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# On the Equation of State of Solar Wind Ions Derived From Helios Measurements

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Observations of solar wind ion velocity distributions made by the Helios spacecraft between 0.3 and 1 AU are used to study the radial evolution of the so-called adiabatic invariants, for example, the ion magnetic moments. Significant differences between the parameters of protons and $\alpha$ particles have been found in dependence on the wind velocity. On the average, adiabaticity is observed to be violated. We interpret this violation of adiabatic invariance as evidence that protons are heated perpendicular to the field in fast streams and, with less statistical significance, that $\alpha$ particles are cooled more strongly than for adiabatic expansion parallel to the magnetic field. The contribution of the differential streaming energy to the total internal energy of the ions is briefly investigated. Also, average heliocentric radial profiles for the ion heat fluxes are presented, and the possible role of the ion heat flux in supplying thermal energy during the radial expansion of the wind is examined. Our findings suggest that wave-particle interactions and (or) Coulomb collisions (or other yet unknown processes) have to be invoked in order to explain the thermal energy state of solar wind ions and their radial temperature profiles.

## 1. INTRODUCTION

The microscopic state of solar wind ions has in situ been investigated in considerable detail. Though ample observational material exists in the form of measured three-dimensional ion distribution functions [*Feldman et al.*, 1974; *Belcher et al.*, 1981; *Marsch et al.*, 1982*a, b*] and derived fluid parameters, a detailed theoretical understanding of the microprocesses governing the dynamic equilibrium and the internal energy state of the plasma is still lacking (see reviews by *Hollweg* [1978] and *Schwartz* [1980]). In particular, the ion thermal equation of state is unknown, if it exists at all. With respect to the various nonthermal features of ion distributions, the frequent assumption of a polytropic equation of state used in the solar wind momentum equations appears to be questionable. Many of the solar wind expansion models actually rely on such, or similar, assumptions, in order to keep the algebra tractable or to avoid the full complexity of the self-consistent energy equation within a fluid picture.

Recent theoretical studies [*Holzer*, 1979; *Leer et al.*, 1982] on the acceleration of the solar wind emphasize the need for additional energy and momentum deposition beyond the critical point in order to reconcile theoretical models with observational constraints in high-speed streams. Also, ongoing research on a solar wind thermally driven by electron heat flux [*Olbert*, 1981] indicates that conductive models based on an appropriately modified thermal conduction law can possibly provide a realistic description of the coronal and solar wind expansion. The present paper intends to elucidate some aspects related to this problem. Helios observations between 0.3 and 1 AU are used to investigate whether an equation of state for the ions exists. The question addressed is to what extent the so-called adiabatic invariants are actually conserved. It will become apparent that considerable differences evolve between proton and helium parameters during the solar wind radial expansion. Special attention is paid to the possible influence of the observed differential ion streaming (see the recent review by *Neugebauer* [1981] and the papers by *Asbridge et al.* [1976] and *Marsch et al.* [1981, 1982*a*]) on the evolution of the intrinsic ion temperatures. Finally, tentative theoretical explanations of the observations are offered within the framework of the fluid equations for a multicomponent plasma. Section 2 recapitulates the general physical picture represented by the double-adiabatic approach and the corresponding equation of state, whereas section 3 is concerned with a comparison between observations and theoretical expectations. Finally, some conclusions are drawn that are believed to be relevant to future work.

## 2. DOUBLE-ADIABATIC EQUATIONS OF STATE AND HEAT TRANSFER EQUATIONS

This section reviews some basic equations of the so-called double-adiabatic theory [*Chew et al.*, 1956] with special emphasis on some important aspects in a multi-ionic plasma with differential ion streaming. The general idea in this approach is to eliminate the explicit dependence of the higher-moment equations on the ion gyrofrequency. (It is this frequency that determines the fastest time scale for the evolution of the moments.) This is achieved with the ansatz

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of a gyrotropic temperature tensor as

$$\mathsf{T} = T_\parallel \hat{\mathbf{B}}\hat{\mathbf{B}} + T_\perp(\mathsf{I} - \hat{\mathbf{B}}\hat{\mathbf{B}}) \qquad (1)$$

where $\hat{\mathbf{B}}$ denotes the magnetic field unit vector. The reduction of the ion temperature tensor basically to a perpendicular ($T_\perp$) and parallel ($T_\parallel$) temperature describes the actual situation fairly well according to many solar wind in situ observations on various spacecraft [*Feldman et al.*, 1973, 1974; *Asbridge et al.*, 1976, 1977; *Marsch et al.*, 1982*a, b*]. The ion heat flux tensor then has only two nonvanishing components as well, namely, $q_\parallel$ corresponding to conduction of thermal energy $T_\parallel$ and $q_\perp$ corresponding to conduction of $T_\perp$ along the magnetic field in relation to the respective ion species' rest frame. Therefore one obtains two energy equations for each ion species, where temperatures are given in energy units, i.e., $k_B = 1$.

$$\frac{D^j}{Dt} T_{j\parallel} + 2T_{j\parallel}\hat{\mathbf{B}} \cdot (\nabla_\parallel \mathbf{V}_j) = \left.\frac{\partial T_{j\parallel}}{\partial t}\right|_{w,c} - \frac{1}{n_j}[\nabla_\parallel q_{j\parallel} - (q_{j\parallel} - 2q_{j\perp})\nabla_\parallel \ln B] \qquad (2)$$

$$\frac{D^j}{Dt} T_{j\perp} + T_{j\perp}[\nabla \cdot \mathbf{V}_j - \hat{\mathbf{B}} \cdot (\nabla_\parallel \mathbf{V}_j)] = \left.\frac{\partial T_{j\perp}}{\partial t}\right|_{w,c} - \frac{1}{n_j}(\nabla_\parallel q_{j\perp} - 2q_{j\perp}\nabla_\parallel \ln B) \qquad (3)$$

Here indices $w$ and $c$ correspond to waves or Coulomb collisions, respectively. $\nabla_\parallel$ is the parallel gradient $\hat{\mathbf{B}} \cdot \nabla$ and $\mathbf{V}_j$ the ion bulk velocity of the $j$th species, and $D^j/Dt$ denotes the corresponding convective derivative. In case there is no energy exchange by collisions or wave-particle interactions and in case the heat fluxes $q_\parallel$ and $q_\perp$ can be neglected in the energy equations (which may be reasonable as a first-order approximation in the region where the solar wind is supersonic), the energy source terms on the right-hand side vanish, and the double-adiabatic equations result. It should be mentioned that no electric field terms corresponding to ohmic dissipation enter (2) and (3), since these equations refer to the respective proper frame of the ionic species. In addition, one has the equation of continuity

$$\frac{D^j}{Dt} \ln n_j + \nabla \cdot \mathbf{V}_j = 0 \qquad (4)$$

and the frozen-in field condition, which by using Maxwell's equations for the field amplitude may be cast into the form

$$\frac{D}{Dt} \ln B + \nabla \cdot \mathbf{V} - \hat{\mathbf{B}} \cdot (\nabla_\parallel \mathbf{V}) = 0 \qquad (5)$$

