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SOLAR WIND TEMPERATURE AND SPEED

by

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ABSTRACT

Averaging on a time-scale of several solar rotations, the solar wind proton temperature, T, increases monotonically with the bulk speed V (Hundhausen et al. 1970; Burlaga, and Ogilvie, 1970). This macroscale T-V relation does not change appreciably with solar cycle. The temperatures corresponding to intervals of increasing speed are only ≈15% higher than those corresponding to decreasing speeds, indicating that the macroscale T-V relation is not appreciably affected by stream interactions.

On a time-scale of a tenth of a solar rotation, there are time-dependent T(t) - V(t) relations which are closely related to the stream profiles, as noted by Hundhausen (1972). These T(t) - V(t) relations can meaningfully be resolved into two components - the macroscale T-V relation and systematic, time-dependent deviations from the macroscale relation.

These results support the view that the macroscale T-V relation is not appreciably affected by non-steady, interplanetary processes, but is determined rather by the proton heating mechanism within ≈50 $R_{\odot}$. The systematic, time-dependent deviations between temperatures measured at streams and those given by the macroscale T-V relation are probably due primarily to non-linear, non-steady processes in the interplanetary medium.

INTRODUCTION

Burlaga and Ogilvie (1970) and Hundhausen et al. (1970) showed that on a scale of 10 solar rotations (macroscale; Burlaga, 1969) there is a quantitative relation between the average solar wind proton temperature T observed at a given speed V and that speed. Burlaga and Ogilvie emphasized the importance of the T-V relation as a constraint on solar wind theories and as a clue to the heating and accelerating mechanism. They suggested that this relation is due to proton heating within 50 $R_\odot$. A mechanism involving heating out to 25 $R_\odot$ has been investigated by Hartle and Barnes (1970) and by Barnes _et al_. (1971) using a spherically-symmetric, steady state model but such extended heating has not yet been proven (Hundhausen, 1972). Section III presents additional experimental evidence that the macroscale T-V relation is determined primarily by processes near the sun rather than by dynamical, non-steady processes in the interplanetary medium.

Hundhausen (1972) emphasizes that on a time scale of a tenth of a solar rotation (mesoscale), T and V are related through time, giving a T(t)-V(t) relation at a stream. Such a relation is implicit in the work of Neugebauer and Snyder (1966), Burlaga _et al_. (1971), and others. Hundhausen (1972), as well as Goldstein (1973) and Burlaga _et al_. (1971) emphasized the need to use a non-linear, non-steady model to explain the time profiles of T and V on a scale of a few days. A linear, co-rotating solar wind model was presented by Siscoe and Finley (1972), showing the importance of temperature perturbations near the sun in generating streams. Hundhausen (1972) pointed out that the macroscale T-V relation is largely the result of the superposition and averaging of many time-dependent, mesoscale T-V relations and can thus be described by non-steady models. An alternate viewpoint is presented in Section IV.

Much of this paper is based on solar wind measurements from the GSFC instrument on Explorer 43 (see Appendix) for the period March 18 to April 8, 1971, which are discussed in Section II. This period is nearly one solar rotation, which is intermediate between the macroscale and mesoscale. A plot of the points (T,V), based on 3-hr averages during this interval, provides a perspective from which one may see the characteristics of both the macroscale and the mesoscale T-V relations.

II. T and V for One Solar Rotation

Relation between T and V - Figure 1 shows a plot of the points (T,V), where T and V are 3-hour averages of temperature and speed for the successive 3-hour intervals in the period March 18 to April 8, 1971 during which Explorer 43 was in the solar wind. The measurements are from the GSFC plasma analyzer on Explorer 43 (see Appendix); the uncertainties in the measurements of T and V are less than 25% and 3%, respectively.

Two features can be seen in Figure 1: a general tendency for T to increase with V, and a large scatter of the points. The former is more clearly seen by the solid curve in the figure, which is a least squares fit of the points to the line $\sqrt{T} = a + bV$. The latter can best be understood by plotting (T(t), V(t)), i.e., by connecting the points in Figure 1 in time sequence, as will be discussed below. These two features will be discussed at greater length in Sections III and IV, respectively.

T(t) and V(t). Figure 2a shows 3-hour averages of V and T plotted as a function of time. Each average is represented as a point plotted in the center of the corresponding 3-hour interval and these points are connected by straight lines to obtain the time profiles which are shown. A few isolated 3-hour averages are missing and are approximated to by connecting the points on both sides of the gap by a straight line. The larger gaps and dashed lines represent periods when the instrument was not measuring the solar wind.

