THE PROTON TEMPERATURE AND THE TOTAL HOURLY VARIANCE OF THE MAGNETIC FIELD COMPONENTS IN DIFFERENT SOLAR WIND SPEED REGIONS*

CHUAN-YI TU

Department of Geophysics, Peking University, Beijing, China

JOHN W. FREEMAN

Department of Space Physics and Astronomy, Rice University, Houston, TX 77251, U.S.A.

and

R. E. LOPEZ

Applied Research Corporation, Landover, MA 20785, U.S.A.

(Received in revised form 3 August, 1988)

Abstract. A comparison has been made between the predictions of the theory for radial variations of both Alfvénic fluctuations and solar wind proton temperatures proposed by Tu (1987, 1988) and the statistical results of hourly averaged plasma and magnetic field data observed by Helios 1 and 2 from launch through 1980 for different solar wind speed regimes. The comparison shows that for speed ranges between 500–800 km s^{-1}, the radial variation of the proton temperature between 0.3 and 1 AU can be explained by heating from the cascade energy determined by the radial variation of the total variance of magnetic field vector. The explanation of the radial variations of both temperature and the total variance of magnetic fields for speed ranges less than 400 km s^{-1} is less clear.

1. Introduction

Helios observations have resulted in studies of radial variations of Alfvénic fluctuations and proton temperature in the solar wind between 0.3–1 AU (Bavassano *et al.*, 1982a, b; Villante, 1980; Villante and Villante, 1982; Denskat, Neubauer, and Schwenn, 1981; Denskat and Neubauer, 1982; Marsch *et al.*, 1982; Marsch, Goertz, and Richter, 1982; Schwenn, 1983; Marsch, 1983; Marsch *et al.*, 1983; Schwartz and Marsch, 1983). Two important results have been found. One is that Alfvénic fluctuations in the solar wind damp much more quickly than expected from WKB propagation. The other one is that the solar wind protons cool much more slowly than expected from pure adiabatic expansion. The mechanisms for the damping of Alfvénic fluctuations and the source for the additional heat of solar wind protons have both been the subject of considerable research (Hollweg, 1987).

Tu (1983, 1987) and Tu, Pu, and Wei (1984) proposed a theoretical model to explain the radial evolution of the power spectrum of Alfvénic fluctuations. Based on this work, Tu (1988, hereafter referred to as Paper I) develop a uniform theory for the heating of

* This project was supported by National Natural Science Foundation of China for Tu's part of the work.

solar wind protons and the damping of Alfvénic fluctuations. The theoretical predictions have been compared with the observed results in the high speed streams examined by Bavassano *et al.* (1982a, b). The results showed that the correspondence is good. Predictions about the radial variations of the magnetic fluctuations for different solar wind speeds have also been made (see Table 1 in Paper I) using the statistical results of the radial variations of proton temperatures performed by Freeman and Lopez (1985). However, no direct comparison of these results with observations is made in Paper I. Figure 9 in Paper I cannot be taken as a serious comparison. Figures 10 and 11 only show that the amplitude of fluctuations calculated from the radial variation of temperature T can be used to explain the radial variation of $T_{\perp}$. It is clear that this theory should be tested against additional observations.

Since most published statistical results for variations of the temperature of solar wind protons and the amplitude of Alfvénic fluctuations are obtained from different periods of observation, these results cannot be used to test a uniform theory for both proton temperature and Alfvénic fluctuations. We have conducted a statistical analysis of radial variations of the magnetic fluctuations for different solar wind speed regimes using the Helios data observed from the same period examined by Freeman and Lopez (1985). These results are used in the present paper for comparison with the predictions presented in Table I in Paper I. A calculation is made based on the model presented in Paper I by using the values of radial component of magnetic field vector averaged over the same period as the statistical analysis. The results are also compared with the statistical results.