Here the ion center of mass velocity is defined in the inertial frame fixed at the sun by $\mathbf{V} = \Sigma_j n_j m_j \mathbf{V}_j / \Sigma_j n_j m_j$, and the corresponding convective derivative is denoted by $D/Dt$. Under the assumption that energy source and sink terms can be discarded, there exists at least one equation of state, which is even independent of the actual heliocentric ion velocity profile. It can be derived from (2)–(5), yielding for each ionic species

$$T_{j\parallel}(T_{j\perp}/n_j)^2 = \text{const} \qquad (6)$$

This equation is completely independent of the three-dimensional structure of the interplanetary magnetic field frozen into the expanding solar wind plasma. From (3) and (5) one gets

$$\frac{D^j}{Dt} \ln \left(\frac{T_{j\perp}}{B}\right) = \hat{\mathbf{B}} \cdot \nabla_\parallel \mathbf{u}_j - \nabla \cdot \mathbf{u}_j - \mathbf{u}_j \cdot \nabla \ln B \qquad (7)$$

where the ion speed relative to the center of mass frame is $\mathbf{u}_j = \mathbf{V}_j - \mathbf{V}$. Equation (7) can be simplified. The dominant component of $\mathbf{u}_j$ is probably due to relative streaming along the ambient field, which would correspond closely to the observations of field-aligned proton double streams or differential proton $\alpha$ particle movement [*Feldman et al.*, 1974; *Asbridge et al.*, 1977; *Belcher et al.*, 1981; *Marsch et al.*, 1982*a, b*]. Because $\nabla \cdot \mathbf{B} = 0$ implies that $\nabla \cdot \hat{\mathbf{B}} + \nabla_\parallel \ln B = 0$, one then obtains with $\nabla_\perp = \nabla - \hat{\mathbf{B}}\,\nabla_\parallel$ the equation (7) in a rewritten form,

$$\frac{D^j}{Dt} \ln \left(\frac{T_{j\perp}}{B}\right) = -\frac{1}{B}\nabla_\perp \cdot (B\mathbf{u}_{j\perp}) \qquad (8)$$

which for $\mathbf{u}_{j\perp} = \mathbf{u}_j - \hat{\mathbf{B}}\, u_{j\parallel} = 0$ leads to the equation of state

$$T_{j\perp}/B = \text{const} \qquad (9)$$

Equation (8) implies that the magnetic moment $\mu_j = T_{j\perp}/B$ of the species $j$ is conserved in its rest frame only if either that frame is identical with the center of mass frame (which is to say, if there is no relative speed at all) or the differential movement is purely field aligned. Violation of the adiabatic invariance therefore indicates either that there is cross-field ion differential streaming or that the initial assumptions are incorrect, i.e., Coulomb collisions, wave-particle interactions, or heat conduction play a role.

Whether (6) and (9) are appropriate in the solar wind can be tested by analyzing the radial profiles of ion densities and temperatures and the magnetic field strength along individual streamlines. It should be noted that the assumption $\mathbf{u}_{j\perp} = \mathbf{0}$ is a priori not well justified, because an ion that does not travel with the center of mass velocity certainly 'sees' an electric field in its proper frame in case of a slight cross-field movement. This electric field would give rise to an $\mathbf{E} \times \mathbf{B}$ drift that may again lead to an enhanced perpendicular velocity. However, in situ solar wind measurements indicate that $\mathbf{u}_{j\perp} = \mathbf{0}$. We recall that the fact that $\mathbf{u}_j$ is field aligned has been confirmed on a statistical basis, as well as for limited time periods on a point-by-point basis [*Asbridge et al.*, 1977].

Equations (6) and (9) can be combined to yield

$$T_{j\parallel}(B/n_j)^2 = \text{const} \qquad (10)$$

which is another way of writing the second double-adiabatic equation of state. Equations (2) and (3) can be joined into a single equation and recasted into a form that elucidates the sinks or sources for ion thermal energy. For this purpose and for comparison with data, we define normalized ion heat fluxes by

$$\hat{q}_{j\parallel,\perp} = q_{j\parallel,\perp}/(n_j T_{j\parallel,\perp} v_{j\parallel}) \qquad (11)$$

Observed values of $\hat{q}$ are generally less than 1; actual numbers can be found in the papers by *Feldman et al.* [1977] and *Marsch et al.* [1982*a, b*]. According to Helios observations, the normalized heat flux, $\hat{q}_\alpha = (\hat{q}_{\alpha\parallel} + 2\hat{q}_{\alpha\perp})/2$, ranges typically between 0.3 and 0.5 except for low-speed wind ($V_\alpha < 400$ km s$^{-1}$) where $0.6 < \hat{q}_\alpha < 0.8$ because of frequently occurring double-peaked distributions. The normalized proton heat flux $\hat{q}_p$ increases slightly with decreasing heliocentric distance from about $\hat{q}_p \simeq 0.4$ at 1.0 AU to 0.6 at 0.3 AU, indicating that the relative skewness of proton distributions along the magnetic field becomes increasingly more pronounced closer to the sun. Using the equation of continuity (4) and the equations (2) and (3), some algebraic manipulations lead to

$$\frac{D^j}{Dt} \ln (T_{j\parallel} T_{j\perp}{}^2/n_j{}^2) = \frac{\partial}{\partial t} \ln (T_{j\parallel} T_{j\perp}{}^2)\big|_{w,c} - v_{j\parallel} \nabla_{\parallel} (\hat{q}_{j\parallel} + 2\hat{q}_{j\perp})$$

$$- \hat{q}_{j\parallel} v_{j\parallel} \nabla_{\parallel} \ln (n_j T_{j\parallel} v_{j\parallel}/B) - 2\hat{q}_{j\perp} v_{j\parallel} \nabla_{\parallel} \ln (n_j T_{j\perp} v_{j\parallel}/B)$$

$$+ 2\hat{q}_{j\perp} \left(1 - \frac{T_{j\perp}}{T_{j\parallel}}\right) v_{j\parallel} \nabla_{\parallel} \ln B \qquad (12)$$

where the parallel thermal velocity is defined by $v_{j\parallel} = (T_{j\parallel}/m_j)^{1/2}$. All terms on the right-hand side represent possible sources for ion heating or sinks for cooling, which can cause a violation of the double-adiabatic equation of state. The first term is due to wave-particle interactions (or collisions). The typical wave frequency $\omega$ involved is expected to determine the relevant time scale ($\partial/\partial t \sim \omega$) at least in order of magnitude. The subsequent terms all are proportional to the normalized heat flux $\hat{q}_{j\parallel,\perp}$ and yield a contribution only if the ion distributions are skewed along the magnetic field direction, which is actually observed in the solar wind. But the corresponding inverse time scale $\sim v_{j\parallel} \nabla_{\parallel}$ (according to the observations) is usually small in comparison to frequencies typical for resonant wave-particle interactions in the interplanetary medium. However, in the presence of intense waves originating from a rearrangement of internal particle energy, the heat flux terms presumably cannot be neglected in comparison to the wave-particle interactions.

For a positive $\hat{q}_j$, the third and fourth terms on the right-hand side of (12) are expected to contribute mainly to heating. Namely, the observed temperatures, densities, and magnetic field amplitude all decrease along the interplanetary magnetic field (IMF) spiral, and the measured radial decline in $B$ [*Musmann et al.*, 1977] is less steep than for the ion density; roughly, $n_j \sim r^{-2}$ according to Helios plasma measurements. Thus $n_j/B$ is slightly decreasing with increasing heliocentric distance. Possibly, the only terms which can lead to cooling (terms contributing negatively to the right-hand side of (12)) are the collisional term, the wave term, or the last term, which explicitly involves the species temperature anisotropy determining the sign of this term. After having outlined the theoretical framework, let us investigate the observations.