Three distinct types of speed profiles are observed in the Explorer 43 data in Figure 2a: 1) simple streams (A), 2) compound streams (B, C_1, C_2), and 3) variable V and T but no large streams. There is no extended interval ($\gtrsim$ 2 days) which could be described as a uniform "quiet" wind.

Distributions of V and T

Table 1 compares the average values and standard deviations of T and V in Figure 2a with those obtained by Vela 3, Explorer 34, and Pioneer 6 for longer periods of time. The Vela 3 averages are those given by Ness *et al*. (1971) for the period July 1965 to July 1967. The Explorer 34 data are from the GSFC-University of Maryland plasma proble, measured in the interval June-December, 1967. The Pioneer 6 results are from data from the M.I.T. instrument for the interval Dec. 18, 1965 to May 4, 1966. The point to be noted is that the average conditions observed by Explorer 43 in a 22 day interval are similar to those observed by other experiments over much longer intervals. In this sense the Explorer 43 results are representative of the macrostructure of the solar wind.

III. Macroscale T-V Relations

Solar Cycle Dependence - Following our earlier work (Burlaga and Ogilvie, 1970), we obtain the macroscale T-V relation by a least squares fit of the 3-hour averages of (T,V) for several solar rotations to a line of the form

$$\sqrt{T(^{o}K) \times 10^{-3}} = a\ V\ (km/sec) + b \qquad (1)$$

We suggested earlier that this relation does not change with solar cycle. Here we present additional evidence which supports that conclusion.

Table 2 shows values of a and b determined at three different parts of the solar cycle. The values near solar minimum were obtained from the Pioneer 6 data for December 18, 1965 to May 4, 1966, obtained by the MIT group. The Explorer 43 data for March 18 to April 8, 1971 give a and b for a period near solar maximum; note, however, that this represents just one solar rotation and is thus not strictly a macroscale relation. An intermediate period (June to December, 1967) is described by the Explorer 43 data from the Goddard Space Flight Center instrument. The results in Table 2 show that a and b did not change appreciably over the last half of the solar cycle.

We have also examined Mariner 2 measurements obtained in 1962, nearly one solar cycle ago. These measurements are consistent with the above conclusion, but uncertainties in the temperatures obtained by this pioneering experiment are larger than those from some later experiments.

Effect of Bulk Speed Gradients - If the macroscale T-V relation were appreciably affected by non-steady, dynamical interplanetary processes, which cause heating in regions where the bulk speed is increasing and cooling where the speed is decreasing (see Section IV), one should find that the macroscale T-V relation obtained from the set of 3-hour intervals across which V increased ($\Delta V > 0$) is appreciably different from that obtained from the set of 3-hour intervals across which V decreased ($\Delta V < 0$). Figure 3 shows such pairs of T-V relations, together with the relation for all V (dashed lines), obtained from the data of Explorer 34, Pioneer 6, and Explorer 43 for the intervals given at the beginning of this section. Values of a and b corresponding to the upper and lower lines in each panel of Figure 3 are given in Table 3.

The results of the Explorer 34 and Pioneer 6 observations, which extend over several solar rotations, are very similar. In each case, the difference between the T-V relation for $\Delta V > 0$ and that for $\Delta V < 0$ is small, the fractional temperature difference $\Delta T/T$ at a given V being less than 15%. For the Explorer 43 data, which extend over only one solar rotation, the difference between the T-V relation for $\Delta V > 0$ and that for $\Delta V < 0$ is larger, $\Delta T/T$ at a given V being approximately 35%. This is because the period covered by the Explorer 43 observations contained more streams than typically occur in one solar rotation, so that the heating and cooling due to stream evolution is more prominent in the T-V relations for that set of data.

Our conclusion is that on a scale of several solar rotations the effects of stream evolution on the statistical T-V relation are relatively small, although on a scale of one solar rotation they may occasionally be important.