2. The Data Used in This Calculation

The data employed are hourly averages of plasma and magnetic field parameters observed by Helios 1 from launch trough 1980 provided to the National Space Science Data Center by R. Schwenn and F. Neubauer. The instruments have been described by Rosenbauer *et al.* (1977) and Musmann, Neubauer, and Lammers (1977). The Helios spacecraft are in elliptical heliocentric orbits between 0.3 and 1 AU.

The plasma and magnetic field data have been used to calculate the best fit exponents of R following a velocity sort at 100 km s^{-1} intervals, similar to that performed by Schwenn (1983) for the proton radial temperature only. We list the results for the magnetic field and proton temperature in Table I and Table III respectively. SDB is defined as

$$\mathrm{SDB} = [\langle(\delta B_x)^2\rangle + \langle(\delta B_y)^2\rangle + \langle(\delta B_z)^2\rangle]^{1/2}, \tag{1}$$

where B_x, B_y, and B_z are the components of interplanetary magnetic field vector $\mathbf{B}$ in the solar ecliptic coordinate system and the δs are the difference between the individual component measurements and the hourly average of the component. $\langle\ \rangle$ indicates the average which is taken over one hour. Thus, SDB is the square root of the total variance of the field components. SDBT is defined as

$$\mathrm{SDBT} = [\langle(\delta\sqrt{B_x^2 + B_y^2 + B_z^2})^2\rangle]^{1/2}. \tag{2}$$

TABLE I

Statistical results of magnetic field parameters

Label	Velocity range	Slope β $R^{-\beta}$	S.D. Slope	Natural log intercept at 1 AU	S.D. intercept	Corr. coef.	Number of data points
SDB (R)	< 300 km s^{-1}	−1.86	0.176	0.055	0.137	−0.7141	1293
	$300 < V < 400$ km s^{-1}	−1.789	0.105	0.444	0.055	−0.7025	10746
(nT)	$400 < V < 500$ km s^{-1}	−1.845	0.113	0.66	0.059	−0.7249	7635
	$500 < V < 600$ km s^{-1}	−1.661	0.118	0.873	0.064	−0.7265	4083
	$600 < V < 700$ km s^{-1}	−1.725	0.113	0.981	0.059	−0.7776	2508
	$700 < V < 800$ km s^{-1}	−1.743	0.17	1.074	0.08	−0.7498	576
SDB/SDBT	$V < 300$ km s^{-1}	−0.691	0.168	1.012	0.131	−0.3694	1293
	$300 < V < 400$ km s^{-1}	−0.557	0.101	1.313	0.053	−0.304	10751
	$400 < V < 500$ km s^{-1}	−0.623	0.107	1.439	0.057	−0.3497	7638
	$500 < V < 600$ km s^{-1}	−0.387	0.116	1.641	0.063	−0.2425	4086
	$600 < V < 700$ km s^{-1}	−0.18	0.13	1.819	0.068	−0.1113	2509
	$700 < V < 800$ km s^{-1}	−0.33	0.198	2.004	0.093	0.1821	576
$B_r(R)$	$V < 300$ km s^{-1}	−2.39	0.238	0.345	0.186	−0.6966	1294
	$300 < V < 400$ km s^{-1}	−2.268	0.159	0.586	0.084	−0.6356	10766
(nT)	$400 < V < 500$ km s^{-1}	−2.196	0.158	0.832	0.084	−0.6653	7639
	$500 < V < 600$ km s^{-1}	−2.114	0.17	0.935	0.092	−0.6844	4084
	$600 < V < 700$ km s^{-1}	−1.939	0.177	1.01	0.093	−0.6657	2507
	$700 < V < 800$ km s^{-1}	−1.796	0.291	0.982	0.137	−0.5648	576

SDBT is the square root of the variance of the field magnitude. The ratio SDB/SDBT has been usually considered indicative of the relative importance of directional and compressive contributions to the field fluctuations. Also,

$$B_r = \langle B_x \rangle \, . \tag{3}$$

The number density used in this paper is that reported by Schwenn (1983) for the same period of observation.