## 3. COMPARISON WITH THE MEASUREMENTS AND DISCUSSION

In this section the validity of the double-adiabatic equations of state (6), (9), and (10) is tested by comparison with in situ ion measurements made on board the Helios spacecraft within the orbital range between 0.3 and 1 AU. Details of the data analysis have been described elsewhere [*Rosenbauer et al.*, 1977; *Marsch et al.*, 1982*a*, *b*]. The plasma analyzer provides full three-dimensional ion distributions from which the required density, bulk speed, and temperatures parallel and perpendicular to the magnetic field can be calculated. Simultaneously with the ion parameters, the magnetic field is measured by the University of Braunschweig flux gate magnetometer [*Neubauer et al.*, 1977]. It should be pointed out that moments of the ion distributions sometimes only crudely reflect the original shape of the underlying distribution function. In considering only the temperatures $T_{j\parallel}$ and $T_{j\perp}$ we are disregarding a great deal of information contained in the three-dimensional distribution functions. A thorough discussion of the features of proton and helium ion velocity distributions for the data set under discussion here can be found in the work by *Marsch et al.* [1982*a*, *b*], where also the ion separation procedure is described in full detail.

Because the Helios analyzer measures ions according to their energy per charge and thus combines protons and alphas in one spectrum, it is necessary to separate the counts pertaining to the two species. This separation unavoidably causes some uncertainty in the ion parameters because the assignment of counts cannot always be done unambiguously. The proton heat flux $\mathbf{Q}_p$ is most sensitive to an erroneous separation of the counting rates in the two or three measurement channels where the distributions overlap. The vector $\mathbf{Q}_p$ has been found on an individual and statistical basis [*Marsch et al.*, 1982*b*, Figures 4, 5, 6] to be in excellent alignment with the independently measured magnetic field direction. Therefore we feel that in most of our data we have correctly subtracted the high-energy proton tails of the alpha distribution. There remain, however, spectra in very hot fast solar wind streams where the overlapping was so extensive that some ambiguity is certainly introduced in the data. Under those conditions, the separation scheme usually would have led to an underestimation of the alpha temperatures if the spectra had not been discarded in the first place. In about 70% of the proton spectra (according to a set of selective criteria that we do not want to repeat here in detail; see again *Marsch et al.* [1982*b*, section 2]), three-dimensional alpha particle distributions could be obtained. No additional selection filters have been put upon the data for the present investigation.

Before embarking on the discussion of actual data, we shall outline the general idea underlying our data evaluation and also address some fundamental questions pertinent to the analysis. In order to investigate whether solar wind ions expand adiabatically or not, one ideally needs to follow a parcel of plasma along a streamline. However, this is practically impossible, because the in situ plasma measurements by one spacecraft provide only information on the state of the plasma for a single point in space and time. Unless one has the spacecraft positioned in a radial lineup configuration (allowing the separation of radial and temporal variations of plasma parameters), one has to look at many plasma parcels measured at different heliocentric distances. This technique implies observations over an extended time span that is needed by the probe to traverse the radial distance range required to derive radial trends in the parameters. If the source regions of the plasma in the corona were not time variable and inhomogeneous, one would then consider the radial trend in our data to represent the 'true' trend.

Apparently, using the described method for real solar wind data, one cannot exclude the possibility that temporal variations and spatial inhomogeneities affect the results. However, if the source regions on the sun from which the plasma emanates are time stationary, one may consider a sample of different plasma parcels, which emanate from a

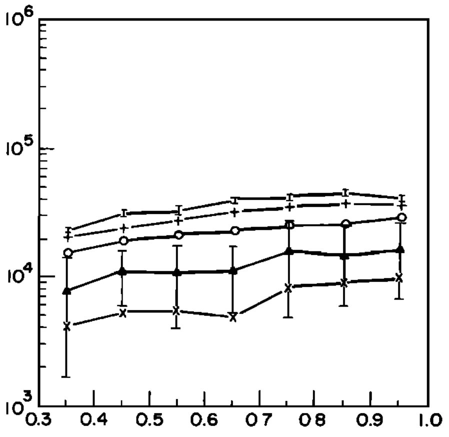

Fig. 1a

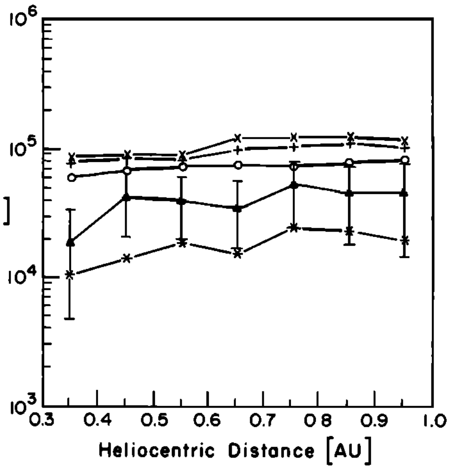

Fig. 1b

Fig. 1. (*a*) Proton and (*b*) $\alpha$ particle magnetic moment versus heliocentric distance for various solar wind velocities ranging from 300–400 km/s (bottom curve) up to 700–800 km/s (top curve). Points have been linearly connected to guide the eye. Error bars indicate the standard deviation of the mean within the respective bins. The error of the mean itself is actually much smaller.

corotating source and are measured by the same spacecraft at different radial distances, as representative of the ideal sample measured by various spacecraft lined up in a radial sequence. Unfortunately, there is only a small subset of Helios data for which the two probes were radially lined up and plasma seen from the inner probe also encountered the outer probe. This limited data set has been studied by *Schwenn et al.* [1981*a*] in order to derive radial temperature gradients. In this study the proton flow velocity (solar wind speed) has been used as a natural order parameter for the data, because significant differences in gradients of parameters for low-, intermediate-, and high-speed solar wind were found. Using the classification of data according to the solar wind speed corresponds roughly to a classification due to the different plasma source regions in the corona.

The time period under discussion here corresponds to solar activity minimum and was characterized by recurrent high-speed streams and a simple sector structure of the IMF [*Behannon et al.*, 1981], and fairly stationary coronal structures. The present data set has been discussed extensively before in the papers by *Rosenbauer et al.* [1977] and *Marsch et al.* [1982*a*, b]. In their studies it was shown that profiles of the temperatures $T_\parallel$ and $T_\perp$ and of the ion heat flux were closely correlated with the velocity profiles for several successive Carrington rotations. The temperature gradients derived in these papers by using the simple classification scheme based on the proton speed are in good agreement with those derived by *Schwenn et al.* [1981*a*] with the data from radial lineup constellations. This agreement makes us confident that one can also derive significant radial trends for parameters like the adiabatic invariants by sorting the measured spectra into radial distance bins for various solar wind velocities. As was pointed out initially, this method implies large variances for the individual bins, because the effects of temporal changes in the solar wind flow and of spatial inhomogeneities cannot be completely eliminated. On the other hand, because of a lack of a broad radial lineup data base, we believe that the method we used is the best we can do with our data. Although the variances are expected to be large, we believe that radial trends of the mean values in terms of least squares fits to the data can be considered as statistically significant.

The figures to be presented are based on the two Helios primary missions. This data set comprises 22,446 spectra for protons and 15,776 $\alpha$ particle spectra obtained during the time periods from day 346 in 1974 until day 95 in 1975 (Helios 1) and during the days 17 to 130 in 1976 (Helios 2), respectively. The statistical analysis is based on more than 1000 points per heliocentric radial distance bin of 0.1 AU width. The time periods of the Helios 1 and Helios 2 mission considered here are separated by almost 10 months. In order to exclude the effects of temporal changes in the plasma state during this 10-month time span, we initially performed our analysis separately for two space probes. The results looked very much alike; therefore we have combined the data of the two probes in the subsequent figures so as to enlarge the data base. Finally, we note that the large variances within a radial distance bin can partially be attributed to the fairly broad width (0.1 AU) of the bins. The figures comprise seven radial distance bins that contain at least two completely independent samples obtained by Helios 1 and Helios 2, respectively.