IV. Mesoscale T(t)-V(t) Relations

Explorer 43 Results - Figure 4 shows plots of the points (T(t), V(t)) for each of the streams in Figure 2a, labeled A, B, C_1 and C_2. There is a definite time-ordered relationship between the points which gives a characteristic looped structure. Such T(t)-V(t) relations have been described by Hundhausen (1972). Three features of these relations must be explained: 1) the existence of high speeds, 2) the tendency for T to increase with V, and 3) the loop pattern. The third of these effects can be separated from the other two by resolving the observed temperature profile T(t) into two components, $T(t) \equiv T_c(t) + \Delta T(t)$, where $T_c(t)$ is computed from the measured V(t) using the macroscale T-V relation, and $\Delta T(t) \equiv T(t) - T_c(t)$. Figure 2b shows $\Delta T(t)$ for the Explorer 43 data. Note that the deviation from the macroscale T-V relation, $\Delta T(t)$, is not random. There is a systematic relation between $\Delta T(t)$ and the stream profile, ΔT being positive where V is increasing, approximately zero where V is maximum, and negative where V is decreasing. This relation between $\Delta T(t)$ and V(t) gives the loop pattern of the mesoscale T-V relations.

Interpretation - Burlaga et al. (1971) suggested that the T(t) and V(t) profiles for streams are basically due to two distinct physical processes: 1) proton heating, occuring near the sun, which produces the high speeds, and 2) proton heating in the interplanetary medium due to adiabatic compression caused by the non-linear evolution of the stream. The resolution of T(t) into two components, as discussed above, separates the effects of these mechanisms. Mathematically the separation is exact, since (1) is an identity. Physically, the separation is an oversimplification, but it is probably a good approximation. The value in such a decomposition is that it allows one to analyze the two physical processes involved quite independently. In particular, it puts a constraint (the macroscale T-V relation) on the acceleration mechanism, which is independent of the dynamical interactions in the interplanetary medium, and it describes the change in the temperature caused by stream evolution, $\Delta T(t)$, which is not directly related to the acceleration mechanism. A theoretical study by Hundhausen (1972) also supports the view that the macroscale T-V relation is determined primarily by temperature changes near the sun, while the loop-structure of the T(t)-V(t) relations is due to dynamical, interplanetary processes.

Heating of Streams - Figure 2b, or equivalently the loop in the mesoscale T-V relation, shows that the solar wind ahead of V_{max} (where V is increasing) is heated with respect to the temperature given by the macroscale T-V relation, while the wind behind V_{max} (where V is decreasing) is cooled. Table 4 shows $\overline{T}$ and $\overline{V}$ for the region of increasing V and the region of decreasing V for each of the streams B, C_1, and C_2 in Figure 2. The average T for the region of increasing V, T_L, is approximately twice that for the region of decreasing V, T_t. This ratio is essentially the same as the ratio of the temperature T_{max} corresponding to V_{max} to the temperatures T_{min} corresponding to V_{min} at the beginning and end on the stream. Clearly, the effect of the evolution of the stream profile on the temperature of a stream is large. This does not imply, however, that the macroscale T-V relations are greatly affected by the evolution of streams. For example, consider the heating. Although the average temperature ahead of V_{max} is nearly twice that given by the macroscale T-V relation, this heating region occupies only approximately one third of the measured duration of the stream, because of the asymmetrical stream profile. The average temperature in the cooling region is only slightly smaller than that given by the T-V relation. Thus, the average temperature of a stream is increased by only $\approx$ 35% by the evolution of the stream. Furthermore, the solar wind is not simply a succession of large streams, so that regions of strong heating occur less than one-third of the time and the increase in the average temperature due to such hot-spots is correspondingly less. In fact, on a large scale, the increase in the average temperature due to the evolution of streams is only $\approx$15%, as shown in Figure 3.

V. Discussion and Summary

Let us return to Figure 1, which shows 3-hour averages of (T,V) for nearly one solar rotation. In view of Figure 4, it is clear that the scatter of points in Figure 1 is not all random. It is due largely to a superposition of the time dependent, mesoscale relations $(T(t), V(t))$, shown in Figure 4. The T-V relation obtained from a least squares fit to these points, which is essentially the same as the macroscale T-V relation, is thus in part due to the superposition of time-dependent relations, as pointed out by Hundhausen (1972). This does not imply, however, that the macroscale T-V relation must be described by a time-dependent model. It was shown that it is meaningful to resolve a mesoscale $(T(t), V(t))$ relation into two components by writing $T(t) \equiv T(V(t)) + \Delta T(t)$, where $T(V)$ is nearly independent of time and $\Delta T(t)$ is related to the shape of the stream profile. Physically, this corresponds to approximately separating the temperature changes associated with the acceleration of the solar wind near the sun from the temperature changes caused by the evolution of the stream in the interplanetary medium.

