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SOLAR WIND FLOW ASSOCIATED WITH STREAM-FREE SECTOR BOUNDARIES AT 1 AU

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Abstract. The correlations between the plasma characteristics of the solar wind flow in the vicinity (± 12 hr) of stream-free sector boundaries near Earth are examined using the composite data base of interplanetary plasma for the period 1965–1980. We confirm the result of Lopez *et al.* (1986) of an inverse relationship of the proton temperature (T_p) with the momentum flux density (NV^2) in the low speed wind at 1 AU. The coefficients of lines of best fit to the T_p vs NV^2 (as well as T_p vs V) distribution in our sample are, however, significantly different from those of the undifferentiated sample of low speed wind considered by Lopez *et al.* such that T_p is, in general, lower than expected. We find further that the proton number density (N) varies as the inverse cube of the flow speed (V) indicating an invariance of the kinetic energy flux density (NV^3) relative to velocity structure in the plasma flow around stream-free boundaries. These average relationships, which are unaffected by interplanetary dynamical processes, are suggested to be due to sub-sonic addition of momentum and energy to the solar wind flow from the source structures, namely coronal streamers.

The bulk properties of the solar wind flow near Earth are well known to be modulated by the velocity structure in the solar wind. Early studies with Mariner 2 and Vela 3 data revealed a direct relationship of the proton temperature (T_p) with the flow speed (V), and an inverse relationship of the proton number density (N) with V (Neugebauer and Snyder, 1966; Burlaga and Ogilvie, 1970a; Hundhausen *et al.*, 1970). Realisation of the possible contamination of proton data by dynamical processes in interplanetary space led to questions of the relevance and usefulness of the average interparameter relationships towards the understanding of solar coronal expansion (e.g., Hundhausen, 1972; Pizzo *et al.*, 1973). Subsequent work nevertheless demonstrated that the macroscale relationship, derived from data averaged over several solar rotations, is not appreciably affected by stream interactions but is determined by physical processes operating close to the Sun (Burlaga and Ogilvie, 1973). Burlaga and Ogilvie (1970b) found for the first time that, when averaged over periods of 3 hr, T_p and V (from measurements aboard Explorer 34) are connected by a relation of the form

$$(T)^{1/2} = A + BV, \tag{1}$$

where A and B are constants. A similar dependence was subsequently reported by Burlaga and Ogilvie (1973) as well as by Pizzo *et al.* (1973). The very recent study of Helios 1 data by Lopez and Freeman (1986) confirmed not only the average positive $T_p - V$ relationship in the solar wind flow at 1 AU, but also the lack of a secular variation in the functional relationship through the solar cycle, a feature first pointed out by Burlaga and Ogilvie (1973).

Although an inverse relationship between N and V was noticed about two decades

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ago as mentioned earlier, definite relation has been established only in recent times. Several workers (Steinitz and Eyni, 1980; Mullan, 1983; Steinitz, 1983; Schwenn, 1983) found that N and V can be related by a function of the form

$$\log N = D + C \log V, \tag{2}$$

where C and D are constants. The value of C derived by these workers from data obtained at different phases of the solar cycle (and, hence, pertaining to different solar wind conditions) was consistently close to -2.0. This remarkable constancy of C indicates an invariance of the momentum flux density (NV^2) relative to the velocity structure in the solar wind, and is interpreted as due to initial constraints governing the evolution of solar wind and that the density cannot be taken as a free parameter in solar wind models (Steinitz and Eyni, 1980; Steinitz, 1983). The average energy flux (the sum of kinetic, thermal, and gravitational energy flux) is found recently to be also insensitive to flow speed (Marsch and Richter, 1984).

The above results strongly suggest an overall momentum-energy budget for the solar wind independent of the velocity structure. As opined by Lopez *et al.* (1986), different states of solar wind at 1 AU could then result from variations in the position along the flow where energy and momentum are deposited, and also how effectively they are deposited. This hypothesis which is based on the solar wind model of Leer and Holzer (1980) and Leer *et al.* (1982) received support from the analysis of Helios 1 solar wind data by Lopez *et al.* (1986). They found that whereas T_p increases with increasing momentum flux density (NV^2) in high-speed streams ($V > 500$ km s^{-1}) at 1 AU, T_p does not increase (and perhaps even decreases) with increasing NV^2 in low speed wind ($V < 500$ km s^{-1}). This fundamental difference in the nature of $T_p - \mathrm{NV}^2$ relationship (which is ascertained to be not significantly affected by stream interactions) has been explained by them as due to momentum and energy addition by MHD waves in the post-sonic and sub-sonic regions of the flow for high-speed and low-speed wind respectively, relying on the modelling work of Leer and Holzer (1980) regarding energy addition in the solar wind.