Figures 1*a* and 1*b* show the dependence of the magnetic moment $\mu_j = T_{j\perp}/B$ of protons and $\alpha$ particles on heliocentric radial distance for various solar wind velocities as indicated. Each velocity bin contains about 400 points on the average. For the curve corresponding to proton speeds between 400 and 500 km $s^{-1}$, standard deviation bars are given as well. The respective mean-square deviations for the points of the other curves are even less and are not shown in the figures so that the radial trends in the data are more obvious. What we consider here are the different mean values of the various bins and not the width of the distributions within a bin. The errors of the means are actually much smaller (reduced by a factor $N^{1/2}$ with respect to the standard deviation, where $N$ denotes the number of spectra sampled in a bin). In the top curve in Figure 1*a* the errors of the mean are shown as well. They are hardly larger in size than the symbols used to indicate the individual points. The same comment applies to Figure 1*b*.

Note that the scales for $T_{j\perp}/B$ are logarithmic in Figures 1*a* and 1*b*. The largest values of $T_{j\perp}/B$ are obtained in fast streams mainly because of the very high ion temperatures observed in high-speed streams [*Bame et al.*, 1975; *Marsch et al.*, 1982*a*, *b*]. Inspection of Figure 1*a* shows that there is a significant trend for the mean values of the proton magnetic moments to increase with increasing heliocentric distance. A similar trend, which is less distinct in the curves for fast wind ($V_\alpha > 500$ km s$^{-1}$), appears for the $\alpha$ particle magnetic moments. We recall that in high-speed streams, helium ions usually move faster than protons by about the local Alfvén speed (see recent review by *Neugebauer* [1981] for a comprehensive reference list) and that they appear to be 'surfing' on the Alfvén waves [*Marsch et al.*, 1981, 1982*a*]. Also, in high-speed wind the steepest average radial temperature gradient ($T_{\alpha\perp} \sim R^{-1.38}$) has experimentally been derived. Under these conditions, $\alpha$ particles seem to expand closest to adiabatically as far as their perpendicular temperature $T_{\alpha\perp}$ is concerned. Least squares fits yield $\mu_p \sim R^{+a}$ with the index varying between $0.6 \leq a \leq 0.9$ for the first adiabatic invariant of solar wind protons. Thus the data support the conclusion that proton perpendicular heating occurs in the interplanetary medium within the radial interval between 0.3 and 1 AU (see also the paper by *Bame et al.* [1975]). A similar conclusion can safely be drawn for low-speed helium ions. Their least squares fits yield $\mu_\alpha \sim R^{+a}$ with the index increasing from $a \simeq 0.3$ to $a \simeq 0.7$ for the velocity decreasing from $V_\alpha \simeq 750$ to $V_\alpha \simeq 350$ km s$^{-1}$. For fast ions the index has an uncertainty of about 10%; for slow ions of about 20%. As a result, for both ion species the magnetic moment tends to increase during the radial expansion from 0.3 to 1 AU.

Before considering the second adiabatic invariant as quoted in (10), it should be noted that the high absolute uncertainty in ion number densities (as measured in situ by electrostatic analyzers) introduces a large amount of scatter into the data, because the squared density enters in $T_{j\parallel}(B/n_j)^2$. This comment particularly applies to the $\alpha$ particle density (which has an error of at least 20–30%). Figures 2*a* and 2*b* show the second adiabatic equation of state versus heliocentric radial distance for protons and alphas, respectively. As has previously been stated, the five curves correspond to solar wind velocities ranging between 300 and 400 km s$^{-1}$, etc., in the sequence from the bottom to the top of Figures 2*a* and 2*b*. For the protons the data corresponding to fast streams yield almost flat curves with the exception of the upper right point in the top curve. We do not have any detailed explanation for this point. For the two curves in the middle part of the figure the least squares fits result in a radial dependence $\sim R^{+a}$ with $a = -(0.35 \pm 0.18)$ for $400 \leq v_p \leq 500$ km s$^{-1}$ and $a = -(0.58 \pm 0.19)$ for $500 \leq v_p \leq 600$ km s$^{-1}$. These velocity bins correspond mainly to trailing and leading edges of high-speed streams for the data set under discussion. Thus for protons on the trailing and leading edges of fast streams, the second adiabatic invariant is apparently violated with a slight decrease of $T_{p\parallel}B^2/n_p{}^2$ during the radial expansion of the wind from 0.3 to 1 AU. Although the variations are somewhat larger, the low-speed wind data do not exhibit any clear trend and yield flat least squares fit radial profiles. It appears as if conservation of the second proton adiabatic invariant is almost compatible with the measurements for fast and slow wind.

In contrast, the $\alpha$ particle parameters indicate that $T_{\alpha\parallel}B^2/n_\alpha{}^2$ slightly decreases with increasing heliocentric distance. This average trend is obvious in fast solar wind, but also appears to be significant in slow wind despite large fluctuations. A least squares fit to the data gives a power law in radial dependence $\sim R^{-a}$ with the index ranging between $0.9 \leq a \leq 1.9$ and an uncertainty of about 20% in fast and more than 50% in slow streams. This finding may be interpreted as evidence that the second adiabatic invariant is violated for solar wind $\alpha$ particles.

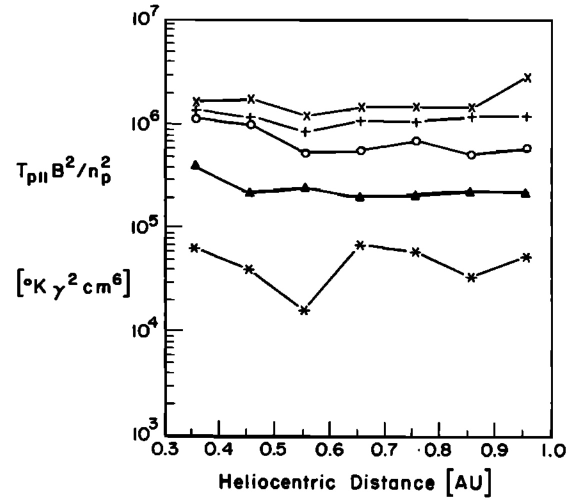

Fig. 2*a*

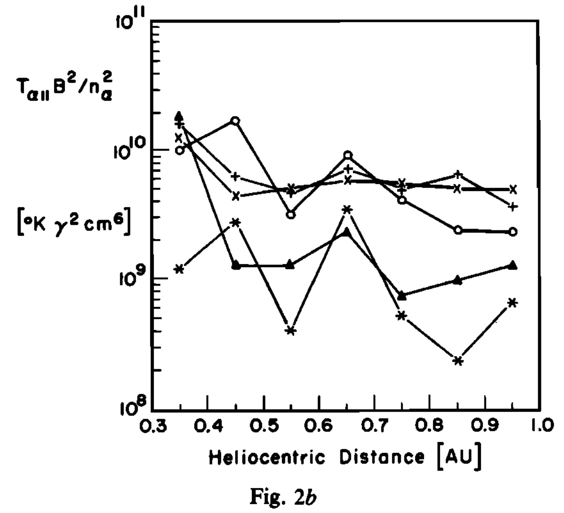

Fig. 2*b*

Fig. 2. Second adiabatic invariant $T_\parallel(B/n)^2$ of (*a*) protons and (*b*) $\alpha$ particles versus heliocentric radial distance for various solar wind velocity ranges indicated by the same symbols as in Figure 1.