It was shown explicitly that the macroscale T-V relation does not depend strongly on the shape of the stream profile, indicating that this relation is not determined by dynamical interplanetary processes. It was also shown to be reproducible in various spacecraft plasma data and to be independent of solar activity.

The systematic, time-dependent deviations from the macroscale T-V relation, $\Delta T(t)$, that are seen at high speed streams, depend strongly on the shape of the speed profile, indicating that they result from the dynamical interactions caused by the evolution of the speed profile. The heating due to stream development may be large (100%) locally, but is small ($\lesssim$ 15%) on the macroscale.

Acknowledgements

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APPENDIX

The GSFC Plasma Experiment on Explorer 43

This experiment consists of 2 detectors, placed 180 degrees apart in the spacecraft, which revolves once every 12 seconds about an axis maintained perpendicular to the ecliptic plane to an accuracy of $\pm$ 2 degrees. One consists of a cylindrical electrostatic analyser with a sensitive angle of width 1 degree in azimuth and $\pm$ 18 degrees in a plane containing the spin axis. This is followed by a drift tube and secondary emission detector, and by recording the counts in angular sectors, has an angular resolution in azimuth of $\sim$ 2 degrees. All the results discussed in this paper were obtained with this detector. The other responds to He^{++} only, and has a sensitive angle of width 1 degree in azimuth and $\pm$ 9 degrees in a plane containing the spin axis. The selection of He^{++} is made by means of a Wien filter, and the ions are detected by a secondary emission detector. This detector has an angular resolution of 11 degrees in azimuth.

Since one of the purposes of this system is to detect non-Maxwellian velocity distribution functions for the protons, the data processing for the energy per charge detector, by which the temperatures and bulk speeds used here were derived, consists of fitting the counts observed with the sum of two Maxwellian distributions, one for the protons, and one for the He^{++}. This yields bulk speeds to an accuracy of $\pm$ 3%, and temperatures to an accuracy of better than 25% over the whole range observed.

TABLE 1

Average Values of V and T

	$\overline{V}$(km/sec)	σ_V(km/sec)	$\overline{T}$(^{0}Kx10^{-3})	σ_T (^{0}K)x10^{-3}
Exp 43 (March 18 - April 8, 1971)	408	57	86	57
Vela 3 (July 1965 - July 1967)	412	72	80	75
Exp 34 (June 1967 - Dec. 1967)	439	91	124	102
Pioneer 6 (Dec. 18, 1965 - May 4, 1966)	435	91	128	98

TABLE 2

Coefficients in the T-V Relation

	a	b
Explorer 43 (March 18 - April 8, 1971)	.033 $\pm$ .001	-4.8 $\pm$ .4
Explorer 34 (June - Dec. 1967)	.036 $\pm$ .004	-5.6 $\pm$ 1.6
Pioneer 6 (Dec. 18, 1965 - May 4, 1966)	.032 $\pm$ .001	-3.3 $\pm$ .4

TABLE 3

	a_1	a_2	b_1	b_2
Explorer 43	.038	.032	-5.8	-4.8
Explorer 34	.039	.035	-6.46	-5.35
Pioneer 6	.034	.031	-4.0	-2.9

TABLE 4

Heating at Streams

Stream	Decimal Day	$\overline{T}(^{o}K)\times10^{-4}$	T_L/T_t	$\overline{V}$
B	88.675 - 90.0	17.9		456
	90.0 - 92.0	9.4	1.9	451
C_1	92.75 - 93.125	18.5		446
	93.125 - 93.675	8.8	2.1	450
C_2	93.675 - 94.5	13.6		419
	94.5 - 96.25	6.8	2.0	417