3. Description of the Calculations

The basic assumptions of the calculation are as follows:

(a) The fluctuations of the magnetic field vector are Alfvénic in nature. The assumptions and conclusions in Paper I can be applied.

(b) The values of the dimensionless constant α and α_1 are the same for all speed intervals, where α_1 is the ratio between the energies of waves propagating outward and inward, and α a dimensionless constant introduced in Paper I, which is result from the dimensional analysis used in this theory and may have a value of the order of 1.

c) The shapes of the spectra in the log-log plot at $r = 0.29$ AU are the same for all speed intervals.

(d) The energy cascade function (see Paper I) for the power spectra of Alfvénic fluctuations is equal to the heating rate of the mean proton temperature.

These assumptions may be approximately valid for high solar wind speed regimes (500–800 km s^{-1}). Calculations show that the results are not sensitive to small changes of parameters α and α_1, and the slope of the spectra. The comparison based on these assumptions may be thought as the first step to test the theory for different solar wind speeds. However, a careful comparison between these assumptions and observations should be undertaken in the future.

For the low-speed range, these assumptions may not be valid. Therefore, we do not expect that the present calculation can describe the real process in low-speed range satisfactorily. The comparison between the present calculation and the observed results for low-speed solar wind streams may give the velocity limit of the theory and may also give some clues for developing a theory for fluctuations in low-speed streams.

The calculation procedure is explained in detail in Paper I and, therefore, is described only briefly here. From a given power spectrum of the fluctuations, $P(f, r)$, we can calculate the parameter $\langle b^2 \rangle_{\Delta T}$. The parameter $\langle b^2 \rangle_{\Delta T}$ is defined as Equation (29) in Paper I, where $(2\Delta T)^{-1}$ may be roughly regarded as a lower limit of the frequency range for the fluctuations that may contribute to the total standard deviation of magnetic components over the time interval ΔT. We do not know exactly what value should be taken for ΔT to compare $\langle b^2 \rangle_{\Delta T}^{1/2}$ with SDB, where SDB is the square root of the total standard deviation of the magnetic field components over the time interval of one hour. However, we may compare the variable range between $\langle b^2 \rangle_{1\,\mathrm{hr}}^{1/2}$ and $\langle b^2 \rangle_{0.5\,\mathrm{hr}}^{1/2}$ with SDB. For this purpose we calculate

$$\langle b^2 \rangle_1 = \langle b^2 \rangle_{0.5\,\mathrm{hr}} = \int_{(60\times 60)^{-1}}^{8.3\times 10^{-2}} P(f)\,\mathrm{d}f\,, \tag{4}$$

$$\langle b^2 \rangle_2 = \langle b^2 \rangle_{1\,\mathrm{hr}} = \int_{(120\times 60)^{-1}}^{8.3\times 10^{-2}} P(f)\,\mathrm{d}f\,. \tag{5}$$

From the same given power-spectrum density $P(f, r)$, we can also evaluate the exponent γ of temperature $T(r)$ based on the model presented in Paper I. We see that γ is connected with $\langle b^2 \rangle_{\Delta T}$. In the calculation presented in this paper, the observed values of γ (Table III) are used as input parameters. We calculate $\langle b^2 \rangle_1$ and $\langle b^2 \rangle_2$ for $r = 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, 0.95$ AU, respectively, for each velocity value. The least-squares fit determines the slopes $\beta_{\Delta T}$, and the intercepts $a_{\Delta T}$ at 1 AU, where $\beta_{\Delta T}$ and $a_{\Delta T}$ are defined in the following equation:

$$\log_{10} \langle b^2 \rangle_{\Delta T} = a_{\Delta T} + \beta_{\Delta T} \log_{10} R\,. \tag{6}$$