In this paper we investigate the characteristics of a subset of non-transient related low-speed solar wind namely, the one that prevails around stream-free sector boundaries at Earth (reversals in the polarity of interplanetary magnetic field that are currently discussed as heliospheric current sheet crossings at Earth). Borrini *et al.* (1981) demonstrated that the solar wind plasma parameters exhibit a characteristic pattern of variation in the vicinity of stream-free boundaries at 1 AU which includes, among other things, a maximum in N and minima in V and T_p. They interpreted this pattern, which is not affected by stream-stream interactions, as a signal of coronal streamers in the solar wind flow at 1 AU. That near-equatorial coronal streamers are major sources of dense low-speed wind containing either a sector boundary or a polarity reversal of interplanetary magnetic field at 1 AU was also shown by Feldman *et al.* (1981) from a study of Vela heavy ion and IMP solar wind data. The plasma flow around stream-free sector boundaries is thus a suitable sample to study coronal expansion processes, because the characteristics of the flow reflect solar rather than interplanetary processes. The motivation for the present effort is that, if the prevailing view (Leer and Holzer, 1980; Lopez *et al.*, 1986) of the origin of low-speed wind as due to sub-sonic deposition of momentum and energy is valid, then the interparameter correlations in the flow around stream-free boundaries are ought to be different from those in the general low-speed wind and other types of flows studied so far by various workers. The negative correlation between T_p and NV^2 is to be prominent in particular, because sub-sonic deposition of momentum leads to an increase of mass flux (NV) rather than energy flux at 1 AU (Leer and Holzer, 1980); as such, in the dense low-speed flow around stream-free boundaries (Borrini *et al.*, 1981), an increase in NV^2 implies a significant increase in particle flux and, hence, a much lower energy per particle available for heating. The principal objective of this communication is to document the evidence obtained that supports such an understanding.

The composite data base of hourly averages of the interplanetary plasma parameters compiled by King (1977, 1979, 1986) from near-Earth spacecraft measurements constitute the basic data used in the present work. Well-defined sector boundaries (SB) with a sharp reversal in the polarity of interplanetary magnetic field, and which were preceded as well as followed by at least 4 days of constant magnetic polarity are selected from the plots and listings of King. This primary selection procedure in adopted to eliminate polarity reversals such as those associated with a 'flapping' of the heliospheric current sheet due to solar activity associated solar wind disturbances (Fry and Akasofu, 1985). The SB data sample is then screened to isolate boundaries which have (a) an interplanetary shock 1–3 days prior to the boundary crossing and/or a transient interplanetary feature termed 'magnetic cloud' (Klein and Burlaga, 1982) around them or (b) a concurrent speed rise or followed within 24 hr by a speed rise associated with the onset of a high-speed stream. Application of these selection criteria led to a final set of 22 stream-free SB over the period 1965–1980, with no obvious clustering of the SB to any particular phase of the solar cycle. Since the signature of coronal streamers

TABLE I

Dates and timings of stream-free sector boundary (SB) crossings near Earth over the period 1965–1980 considered in the present study[a]

S. No.	Date	Time (UT)	S. No.	Date	Time (UT)
1	24 Nov. 1965	01	12	25 June 1975	17
2	18 Jan. 1967	12	13	26 Feb. 1976	02
3	4 Aug. 1967	13	14	25 May 1976	08
4	21 Aug. 1968	07	15	25 Nov. 1976	03
5	9 Feb. 1970	22	16	31 Aug. 1977	04
6	10 Apr. 1972	11	17	25 Oct. 1977	00
7	12 May 1973	11	18	2 Dec. 1978	18
8	8 Oct. 1973	15	19	20 Oct. 1979	00
9	3 Nov. 1973	19	20	25 Apr. 1980	16
10	16 Apr. 1974	09	21	5 May. 1980	09
11	9 June 1974	05	22	27 Sept. 1980	22