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FIGURE CAPTIONS

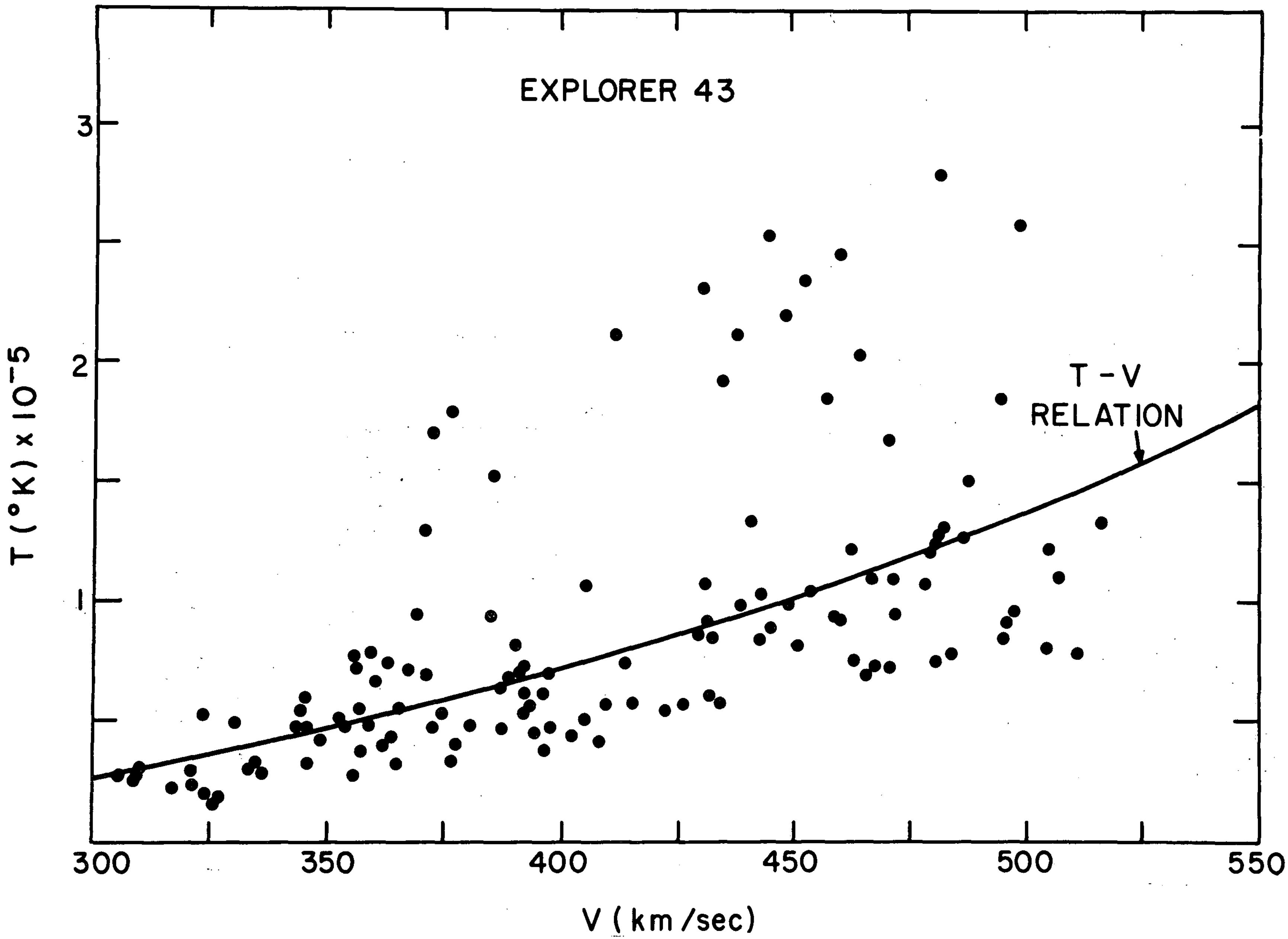
Figure 1. A plot of the 3-hour averages of V and T from Explorer 43. The T-V relation $\sqrt{T(^{o}K)x10^{-3}} = (0.033 \pm 0.001)\ V(km/sec^{-1}) - (5.5 \pm 1.5)$ is shown by the solid line.

Figure 2. (a) Three hour averages of bulk speed and proton temperature measured by a GSFC plasma instrument on Explorer 43. Periods A and B show well defined high speed streams and periods C_1 and C_2 show two such streams forming a compound stream. Also note the interval with no large streams.

(b) A plot of the difference between the measured proton temperature and the proton temperature predicted for the contemporary bulk speed using the T-V relation.

Figure 3. This shows T-V relations for the intervals of increasing V and the intervals of decreasing V. The "splitting" is probably due to stream interactions and is a measure of the effects of these interactions on the macrostructure. Note that this effect is largest for Explorer 43, where streams make up a substantial proportion of the observing time.