We then calculate the intercepts of ln $\langle b^2 \rangle_{\Delta T}^{1/2}$ at 1 AU as

$$a_1 \equiv \ln \langle b^2 \rangle_1^{1/2} |_{r=1\,\mathrm{AU}} = a_{0.5\,\mathrm{hr}}(0.5/\log_{10} e)\,, \tag{7}$$

$$a_2 \equiv \ln \langle b^2 \rangle_2^{1/2} |_{r=1\,\mathrm{AU}} = a_{1\,\mathrm{hr}}(0.5/\log_{10} e)\,, \tag{8}$$

and the radial slopes of $\langle b^2 \rangle_1^{1/2}$ and $\langle b^2 \rangle_2^{1/2}$ as

$$\beta_1 = 0.5\beta_{0.5\ \mathrm{hr}}, \quad (9)$$

$$\beta_2 = 0.5\beta_{1\ \mathrm{hr}}. \quad (10)$$

4. The Calculated Results and Comparison with Observations

We first made a comparison between the predictions in Table I in Paper I and the statistical results in Table I. In this calculation, values of n(1 AU) are taken from Schwenn (1983), B_r (0.3 AU) from Marsch *et al.* (1982, 1983), T(1 AU) from Lopez and Freeman (1986), γ from Freeman and Lopez (1985), β_i and a_i (i = 1, 2) are defined in Equations (6)–(10) and are calculated from the values of $\langle b^2 \rangle_{\Delta T}$ predicted by the present model for r = 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, and 0.95. The radial slopes of $\langle b^2 \rangle_1^{1/2}$ and $\langle b^2 \rangle_2^{1/2}$ and the natural logs of the intercepts of the least-squares fit at 1 AU are presented in Table II. The comparison between these results and statistical results (SDB, Table I) shows that for velocities 550, 650, 750 km s^{-1}, the theoretical results are consistent with the statistical result in Table I.

TABLE II

Predicted values of the slopes and intercepts

V_s (km s^{-1})	Slope $\beta_1(\langle b^2 \rangle_1^{1/2} \sim R^{+\beta_1})$	Slope $\beta_2(\langle b^2 \rangle_2^{1/2} \sim R^{+\beta_2})$	Intercept at R = 1 (AU)	
			ln $\langle b^2 \rangle_1^{1/2}$ (nT)	ln $\langle b^2 \rangle_2^{1/2}$ (nT)
750	−1.70	−1.66	1.01	1.17
650	−1.71	−1.66	0.94	1.11
550	−1.73	−1.69	0.81	0.98
450	−1.72	−1.69	0.62	0.79
350	−1.72	−1.69	0.12	0.28
250	−1.58	−1.53	−1.04	−0.91

In the calculation described in Section 5 in Paper I the parameter B_r (r = 0.3 AU) is determined by Marsch *et al.* (1982, 1983). The values of B_r (1 AU) predicted by this calculation are larger than the results shown in Table I. For a more accurate comparison, we made the calculations again with the values of B_r (1 AU) presented in Table I as input values of the model. The other parameters, such as n (1 AU), T(1 AU), $\gamma(T \sim R^{-\gamma})$ are determined from Schwenn (1983), Lopez and Freeman (1986), and Freeman and Lopez (1985), respectively. These parameters are presented in Table III. The results from this calculation are presented in the same table. The comparison between these results and the results of SDB are shown in Figures 1 and 2. We see that the theoretical results and the statistical results are consistent.

If we compare Table II and Table III, we can see that the predictions for β and the intercept of ln $\langle b^2 \rangle^{1/2}$ at 1 AU are not very sensitive to the values of B_r (1 AU).