[a] Source: King (1977, 1979, 1986).

in the solar wind at 1 AU is apparent for about a day centred on the times of passage of stream-free boundaries (see Figure 7 of Borrini *et al.*, 1981), and since all individual boundaries do not necessarily exhibit such a signature, our analysis proceeds on a statistical basis and concerns plasma data ± 12 hr of boundary crossings at Earth. Details of the dates and times of the stream-free SB crossings at Earth considered here are listed in Table I. A total of 478 hourly values of N, V, and T_p constitute our data set, and most of these measurements (~ 86%) were from instrumentation on IMP series of spacecraft rendering them a more or less homogeneous set.

The fact that we are dealing here with an essentially dense, low-speed solar wind structure is reiterated through Table II, wherein the average values of certain important flow properties (N, V, NV, NV^2, and NV^3) of it are summarised along with those of the flows studied by Steinitz and Eyni (1980) and Mullan (1983) for interparameter relationships. The corresponding values for the general low-speed wind data set of Lopez *et al.* (1986), which are particularly relevant here, could not be included as they were not given in their paper. Instead, average values of N, V, and NV pertaining to low-speed wind (defined as flows with nonpositive speed gradients and $V < 350$ km s^{-1}) are listed at the bottom of Table I from Feldman *et al.* (1977). The close correspondence of our solar wind data set with the low-speed wind, and a

TABLE II

Averages of selected flow properties of solar wind analysed for interparameter relationships

Author	$\langle N \rangle$ cm^{-3}	$\langle V \rangle$ km s^{-1}	$\langle NV \rangle$ 10^8 cm^{-2} s^{-1}	$\langle NV^2 \rangle$ 10^{16} cm^{-1} s^{-1}	$\langle NV^3 \rangle$ 10^{23} s^{-1}	Remarks
Steinitz and Eyni (1980)	5.25	499	2.7	1.33 ± 0.06	6.9	Wind flow with small velocity dispersion-data from Helios 1 and Mariner 2
Mullan (1983)	8.3	420	3.2	1.29	5.42	Wind flow over the period August 1978–February 1980; data from ISEEC
Current work	12.65 ± 6.74	350 ± 43	4.3 ± 2.18	1.48 ± 0.75	5.13 ± 2.78	Wind flow ± 12 hr of stream-free sector boundaries of 1 AU – composite data base of King (1977, 1979, 1986)
Feldman *et al.* (1977)	11.9 ± 4.5	327 ± 15	3.9 ± 1.5	–	–	Low-speed wind with non-positive speed gradients and $V < 350$ km s^{-1}; data from IMP 6–8

prevalance of higher mass flux and momentum flux density in it compared to the ones in the data sets used by Steinitz and Eyni (1980) and Mullan (1983) are quite apparent from the statistical data of Table II.

Figure 1 depicts the dependence of T_p on V and the least squares fit to Equation (1) obtained with our data set. The same functional form of $T_p - V$ relationship eported by earlier workers (Burlaga and Ogilvie, 1970b; Burlaga and Ogilvie, 1973; Pizzo *et al.*, 1973; Lopez and Freeman, 1986) are also shown in the figure to facilitate comparison. The constants of the lines of best fit to Equation (1) obtained by the various workers are given in Table III, together with information on the solar wind conditions they correspond to. It is evident from Figure 1 and Table III that although a positive correlation prevails between T_p and V as can be expected, the $T_p - V$ coefficients describing the flow around stream-free boundaries are significantly different from those of other types of flows in particular, the undifferentiated low-speed wind and wind with small velocity gradients investigated by Lopez and Freeman (1986) and Pizzo *et al.* (1973), respectively. The nature of the differences is such that T_p is, in general, lower