Figure 4. Time-dependent T-V relations for each of the streams A, B, C_1, and C_2 in Figure 2.



EXPLORER 43
T - V
RELATION
T (°K) x 10^-5
3
2
1
300
350
400
450
500
550
V (km/sec)

20

FIGURE 1

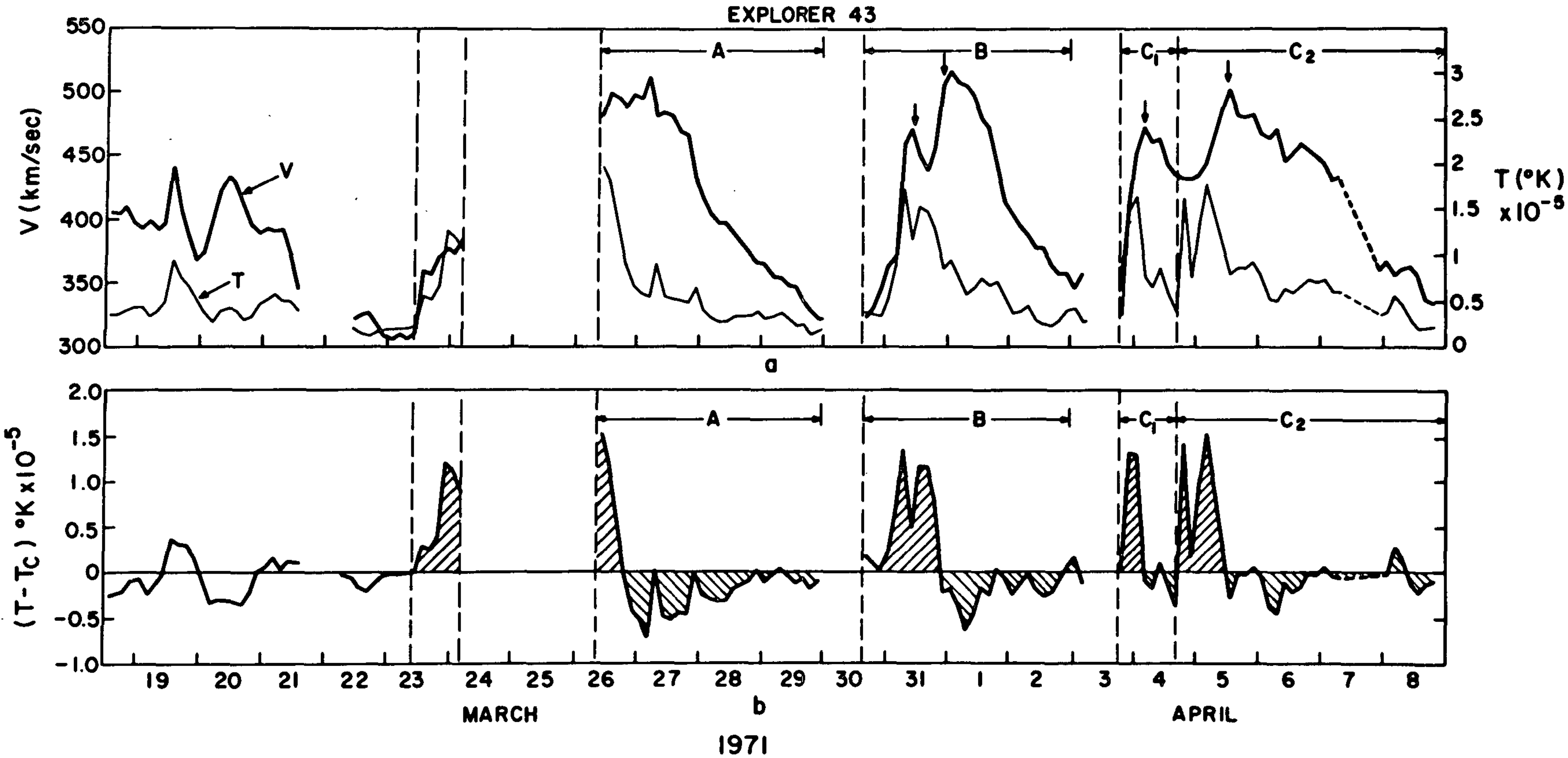

EXPLORER 43
V (km/sec)
T (°K) x10^-5
V
T
A
B
C1
C2
a
(T - Tc) °K x10^-5
b
MARCH
APRIL
1971