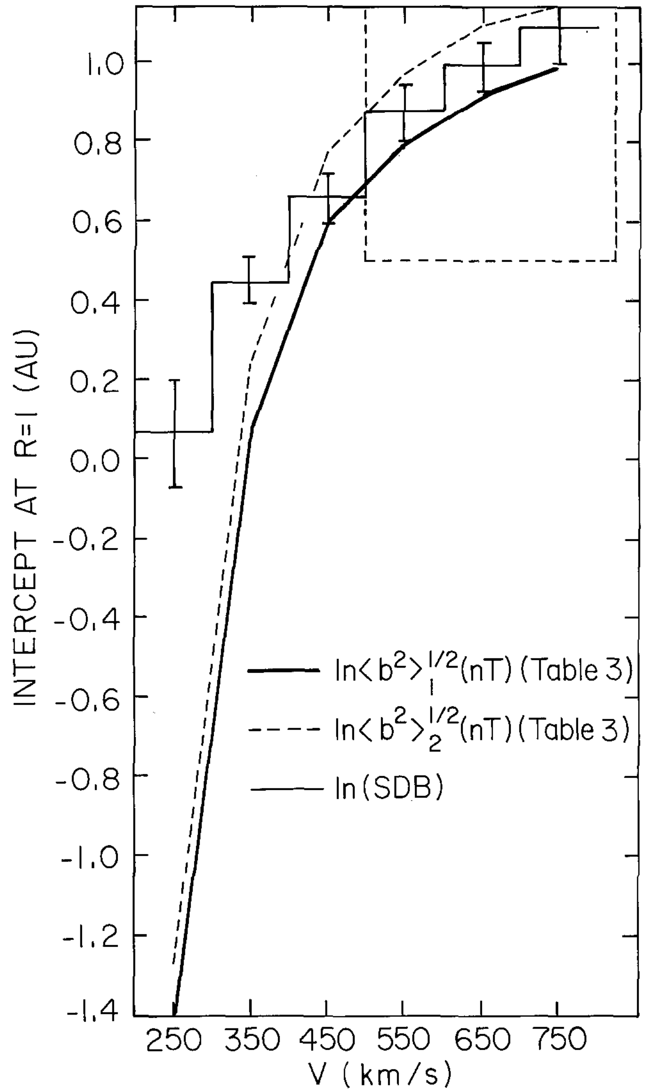

Fig. 1. Comparison between the theoretical predictions (heavy solid line and dashed line) and the statistical results (stepped line with vertical bars) for the radial slope of the square root of the total variance of magnetic components. The theoretical results are calculated from B_r given in Table I.

5. Conclusions and Discussions

A statistical analysis of radial variations of magnetic fluctuations for different solar wind speeds has been performed using Helios data. The results are shown to be consistent for the speed regimes between 500–800 km s^{-1} with both the prediction presented in Paper I and the calculation results based on equations in Paper I with B_r taken from the same period as the statistical analysis. The conclusions and discussions are as follows:

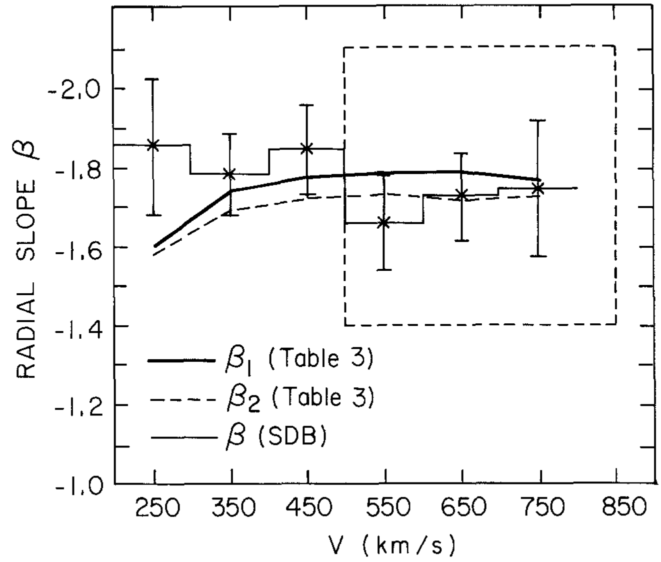

Fig. 2. Comparison between the theoretical predictions (heavy solid line and dashed line) and the statistical results (stepped line with vertical bars) for the intercept, at 1 AU, of the natural log of the square root of total variance of magnetic components. The theoretical results are calculated from B_r given in Table I.