We would like to mention at this point that the alpha particle density is the parameter that is the most affected by measurement uncertainties within single spectra. Also, generally, $n_\alpha$ is highly time variable, and the alpha particle content in the solar wind shows large variations corresponding to the macroscopic stream structure and the underlying coronal source conditions [see *Neugebauer*, 1981]. Thus an analysis involving $n_\alpha$ is most prone to producing large variances in the data due to measurement errors, time variability, and spatial inhomogeneities in the wind. A fair amount of the scatter in the data of Figure 2*b* (and also Figure 3*b*) in slow wind may be attributed to this fact.

Furthermore, data obtained in low-speed wind for the time period under discussion correspond to stream interaction regions and current layers at magnetic sector boundaries. It is very likely that mixing of plasma parcels from different

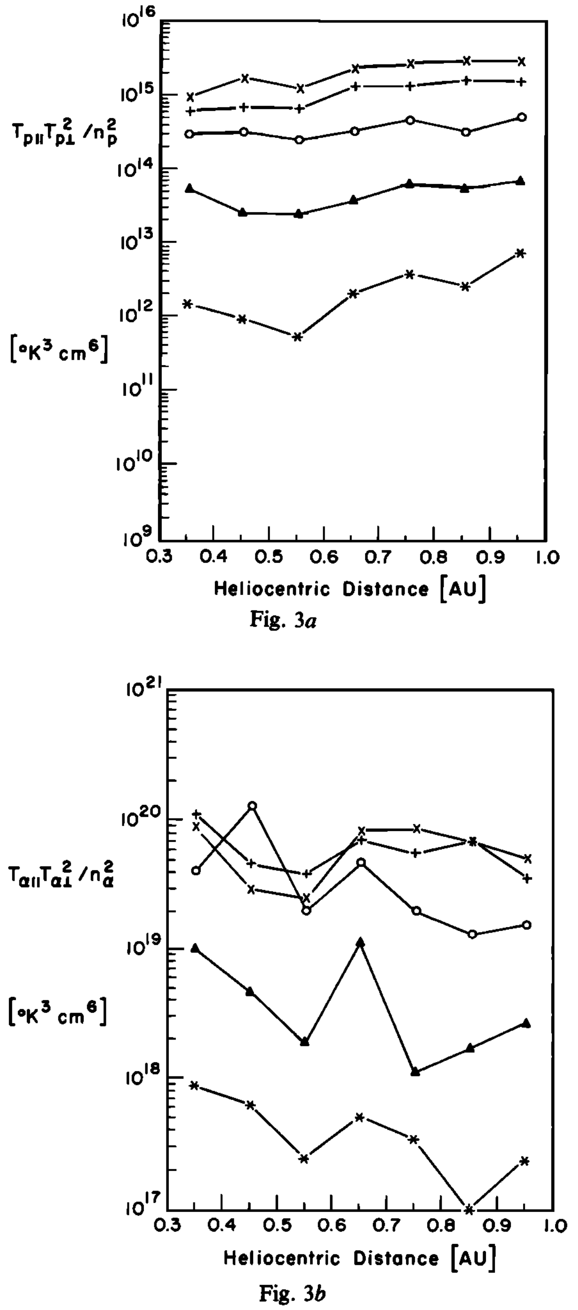

Fig. 3*a*

Fig. 3*b*

Fig. 3. Double-adiabatic equation of state $T_\parallel T_\perp^2/n^2$ for (*a*) protons and (*b*) $\alpha$ particles versus heliocentric distance for various solar wind speeds indicated by the same symbols as in Figure 1.

streamlines occurs in these regions. In this case, our results represent rather crude averages. On the other hand, one also expects collisional processes in these regions to be strongest [see *Neugebauer,* 1981; *Marsch,* 1982*b*]. Then deviations from adiabaticity would not come as a surprise, and one could partly explain them by an enhanced number of Coulomb collisions between the ions. By investigation of the normalized proton number flux density, *Schwenn et al.* [1981*b*] could demonstrate that for slow- and intermediate-speed wind the flow tubes expand by more than 25% in solid angle on their way out from 0.3 to 1 AU. This expansion may imply considerable interaction between different flow tubes and plasma parcels, leading to a nonadiabatic evolution. Fast wind flow tubes were found to be compressed only slightly (5–10%); thus in the body of fast recurrent streams one can expect to find more easily the homogeneous conditions that were assumed for our analysis.

In our opinion, the result of Figure 2*b* for fast streams could well be related to the radial evolution of the relative speeds of the ions in their center of mass frame. Namely, the total pressure tensor in the solar wind rest frame has to be written as

$$\mathsf{P} = \Sigma_j \mathsf{p}_j = \Sigma_j n_j(\mathsf{T}_j + m_j \mathbf{u}_j\mathbf{u}_j) \tag{13}$$

Experimentally, the relative speed of the *j*th species, $\mathbf{u}_j = \mathbf{V}_j - \mathbf{V}$, has on an individual and statistical basis been shown to be aligned with the local IMF, i.e., $\mathbf{u}_j = u_j\hat{\mathbf{B}}$ in fast streams. The speed $u_\alpha$ also has been found to follow closely the local Alfvén speed $v_A$ [*Asbridge et al.,* 1976; *Belcher et al.,* 1981; *Marsch et al.,* 1982*a*], which roughly scales like $R^{-1}$. Therefore the relative streaming kinetic energy $m_\alpha u_\alpha^2$ is certainly not conserved during the solar wind expansion. It is entirely possible that this energy decreases because of the action of a conservative force without impact on the evolution of the ion temperatures. However, it is also likely that this type of internal ion energy goes via microinstabilities [see *Schwartz,* 1980] into proper ion thermal energy $T_{j\perp}$ with the result that adiabatic invariance cannot be expected for these quantities. Similar ideas have been proposed by *Schwartz et al.* [1981] in order to identify the source of the proton temperature anisotropy in high-speed solar wind and have recently been put forward in more detail by *Marsch et al.* [1982*c*]. It should be emphasized as well that the $\alpha$ particle differential streaming energy actually contributes an important part to the total ion pressure tensor. The ion plasma beta is less than 1 under typical high-speed wind conditions and $u_\alpha \simeq v_A$, and therefore $n_\alpha m_\alpha u_\alpha^2$ can be as large as $n_p T_p$ (for relevant numbers, see *Feldman et al.* [1977] and *Marsch et al.* [1982*a, b*]). This fact has not been taken into account carefully enough in most solar wind expansion theories.

As was shown above, a violation of the first two adiabatic invariants in (9) and (10) can also be caused by the ion differential streaming across the magnetic field. In contrast, (6) is completely independent of the interplanetary magnetic field strength and topology and does not even depend explicitly on the velocity $\mathbf{V}_j$ or, consequently, on the relative speed $\mathbf{u}_j$ as well. Therefore (6) appears to be most appropriate in demonstrating that energy dissipation processes occur in the interplanetary medium during solar wind expansion. Unfortunately, this equation involves $T_{j\parallel}T_{j\perp}^2$, and thus one can only derive conclusions about this product but not about the individual temperatures themselves.