FIGURE 2

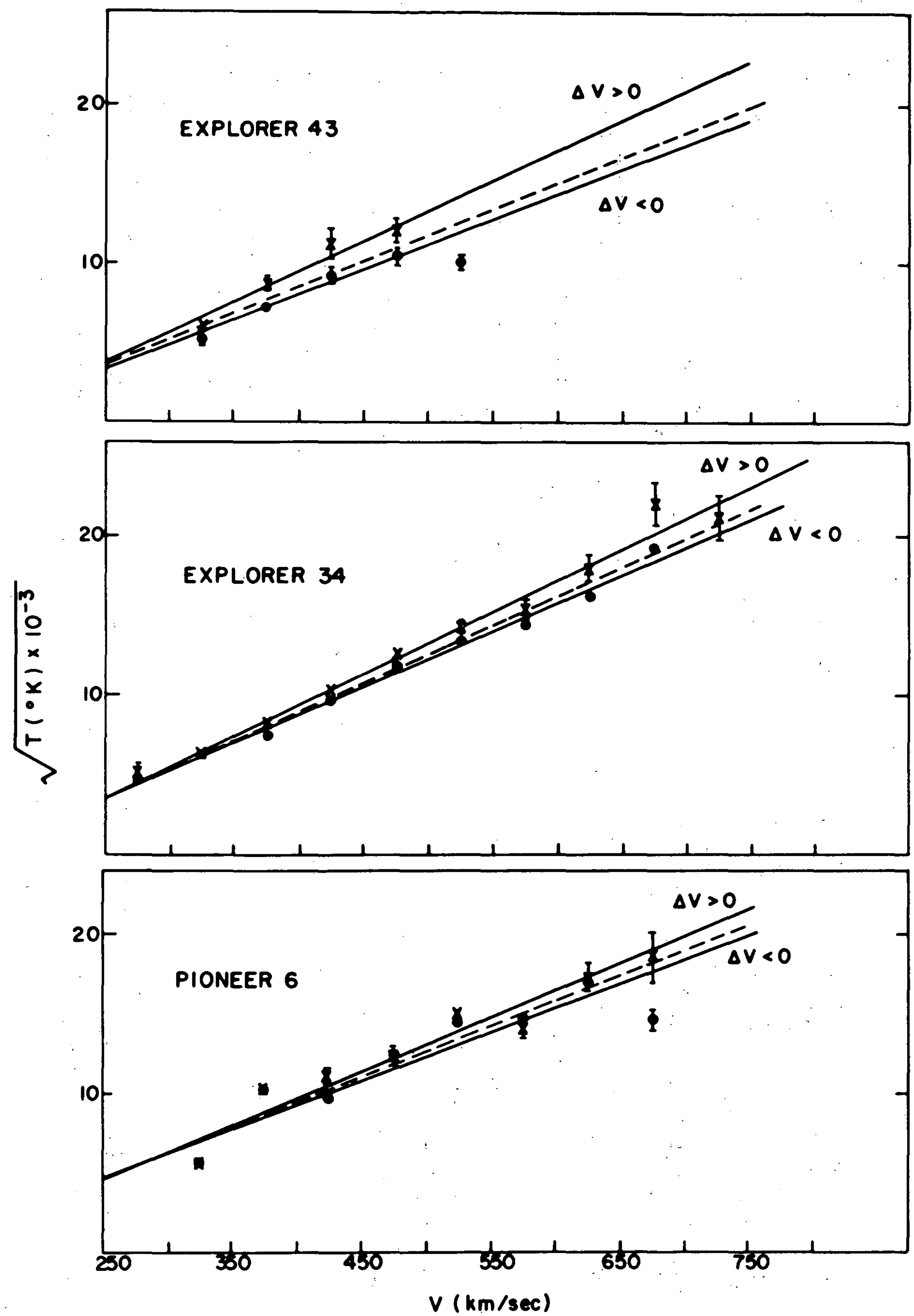
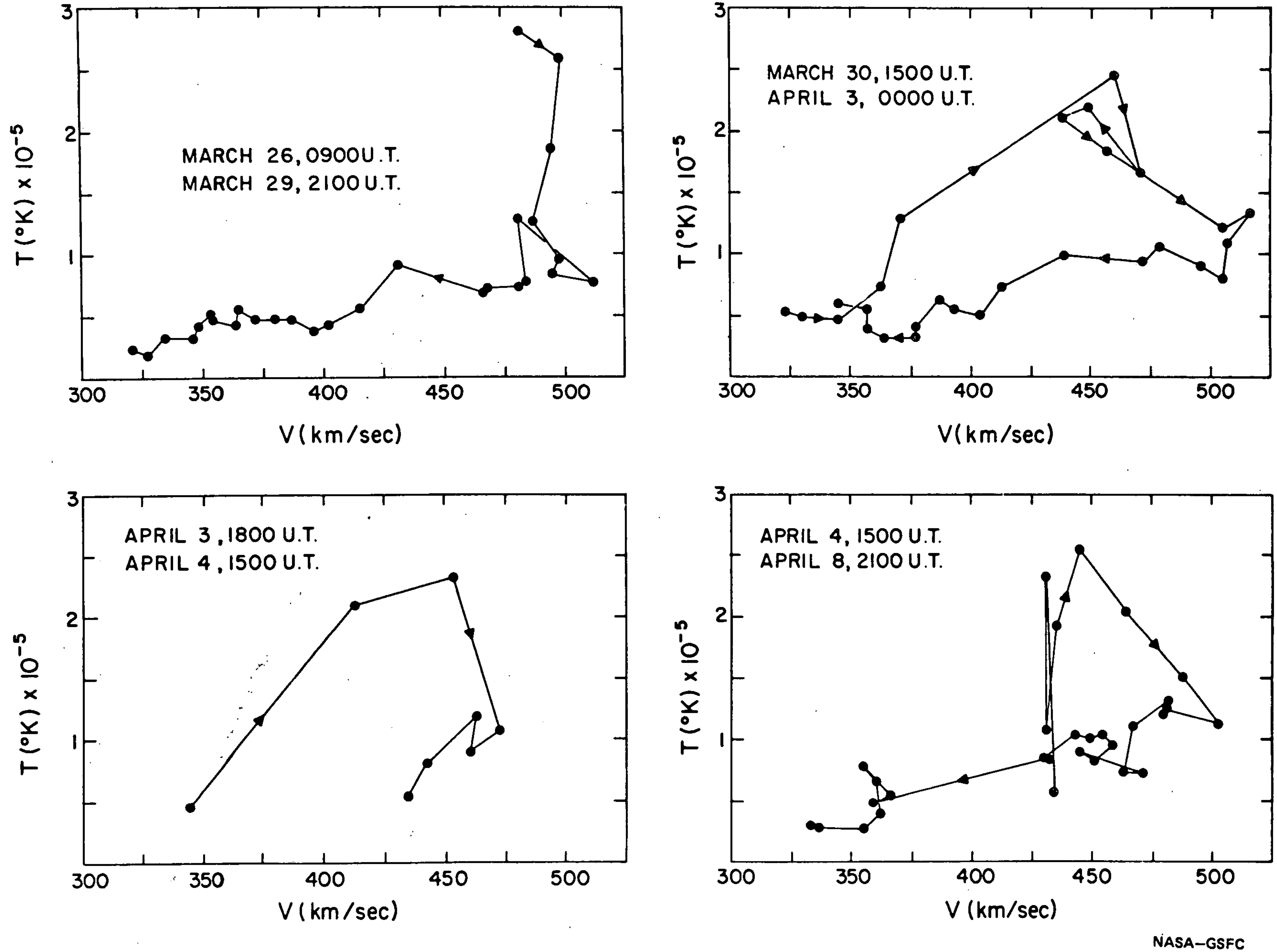

EXPLORER 43
ΔV > 0
ΔV < 0
EXPLORER 34
ΔV > 0
ΔV < 0
PIONEER 6
ΔV > 0
ΔV < 0
20
10
√T (°K) x 10^-3
250
350
450
550
650
750
V (km/sec)

FIGURE 3

22



MARCH 26, 0900 U.T.
MARCH 29, 2100 U.T.
MARCH 30, 1500 U.T.
APRIL 3, 0000 U.T.
APRIL 3, 1800 U.T.
APRIL 4, 1500 U.T.
APRIL 4, 1500 U.T.
APRIL 8, 2100 U.T.
T (°K) x 10^-5
V (km/sec)
NASA–GSFC

— FIGURE 4