(a) For the speed range between 500–800 km s^{-1}, the radial variation of the proton temperature between 0.3 and 1 AU can be explained by the heating of the cascade energy of Alfvénic fluctuations described by the theory in Paper I. In this velocity range, the values of SDB/SDBT are large (5–8). This may indicate that the compressive component is very small, and the energy of the compressive component may be negligible compared with the non-compressive component.

(b) For the velocity range between 250–400 km s^{-1}, the theoretical results are different from the statistical results. We also made calculations with different spectral slopes (-1 to $-\frac{5}{3}$) for low frequencies at 0.29 AU and with some radial functions of $\alpha_1(r)$. However, these calculational results are still not consistent with observations. This may mean that the theory presented in Paper I cannot describe the statistical results for low speed regimes. The reason may be that two assumptions in Paper I cannot be applied to low speed regimes. First, the values of SDB/SDBT are not very large (3–4). This may indicate that the compressive component may not be negligible for this low-speed range. Second, the values of α_1 in low-speed stream usually are not very small at 1 AU. The explanation of the radial variations of the fluctuations in the low speed solar wind is an open theoretical work.

(c) In the calculations, we assume

$$B_r = B_r(1\ \text{AU})\, R^{-2}\,. \tag{10}$$

This is consistent with the statistical results for velocity range 500–800 km s^{-1}.

(d) The assumptions in Section 3 have not yet been justified straight away. More work

TABLE III

Predicted values of other parameters ($f_{c0} = 2 + 10^{-3}$ Hz, $\alpha\alpha_1 = \frac{1}{16}$, $B_r \sim r^{-2}$)

V_s (km s^{-1})	n (1 AU)[a] (1/cm^3)	B_r (1 AU) (nT)	T (1 AU)[b] ($\times 10^5$ K)	$\gamma(T \sim r^{-\gamma})$[c]	g_0 (10^{-3} G cm$^{+3/4}$)	Intercept at R = 1 (AU)			
						$\beta_1(\langle b^2 \rangle_1^{1/2} \sim R^{+\beta_1})$	$\beta_2(\langle b^2 \rangle_2^{1/2} \sim R^{+\beta_2})$	ln $\langle b^2 \rangle_1^{1/2}$ (nT)	ln $\langle b^2 \rangle_2^{1/2}$ (nT)
750	2.65	2.66	3.13	0.83	0.51	−1.76	−1.72	0.98	1.14
650	3.08	2.75	2.38	0.77	0.43	−1.78	−1.71	0.91	1.09
550	4.00	2.55	1.60	0.82	0.38	−1.78	−1.73	0.79	0.97
450	6.50	2.30	0.92	1.02	0.31	−1.77	−1.72	0.60	0.77
350	10.00	1.80	0.42	1.22	0.19	−1.74	−1.69	0.08	0.24
250	14.00	1.41	0.11	1.33	0.03	−1.60	−1.59	−1.40	−1.28

[a] Schwenn (1983).
[b] Lopez and Freeman (1986).
[c] Freeman and Lopez (1985).

should be done in the future to make a comparison between these assumptions and observations.

(e) The derivation of the equations presented in Paper I uses the characteristic method. If the characteristics are traced from 0.29 to 1 AU, it turns out that the entire spectrum at 1 AU in the frequency range $3 \times 10^{-4} < f < 10^{-1}$ Hz originates from information at 0.29 AU in the range $10^{-4} < f < 4 \times 10^{-4}$ Hz (see Paper I). The predictions at 1 AU really come from an extrapolation of the 0.29 data to lower frequencies. Some observed results for this low-frequency range (Denskat and Neubauer, 1982; Bruno, Bavassano, and Villante, 1985) are consistent with the extrapolation. However, more analysis should be done for this low-frequency range to compare the extrapolation with observation. Hollweg (1987) pointed out the limitation of this model.

(f) We should use BxSEQ as B_r. Since we do not have data of B_r, we use BxSE as B_r in this calculation. The error which results may not be important, because B_r is not a sensitive parameter of the model.