Figures 3*a* and 3*b* show $T_{j\parallel}T_{j\perp}^2/n_j^2$ versus heliocentric radial distance. Average values of these parameters have been calculated for radial distance bins of width 0.1 AU and solar wind velocities ranging between 300 and 800 km s$^{-1}$ as indicated at the curves. There appears a significant trend for $T_{p\parallel}T_{p\perp}^2/n_p^2$ to increase for very fast streams and slow solar wind, whereas for speeds between 400 and 600 km s$^{-1}$ a less steeply increasing trend can be recognized. Least squares fits to the data points yield power laws $\sim R^{+a}$ with values $0.6 \leq a \leq 1.2$ (and $a \sim 1.8$ for wind speeds ranging from 300 to 400 km s$^{-1}$). Because of the large variations in the data the mean square deviations in the index are fairly large (about 10% for the upper two and $\geq$40% for the lower three curves). Nevertheless, the conclusion may safely be drawn that the adiabatic invariance is violated. $T_{p\parallel}T_{p\perp}^2/n_p^2$ seems to increase mainly because the magnetic moment of the protons grows with increasing radial distance as demonstrated in Figure 1*a* and as can be inferred from Figure 2*a*.

Recent proton temperature measurements made between 1 and 10 AU by the Voyager plasma instruments [*Gazis and Lazarus*, 1982] have shown the proton temperature to decrease more slowly than expected for an adiabatic expansion. The investigation of $T_p/n_p^{2/3}$ revealed that adiabatic invariance is violated and that considerable heating occurs even at large heliocentric distances. Because the wind appeared to be anomalously hot at the leading edges of fast streams, the authors concluded that most of the heating was due to a direct conversion of bulk kinetic into thermal energy.

On the other hand, we believe that the perpendicular heating of the protons observed by Helios in fast wind between 0.3 and 1 AU in the inner part of the solar systems is more likely to be caused by waves (for example, by cyclotron resonance with left-handed polarized waves in the frequency range below $\Omega_p$). Ample evidence that such processes occur has been found in the detailed three-dimensional distribution functions of solar wind protons [*Bame et al.*, 1975; *Feldman et al.*, 1973, 1974; *Marsch et al.*, 1982*a*] and in wave measurements [*Denskat and Neubauer*, 1982]. Additional support for this idea has been obtained in a recent theoretical paper by *Dusenbery and Hollweg* [1981] and from a self-consistent model calculation for the radial evolution of ion internal energy (characterized by the parameters $u_j$, $T_{j\parallel}$, and $T_{j\perp}$) by *Marsch et al.* [1982*c*]. A recent theoretical letter by *Marsch and Chang* [1982] discusses the possibility that electrostatic lower-hybrid waves may also heat the ion distributions transverse to the magnetic field by Landau damping. Thus these waves could locally enhance the ion magnetic moments, provided they occur with high enough intensity.

Inspection of Figure 3*b* shows that on the average, $T_{\alpha\parallel}T_{\alpha\perp}^2/n_\alpha^2$ decreases with increasing heliocentric radial distance corresponding to a power law $\sim R^{-a}$ with indices ranging between $0.8 \leq a \leq 1.6$ but with large errors of 50% and more. A comparison with Figures 1*b* and 2*b* shows that the decline of this quantity is mainly due to a steep decline in $T_{\alpha\parallel}$ whereas the magnetic moment (compare with Figure 1*b*) was found to increase slightly in fast solar wind (compare also with the ion temperature profiles of *Marsch et al.* [1982*a*, *b*]). Despite large fluctuations and uncertainties, we believe that the decreasing radial course of $T_{\alpha\parallel}T_{\alpha\perp}^2/n_\alpha^2$ is statistically significant. Such a trend is in distinct contrast to that of the proton parameters in Figure 3*a*. We recall that all the comments we had on Figure 2*b* also apply to Figure 3*b*.

The above result has some interesting implications. If we assume for the moment that the ion temperatures are isotropic ($T_{j\parallel}/T_{j\perp} \neq 1$ does not give qualitatively different results), then (12) can be cast into a simpler form ($T_j = \frac{1}{3}(T_{j\parallel} + 2T_{j\perp})$ is the mean temperature) corresponding to the standard heat transfer equation:

$$\frac{D^j}{Dt} \ln (T_j n_j^{-2/3}) = \frac{\partial}{\partial t} \ln T_j \Big|_{w,c} - \frac{2}{3 n_j T_j} \nabla \cdot \mathbf{Q}_j \qquad (14)$$

Here, $\mathbf{Q}_j$ is the heat flux vector, $\mathbf{Q}_j = \frac{1}{2}(q_{j\parallel} + 2q_{j\perp})\hat{\mathbf{B}}$, which is field aligned pointing away from the sun in accord with in situ observations [*Asbridge et al.*, 1977; *Marsch et al.*, 1982*a*, *b*]. There is no observational evidence between 0.3 and 1.0 AU for $\mathbf{Q}_j$ to be related in any sense to a temperature gradient as in the case of a collision-dominated plasma. The ion data exhibit a clear tendency for $\mathbf{Q}_j$ to decrease steeply with heliocentric distance, which means that its negative divergence represents a positive energy source that in principle should raise $T_j n_j^{-2/3}$ above the constant adiabatic value in the interplanetary medium accessible to in situ observations. The same statement applies to the protons as well as to the $\alpha$ particles.

Figures 4*a* and 4*b* display the observed ion heat fluxes as functions of heliocentric radial distance for various solar wind velocities in the format used before. Apparently, the heat flux densities exhibit a steep radial decline with increasing solar distance. The steepest profiles correspond to low-speed wind, whereas for both species in high-speed wind the radial profiles are somewhat flatter. A least squares fit to the data yields a power law $Q_p \sim R^{-a}$ with values for the index as follows: $a = 3.78 \pm 0.18, 3.63 \pm 0.14, 3.56 \pm 0.19, 3.83 \pm 0.55$, and $4.68 \pm 0.17$ for the protons in Figure 4*a*. The corresponding average heat fluxes at 1 AU are $Q_0 = 3.31$, 3.71, 3.66, 2.03, and 0.62 $10^{-4}$ ergs cm$^{-2}$ s$^{-1}$. The sequence of numbers corresponds to the curves from top to bottom or from high- to low-speed wind. For the alphas in Figure 4*b* one obtains indices varying between 3.4 and 5.0 with flattest profiles for intermediate-speed wind.

It should be pointed out, however, that the alpha particle heat flux density is a quantity with a large error, because the low helium ion flux in the solar wind makes it extremely difficult to reliably identify a field-aligned skewness of the alpha distribution function (although it can sometimes be done fairly well [see *Feldman et al.*, 1973; *Marsch et al.*, 1982*a*]). The larger values for $Q_\alpha$ in Figure 4*b* at 0.5 AU should not be taken too seriously. This does not reflect a true average characteristic of the heat flux profile, but is more indicative for data from single events which point out so strongly, because the data set is limited. As was mentioned in the beginning, it covers only a few solar rotations. The average trend as derived from the least squares fit is certainly statistically significant for the protons, but may only be considered as a good order of magnitude estimate for the alphas.

It is obvious from the actual numbers that the contribution of the ion heat fluxes to the total ion energy flux density (including the bulk motion) is negligibly small. However, if no collisional or wave-particle energy dissipation processes occur, then $\nabla \cdot \mathbf{Q}_j$ alone would determine the local ion thermal energy state corresponding to (12) and (14). The negative divergence of $\mathbf{Q}_j$ on the average actually turns out to be positive according to the declining course of $Q_j$. Thus the measured $-\nabla \cdot \mathbf{Q}_j$ represents an overall positive source of ion thermal energy, and therefore it is instructive to examine whether it is sufficient to account for the radial course of the adiabatic invariants. In more exact terms, the convective derivate of $T_{p\parallel}T_{p\perp}/n_p^2$ is determined by a slightly more complicated expression in (12) than just $\nabla \cdot \mathbf{Q}_p$. Therefore it is hard to make any precise numerical statements from the present investigation. Nevertheless, let us make some simple calculations.