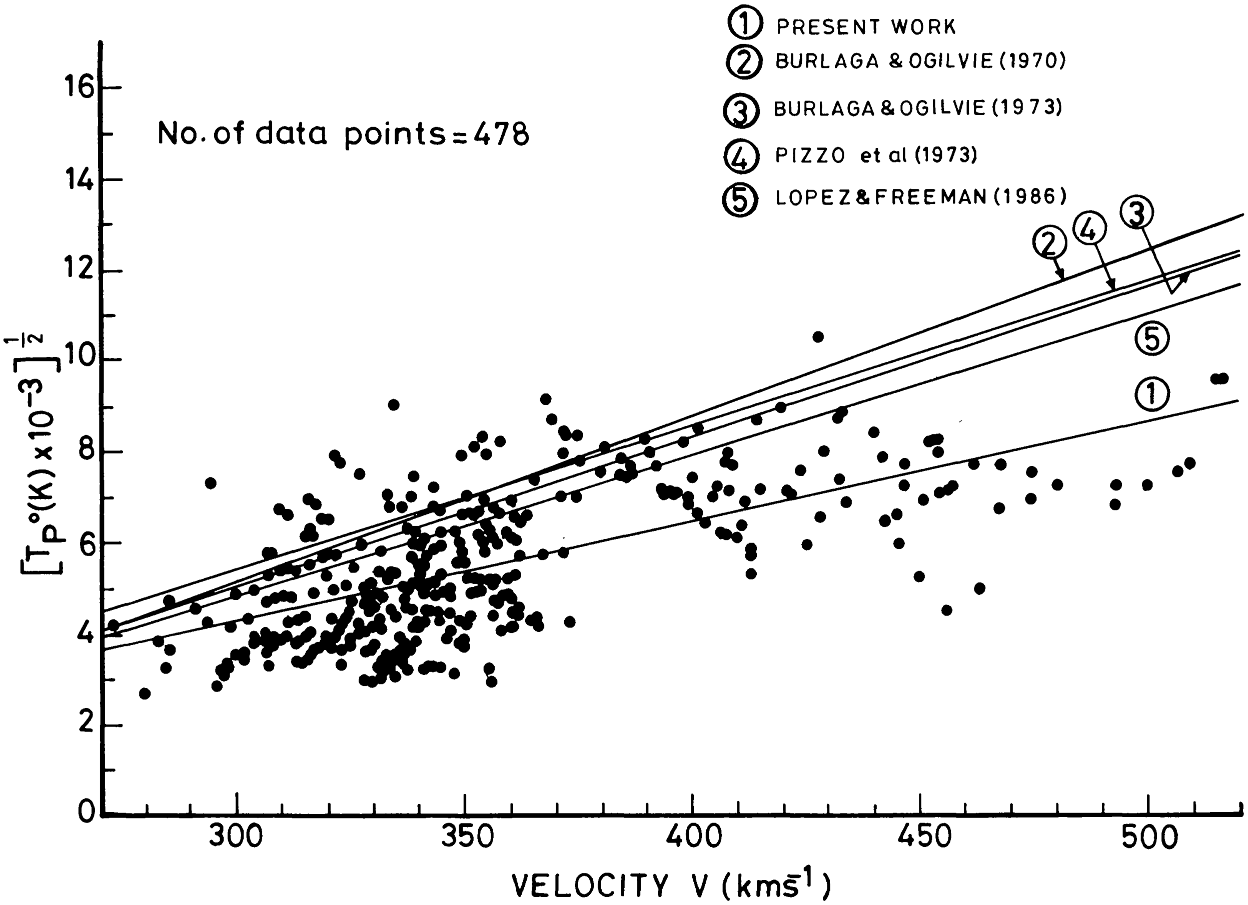

Fig. 1. Correlation between proton temperature (T_p) and velocity (V) in the solar wind flow around stream-free sector boundaries at 1 AU. The straight lines represent least-squares fits to the $T_p - V$ distribution shown and those reported earlier for other types of solar wind flow (see text and Table II for details). The weaker positive dependence of T_p on V and a prevalence of lower T_p values in the flow around stream-free boundaries may be noted.

