmic Electrodyn., 2:423.
- Hollweg, J. V. (1973): Alfvén waves in a two fluid model of the solar wind. Astrophys. J., 181:547.

- Hundhausen, A. J. (1970): Composition and dynamics of the solar wind plasma. Rev. of Geophys. and Space Phys., 8:729.
- Hundhausen, A. J. (1972): Coronal Expansion and Solar Wind, Springer-Verlag, New York-Heidelberg.
- Hundhausen, A. J., S. J. Bame, J. R. Asbridge, and S. J. Sydorik (1970): Solar wind proton properties: Vela 3 observations from July 1965 to June 1967. J. Geophys. Res., 75:4643.
- Krieger, A. S., A. F. Timothy, and E. C. Roelof (1973): A coronal hole and its identification as the source of a high velocity solar wind stream. Solar Phys., 29:505.
- Krieger, A. S., A. F. Timothy, G. S. Vaiana, A. J. Lazarus and J. D. Sullivan (1974): X-ray observations of coronal holes and their relation to high velocity solar wind streams, in Solar Wind Three, C. T. Russell, ed., Inst. of Geophys. and Planet. Phys., UCLA, CA, 1974, p. 132.
- Montgomery, M. D. (1972): Thermal energy transport in the solar wind, in Cosmic Plasma Physics, K. Schindler, ed., Plenum, New York, p. 61.
- Montgomery, M. D., S. J. Bame, and A. J. Hundhausen (1968): Solar wind electrons: Vela 4 measurements. J. Geophys. Res., 73:4999.
- Montgomery, M. D., S. P. Gary, D. W. Forslund, and W. C. Feldman (1975): Electromagnetic ion-beam instabilities in the solar wind. Phys. Rev. Lett., 35:667.
- Montgomery, M. D., S. P. Gary, W. C. Feldman, and D. W. Forslund (1976): Electromagnetic instabilities driven by unequal proton beams in the solar wind. Accepted by J. Geophys. Res.
- Nolte, J. T., A. S. Krieger, A. F. Timothy, R. E. Gold, E. C. Roelof, G. Vaiana, A. J. Lazarus, J. D. Sullivan, and P. S. McIntosh (1976): Coronal holes as sources of solar wind. Accepted by Solar Phys.
- Perkins, R. W. (1973): Heat conductivity, plasma instabilities and radio star scintillations in the solar wind. Astrophys. J., 179:637.
- Schulz, M., and A. Eviatar (1972): Electron-temperature asymmetry and the structure of the solar wind. Cosmic Electrodynamics, 2:402.
- Sheeley, N. R., Jr., J. W. Harvey, and W. C. Feldman (1976): Coronal holes, solar wind streams, and recurrent geomagnetic disturbances: 1973-1976. Accepted by Solar Phys
- Whang, Y. C. (1971): Higher-moment equations and the distribution function of the solar wind plasma. J. Geophys. Res., 76:7503.

Withbroe, G. L., D. T. Jaffe, P. V. Foukal, M. C. E. Huber, R. W. Noyes,
E. M. Reeves, E. J. Schmahl, J. G. Timothy, and J. E. Vernazza
(1975): EUV transients observed at the solar pole. Center for
Astrophys. Preprint series No. 325.