If one takes the fits to the data presented in Figure 4*a* and 4*b*, one can roughly estimate the strength of the interplanetary heating source by integration over the radial heat flux profiles. For example, the expected mean temperature in-

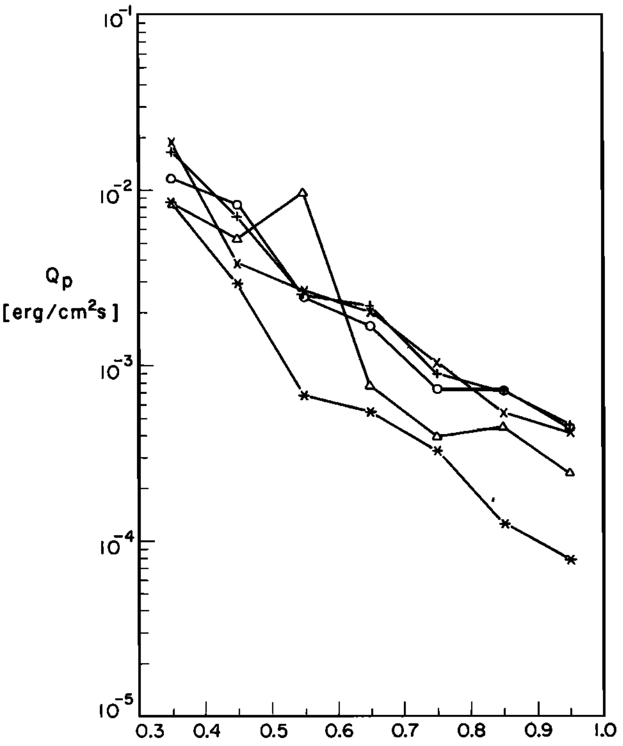

Fig. 4*a*

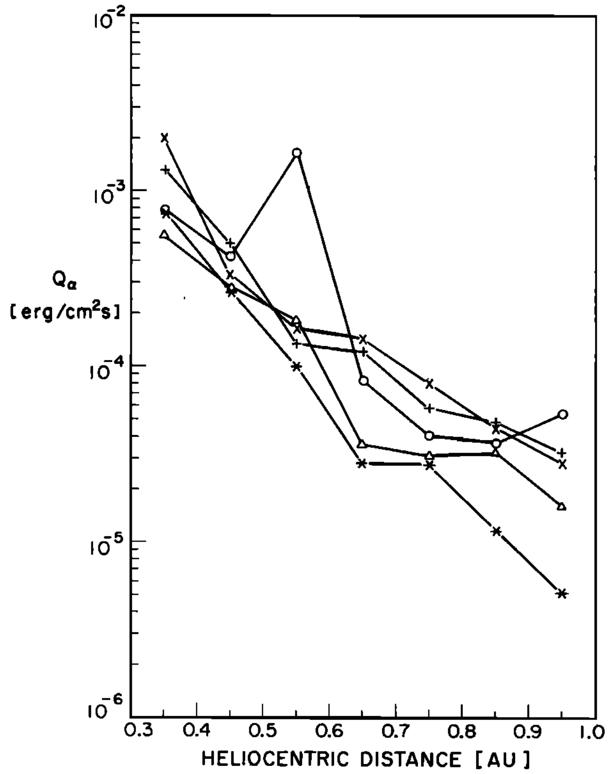

Fig. 4*b*

Fig. 4. Heat flux density $Q$ for (*a*) protons and (*b*) $\alpha$ particles versus heliocentric radial distance for various solar wind speeds indicated by the same symbols as in Figure 1. The vertical scale for $Q$ is logarithmic, extending over 4 orders of magnitude.

crease $\Delta T$ due to the total heat inflow into a unit volume convected with the solar wind from $r = 0.3$ AU to $r_0 = 1.0$ AU at the speed of $V_0 = 750$ km s$^{-1}$, say, is obtained from

$$\Delta T = -\frac{2}{3n_0 r_0^2 V_0}\int_r^{r_0} dr' \frac{d}{dr'}(r'^2 Q_{r'}) \qquad (15)$$

The data fits for high-speed protons yield the radial profile $Q_r = Q_0(r/r_0)^{-a}$ with $a = 3.78$ and $Q_0 = 3.31 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$. The integral can then be written as

$$\Delta T = \frac{2Q_0}{3n_0V_0}\left[\left(\frac{r}{r_0}\right)^{2-a} - 1\right] \qquad (16)$$

Putting the above figures into (16), one obtains for $n_0 \simeq 5$ an increment $\Delta T \simeq 3.6 \times 10^4$ °K, which is about an order of magnitude below the actual decrease in temperature derived from the in situ measured profiles [*Marsch et al.* 1982*b*]. Similar results are obtained for various other wind velocities. In conclusion, the observed ion temperature profiles are only marginally influenced by the ion heat fluxes in the radial distance range 0.3–1 AU accessible to the Helios probes. Basically, the reason is that in the supersonic regime the divergence of the heat flux is smaller than the convective derivatives of the temperatures by a factor of $v_{j\parallel}/V_j$. The situation might be quite different in a subsonic flow.

Under time stationary conditions and with the assumption $n_p \sim r^{-2}$, (14) can be integrated with the result

$$\Delta\left(\frac{T}{n^{2/3}}\right) = \frac{4-2a}{10-3a}\,\frac{Q_0}{V_0 n_0^{5/3}}\left[1-\left(\frac{r}{r_0}\right)^{10/3-a}\right] \qquad (17)$$

Inserting the least squares fit numbers from Figure 4*a* for the protons and a reference density $n_0 = 2.4$ at $r_0 = 1$ AU (for typical values, see again *Feldman et al.* [1977]), one finds the right-hand side in (17) to be smaller than the left-hand side by a factor of 3–5 under high-speed solar wind conditions and by more than an order of magnitude for slow wind. These results suggest that a positive term $\partial/\partial t \ln T_p|_{w,c}$ has to be invoked in (14) in order to reconcile the proton observations with the theory and to account for the measured increase of $T_p n_p^{-2/3}$ during the radial expansion from 0.3 to 1.0 AU.

Given the observations for the radial course of $Q_\alpha$, one in principle would expect $T_\alpha n_\alpha^{-2/3}$ to increase as well and not to decrease with increasing solar distance, as can be inferred from Figure 3*b*. This controversial aspect in the He$^{2+}$ data is most striking in slow solar wind. Our analysis suggests that a nonvanishing term $\partial/\partial t \ln T_\alpha|_{w,c}$ may have to be invoked that should be negative (corresponding to cooling of the parallel degree of freedom ($T_{\alpha\parallel}$)) in order to account for the decreasing course of the observed $T_{\alpha\parallel}T_{\alpha\perp}^2/n_\alpha^2$ profiles. It is hard to provide details about the underlying processes. Whether these actually are some sort of wave-particle interactions or even classical Coulomb collisions or macroscopic stream mixing cannot be decided from the present investigation. There is observational evidence that Coulomb collisions, at least in slow solar wind, play a role in determining the ion internal energy [*Neugebauer,* 1981]. That would imply a nonadiabatic coupling between $T_{j\parallel}$ and $T_{j\perp}$.

The fast solar wind we expect the interaction with waves to strongly influence the ion temperatures. Our analysis suggests that the corresponding terms in (12) and (14) are more important than the heat flux terms. This seems to us to be particularly the case for $T_{j\perp}$. Namely, inspecting (3), one can see that only $q_{j\perp}$ enters this equation. Measured ion distributions show that most of the time $q_{j\perp}$ is nearly an order of magnitude smaller than $q_{j\parallel}$, so that it appears likely that a positive wave term $\partial T_{j\perp}/\partial t|_w$ contributes prominently to the perpendicular heating of the ions. Concerning this process, one can hardly imagine that Coulomb collisions are important, because their main effect is to reduce the free energy in nonthermal distributions and not to build up anisotropies.