TABLE III

$T - V$ relationship $(T)^{1/2} = A + BV^{a}$

Author(s)	A	B	Remarks
Burlaga and Ogilvie (1970)	-5.54 ± 1.5	0.036 ± 0.003	Solar wind data for the interval June–December 1967 from Explorer 34
Burlaga and Ogilvie (1973)	-4.8 ± 0.4	0.033 ± 0.001	Solar wind for the interval March to April 1971; data from Explorer 43
Pizzo *et al.* (1973)	-3.89	0.0313	Solar wind flow with small velocity gradients (1 km s^{-1} hr^{-1} period); data from Vela 3
Lopez and Freeman (1986)	-4.39 ± 0.08	0.031 ± 0.002	Low-speed solar wind ($V = 500$ km s^{-1}); data from Helios 1 (1974–1980)
Current work	-2.25 ± 0.963	0.022 ± 0.003	

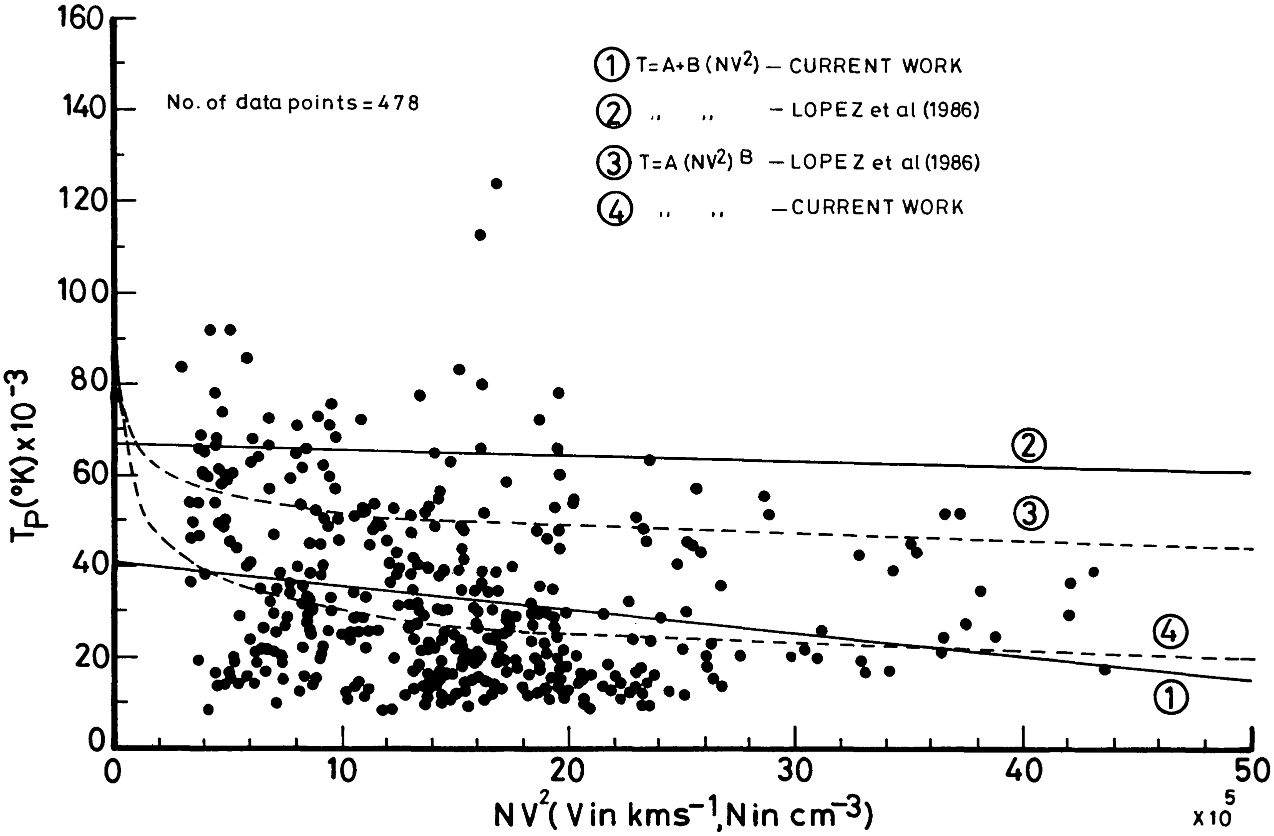

Fig. 2. Scatter plot illustrating the inverse relationship between proton temperature (T_p) and momentum flux density (NV^2) in the solar wind flow around stream-free sector boundaries at 1 AU. The best fits to the linear and power-law forms of relationship between the parameters obtained here and by Lopez *et al.* (1986) for a general low-speed wind ($V < 500$ km s^{-1}) data set are also shown. The stronger negative correlation of T_p with NV^2 and a prevalence of lower T_p values in the flow around stream-free boundaries may be noted.