(g) This extension of the theory presented in Paper I to different solar wind speed regimes may help to develop wave-driven solar wind models. The variations of the radial slope of the proton temperature provide further constraints on theoretical work about coronal expansion and the solar wind. To explain these different heatings, the previous saturated wave model may need to assume different levels for different speed regimes. However, these different saturated levels may be very difficult to understand. The present theory only assumes different amplitudes of fluctuations at $r = 0.29$ AU, and no assumption about the evolution is needed.

(h) The effect of alpha particles is not considered in the present theory. Since this theory deals with the energy cascade process from low-frequency to high-frequency range, it may be favorable to the preferential acceleration and heating of alpha particles by ion-cyclotron resonance. However, this problem should be examined carefully in the future.

Acknowledgements

We extend our thanks to R. Schwenn and F. Neubauer for making the Helios data available to the National Space Science Data Center and to the NSSDC for providing it to Rice University. The work of Lopez and Freeman has been supported by NASA grants NGL-44-006-012 and NAGN-773.

References

Bavassano, B., Dobrowolny, M., Mariani, F., and Ness, N. F.: 1982a, *J. Geophys. Res.* **87**, 3617.
Bavassano, B., Dobrowolny, M., Fanfoni, G., Mariani, F., and Ness, N. F.: 1982b, *Solar Phys.* **78**, 373.
Bruno, R., Bavassano, B., and Villante, U.: 1985, *J. Geophys. Res.* **90**, 4373.
Denskat, K. R. and Neubauer, F. M.: 1982, *J. Geophys. Res.* **87**, 2215.
Denskat, K. R., Neubauer, F. M., and Schwenn, R.: 1981, in H. Rosenbauer (ed.), *Solar Wind 4*, p. 374, Max-Plank-Institut für Aeronomie and Max-Plank-Institut für Extraterrestrische Physik, West Germany, p. 374.

Freeman, J. W. and Lopez, R. E.: 1985, *J. Geophys. Res.* **90**, 9885.
Hollweg, J. V.: 1987, *Proc. 21st ESLAB Symposium*, ESA SP-275, Bolkesjo, Norway, p. 161.
Lopez, R. E. and Freeman, J. W.: 1986, *J. Geophys. Res.* **91**, 1701.
Marsch, E.: 1983, in M. Neugebauer (ed.), *Solar Wind Five*, NASA Conference Publication 2280, p. 355.
Marsch, E., Goertz, C. K., and Richter, K.: 1982, *J. Geophys. Res.* **87**, 5030.
Marsch, E., Muhlhauser, K. H., Rosenbauer, H., and Schwenn, R.: 1983, *J. Geophys. Res.* **88**, 2982.
Marsch, E., Muhlhauser, K.-H., Schwenn, R., Rosenbauer, H., Pilipp, W., and Neubauer, F. M.: 1982, *J. Geophys. Res.* **87**, 52.
Musmann, G., Neubauer, F. M., and Lammers, E.: 1977, *J. Geophys.* **42**, 591.
Rosenbauer, H., Schwenn, R., Marsch, E., Meyer, B., Miggenrieder, H., Montgomery, M. D., Muhlhauser, K. H., Pilipp, W., Voger, W., and Zink, S. M.: 1977, *J. Geophys.* **42**, 561.
Schwartz, S. J. and Marsch, E.: 1983, *J. Geophys. Res.* **88**, 9919.
Schwenn, R.: 1983, in M. Neugenbauer (ed.), NASA Conference Publication 2280, 489.
Villante, U.: 1980, *J. Geophys. Res.* **85**, 6869.
Villante, U. and Villante, M.: 1982, *Solar Phys.* **81**, 367.
Tu, C.-Y.: 1983, *Acta Geophys. Sinica* **26**, 405.
Tu, C.-Y.: 1987, *Solar Phys.* **109**, 149.
Tu, C.-Y.: 1988, *J. Geophys. Res.* **93**, 7.
Tu, C.-Y., Pu, Z.-Y., and Wei, F. S.: 1984, *J. Geophys. Res.* **89**, 9695.