## 4. SUMMARY AND CONCLUSIONS

The present study was concerned with an investigation of ion parameter combinations corresponding to the adiabatic invariants. A previous study on a similar subject, based on data from the earthbound Heos satellite, dealt with deriving evidence for extended solar wind heating by fast hydromagnetic waves [*Auer and Rosenbauer*, 1977]. The basic assumption in their paper was that the values of the adiabatic invariant established in the corona would survive the transit to 1 AU unchanged by irreversible interplanetary processes. However, in the present paper, observational evidence was found that the adiabatic invariants are violated in the solar wind to various degrees. The equation of state in the form $T_{j\parallel}T_{j\perp}{}^2/n_j{}^2$ on the average holds neither for protons nor for $\alpha$ particles. Whereas for the protons a significant trend appeared for this quantity to increase slightly with increasing heliocentric distance, the contrary trend was observed for the $\alpha$ particles. The most obvious differences exist in slow solar wind with velocities smaller than 500 km $s^{-1}$.

A separate investigation of the particles' measured magnetic moment revealed a definite increase of $\mu_p$ with growing radial solar distance, suggesting that extended perpendicular proton heating occurs within the whole orbital range (0.3–1 AU) accessible to the Helios spacecraft. For fast $\alpha$ particles the magnetic moment $\mu_\alpha$ appears to be almost conserved during the radial expansion of the fast wind. For slow-speed helium ions ($V_\alpha < 400$ km $s^{-1}$) a definite increase of $\mu_\alpha$ with increasing heliocentric distance could be derived from the Helios data. It has been argued that the differences in $\mu_\alpha$ and $\mu_p$ may somehow be related to the different radial profiles of the relative speeds $\mathbf{u}_j$ of the two species or more likely may be caused by different perpendicular wave heating processes.

It can be concluded that the average ion observations do not support the idea that an ion thermal equation of state actually exists in the solar wind in the strict theoretical meaning of this term. Deviations from adiabatic invariance have been detected which are probably caused by interplanetary heating (protons) as well as cooling which is stronger than adiabatic ($\alpha$ particles), whereby the results exhibit dependence on the solar wind flow speed. Some of these deviations are certainly not pronounced considering the actual numbers. However, a rough coincidence with the double-adiabatic values might be fortuitous. This could occur simply because possible source and sink terms on the right-hand side of the energy equations (2) and (3) could on the average cancel each other. In order to understand the detailed, observed distribution functions (for example, the large proton core temperature anisotropy $T_{\perp c}/T_{\parallel c} > 1$ [*Bame et al.*, 1975; *Marsch et al.*, 1982*b*]), one still would have to invoke wave-particle interactions, although in referring only to the total moments of the distributions, the protons sometimes may appear to behave almost adiabatically. A similar comment applies to the $\alpha$ particles. The kinetic energy represented by their differential motion ($u_\alpha \simeq v_A$) relative to the ion center of mass frame contributes a major part to the total internal ion energy budget. However, there may exist no theoretical 'equation of state' at all for $u_j$ as a function of $T_{j\parallel}$, $T_{j\perp}$, $n_j$, and $B$. Then one would instead have to set up and solve a differential equation for $\mathbf{u}_j$ self-consistently in order to describe the radial evolution of this quantity within a theoretical model.

The conclusions drawn so far have been based on observations between 0.3 and 1 AU. In this radial solar distance range the internal ion energy certainly is without major dynamic importance for the motion of the wind itself, because the wind speed has already become super-Alfvénic (or supersonic). But if one is allowed to extrapolate the present conclusions to the coronal acceleration region, our results strongly suggest that for modeling the solar wind in the critical régime one certainly should not artificially close the chain of moment equations by some polytropic or double-adiabatic equations of state but rather try to find self-consistent solutions of these equations including appropriate wave-particle interaction terms.

Helios observations have demonstrated that generally, the nonthermal features of ion distributions become most pronounced at 0.3 AU [*Marsch et al.*, 1982*a, b*]. For example, $T_{\alpha\parallel,\perp}$ even reaches values of more than $10^6$ °K at 0.3 AU in streams with $V_\alpha > 700$ km $s^{-1}$, which means that the maximum in the temperature profile could actually be located somewhere between the corona and 0.3 AU. Temperatures of minor ions, e.g., oxygen and iron, are still higher even at 1 AU (see, for example, *Mitchell et al.* [1981] and references therein). The proton core temperature anisotropy $(T_{\perp c}/T_{\parallel c})_p$, which can be larger than 3 at 0.3 AU, shows a tendency to increase even further closer to the sun if the measured radial profiles are extrapolated to shorter heliocentric distances. The same comment applies to the observed variation of ion differential speeds [*Marsch et al.*, 1981, 1982*a*] with solar radial distance. As was mentioned in connection with (11) before, the 'pressure' due to differential ion movement is expected to contribute an essential part to the total pressure in fast solar wind. Therefore the assumption that a polytropic-type equation of state for the total ion pressure or a double-adiabatic equation is applicable does not seem to be justified.

Finally, we would like to emphasize that proton heat conduction should be reconsidered as well, at least in the subsonic region. Namely, a marked field-aligned skewing of the distribution function constituting a heat flux has been observed most of the time in solar wind ion distributions in the interplanetary medium [*Feldman et al.*, 1973, 1974; *Goodrich and Lazarus*, 1976; *Marsch et al.*, 1982*a, b*]. Even here, values for the normalized heat flux $\hat{q}_j$ (which measures the relative skewing of the distribution) of the order of 1 have temporarily been observed. As can be seen from (2) and (3) and (13) and (14), in the subsonic region ($V_j < (T_{j\parallel}/m_j)^{1/2}$) the heat conduction terms certainly are comparable to or even dominate the convective terms, not to mention possible wave-particle interaction terms [*Hollweg*, 1978]. Thus it is by no means self-evident that an equation of state even exists under those conditions.

It has been argued by *Auer and Rosenbauer* [1977] that the frequently occurring proton double streams and shoulders in the distributions that constitute the heat flux might actually be the relic of fast-mode wave heating in the corona as proposed by *Barnes* [1969]. His theory was concerned with collisionless heating of the solar wind plasma by Laudau damping of compressional waves originating at the base of the corona. We are not able to prove or disprove this theory with our data. However, we think that because of the violation of the adiabatic invariants caused by dissipative interplanetary processes, one cannot rely on observation of these 'invariants' at 1 AU in order to derive conclusions about the plasma state in the corona. There is also no evidence in the data that would clearly indicate that Barnes' parallel heating process is important (within the orbital range of Helios) in the interplanetary medium.

Concerning wave-particle interactions, *Dusenbery and Hollweg* [1981] and *Marsch et al.* [1982*c*] have developed some new ideas that may account for the increasing radial trend in the proton magnetic moment and the regulation of the ion heat flux. The model by *Marsch et al.* [1982*c*] describes some basic characteristics in observed ion distributions as being related to cyclotron damping of field-aligned magnetosonic and ion-cyclotron waves, which constitute the higher-frequency part of the right-handed polarized branch of MHD waves and Alfvén waves. There is possible observational evidence that Alfvén waves are actually radiated by the sun with sufficient energy to heat solar wind ions [*Hollweg et al.*, 1982]. In any case, in our opinion, the question of what governs the ion heat conduction in detail is worth careful reconsideration in future work.

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