than the expected especially for $V > 350$ km s^{-1}. An essentially similar pattern is also seen with other functional forms of $T_p - V$ relationship (see Lopez and Freeman, 1986, for details) and is not shown here to avoid repetition. The $T_p - V$ relationship thus suggests that the distribution among the various modes of energy transport (kinetic and thermal) in the flow around stream-free boundaries at 1 AU is different from that in general low-speed wind and other types of flows – an expected trend as per the arguments presented above.

Figure 2 illustrates the variation of T_p as a function of NV^2 and the least squares fits to the linear and power law forms of relationship between the parameters derived with our data sample. The corresponding relationships obtained by Lopez *et al.* (1986) for a low-speed wind data set are also included in the figure for comparison. The T_p versus NV^2 distribution in Figure 2 and the coefficients of the lines of best fit listed in Table IV demonstrate an inverse dependence of T_p and NV^2 confirming the trend very recently noticed in Lopez *et al.* (1986). But the important and anticipated feature to be noticed in Figure 2 is that the decrease in T_p with increasing NV^2 is prominent in the dense low-speed wind around stream-free boundaries, than in the general low-speed wind.

TABLE IV

$T - NV^2$ relationship[a]

Author(s)	A	B
	I. $T = A + B(NV^2)$	
Lopez *et al.* (1986)	67.1 ± 0.4	$-1.14 \times 10^{-6} \pm 7.4 \times 10^{-8}$
Current work	41.1 ± 3.8	$-5.21 \times 10^{-6} \pm 2.3 \times 10^{-6}$
	II. $T = A(NV^2)^B$	
Lopez *et al.* (1986)	208 ± 12	-0.1 ± 0.0005
Current work	1052 ± 3.8	-0.256 ± 0.095

[a] T in K × 10^3, N in cm^{-3} and V in km s^{-1}.

Coronal streamer related solar wind plasma flow at 1 AU thus seems to possess characteristic interparameter relationships. The widely known positive dependence of T_p on V is weaker, and the very recently evidenced trend of a negative relationship of T_p with NV^2 is stronger in such a wind compared to other types of solar wind flows studied earlier. This finding lends further qualitative support to the current views of the relevance of sub-sonic coronal processes to the low speed state of solar wind flow at 1 AU (Leer and Holzer, 1980; Leer *et al.*, 1982, Lopez *et al.*, 1986). Since one of the predicted consequences of sub-sonic deposition of momentum and energy to the fluid flow in the corona is a near constancy of energy flux at 1 AU (Leer and Holzer, 1980), the characteristics of $N - V$ relationship in our data set are studied for such a feature. The result is that the statistical description of the known negative relationship between N and V, i.e., Equation (2) is markedly different from those previously reported. This can be seen from the $\log N$ versus $\log V$ distribution shown in Figure 3, and the

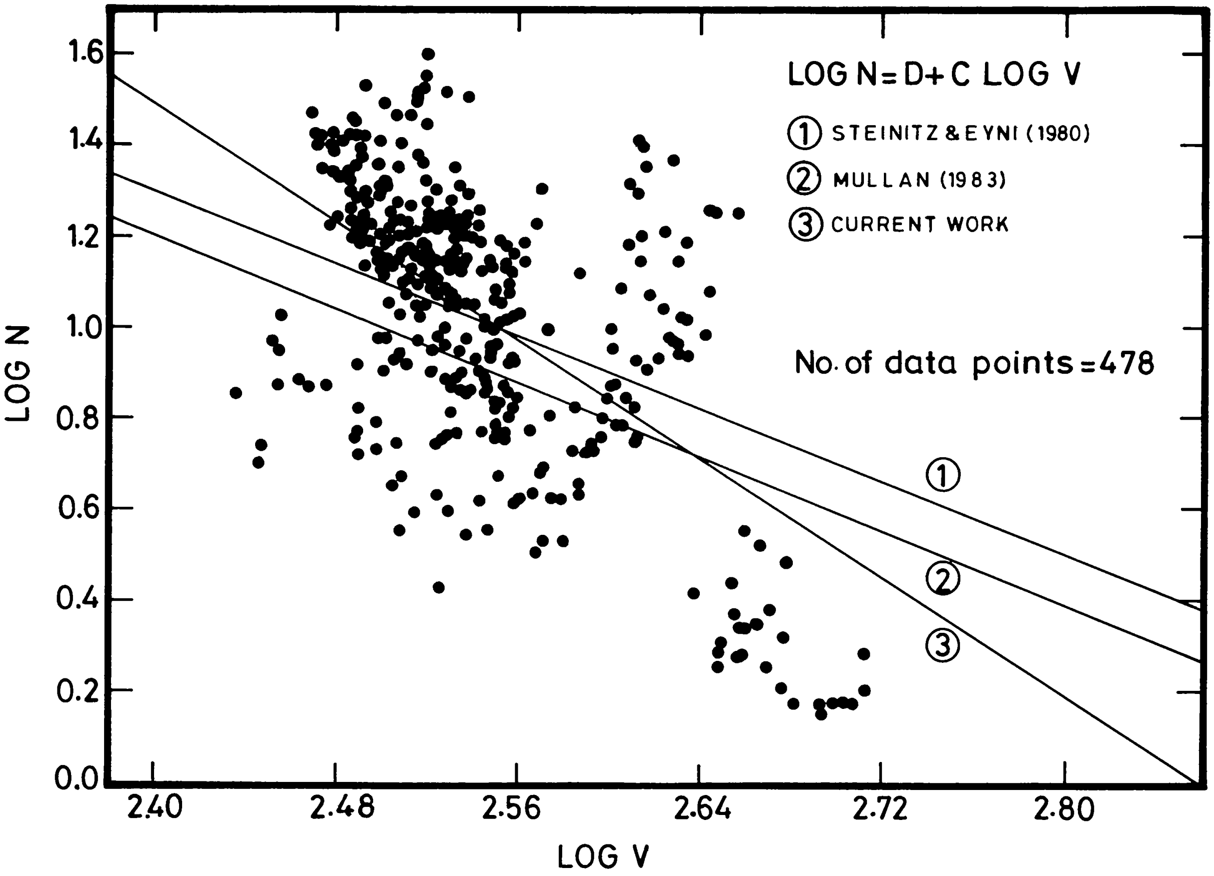

Fig. 3. Scatter plot depicting the negative correlation between the proton number density (N) and the flow speed (V) in the solar wind around stream-free sector boundaries at 1 AU. The solid lines represent the best fits to Equation (2) obtained by us and by other workers with data corresponding to different solar wind conditions (see text and Table I for details). The slope of the regression line (-3.257 ± 0.428) to our $N - V$ distribution suggests an invariance of the kinetic energy flux density in the flow around stream-free boundaries (units of N: cm^{-3}; units of V: $\mathrm{km\ s}^{-1}$).

coefficients of the lines of best fit to Equation (2) derived by us and others listed in Table V. The value of C in our data set is -3.257 ± 0.428 (instead of close to -2.0 as consistently reported, for example, by Steinitz and Eyni, 1980; Steinitz, 1983; Mullan, 1983, for other types of flows) suggesting an invariance, as expected, of the kinetic energy flux density (NV^3) in the flow around stream-free boundaries. We, however, feel it pertinent to remark before closing that the low proton temperatures

TABLE V

$N - V$ relationship $\log N = C \log V + D^{a}$

Author(s)	D	C	Corr. coeff. γ
Steinitz and Eyni (1980)	6.1	−2.0	–
Mullan (1983)	6.112	2.045	−0.501
Current work	9.306	−3.257	−0.579
	(±1.09)	(±0.428)	

[a] N in cm^{-3}, V in $\mathrm{km\ s}^{-1}$.

characteristic of the solar wind flow studied here might, in part, be due to other causes. The different radial temperature gradients along the axis and edges of coronal streamers presumably due to variations in the stream tube divergence-convergence characteristics (Feldman *et al.*, 1981), and a non-radial spreading of stream lines in interplanetary space have, in fact, been suggested as partly responsible for the low proton temperatures at sector boundaries (Borrini *et al.*, 1981).

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