ELECTRON HEATING AT INTERPLANETARY SHOCKS

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ABSTRACT

Data for 41 forward interplanetary shocks measured between August 1978 and December 1979 show that the ratio of downstream to upstream electron temperatures, $T_e(d/u)$ is variable in the range between 1.0 (isothermal) and 3.0. On average, $<T_e(d/u)> = 1.5$ with a standard deviation, $\sigma_e = 0.5$. This ratio is less than both the average ratio of proton temperatures across the same shocks ($<T_p(d/u)> = 3.3$ with $\sigma_p = 2.5$) and the average ratio of electron temperatures across the earth's bow shock. Individual samples of $T_e(d/u)$ and $T_p(d/u)$ appear to be weakly correlated with the number density ratio. However the amounts of electron and proton heating are well correlated with each other as well as with the bulk velocity difference across each shock. The stronger shocks appear to heat the protons relatively more efficiently than they heat the electrons.

Introduction

Although extensive research has been devoted to the various characteristics of interplanetary shocks, not much work has been devoted to their effects on solar wind electrons. Early work based on data measured using the Vela 4 plasma analyzers indicated a low efficiency for heating the ambient plasma electrons (Hundhausen et al., 1970; Hundhausen, 1970a). This result was interpreted to be a consequence of the high solar wind thermal conductivity. Any heating would then be quickly distributed over a large volume of plasma thereby increasing the thermal energy per electron only slightly (Hundhausen and Montomgery, 1971).

Most studies of solar wind electrons have been made using measurements from satellites in near earth orbit. The earth's bow shock is known to preheat the magnetically connected upstream solar wind by variable amounts having an average magnitude (Feldman et al., 1973) of the order of that caused by interplanetary shocks (Hundhausen, 1970a; Hundhausen et al., 1970). Since it is difficult to isolate data measured from these orbits which are completely unperturbed by the bow shock, the early Vela 4 shock results have not been followed by more extensive and deeper studies. This difficulty has been overcome by the launch of ISEE-3 which was stationed for approximately 4 years about 10^6 km upstream of the earth. This orbit was sufficiently far upstream that ISEE-3 was usually not connected magnetically to the earth's bow shock (Feldman et al., 1982).

This paper reports the results of a study of electron heating at interplanetary shocks using data measured with the Los Alamos electron plasma analyzer aboard ISEE 3. Analysis procedures are described briefly in Section 2 and the results and conclusions are given in Sections 3 and 4 respectively.

In the following presentation, a standard notation is adopted. The symbols N, V, and T will denote the proton density, bulk velocity and numerically-integrated total temperature. Subscripts e and p on the temperature refer to electrons and protons respectively. Parenthetical use of the combinations (d/u) and (d-u) denote the ratio of downstream to upstream parameters and the difference between downstream and upstream parameters respectively.

2) Data and Analysis Procedures

Details of the Los Alamos ISEE-3 plasma analyzers along with their operation modes have been published elsewhere (Bame et al., 1979a). Ion and electron plasma data measured between August 1978 and December 1979 were used in the present study. Fluid parameters were calculated by integrating numerically over that portion of the ion count-rate distribution dominated by protons and over the electron velocity distribution between about 10 eV and 1 keV.

A list of possible shocks passing ISEE 3 between 18 August 1978 and 1 January 1980 was prepared using the ion data in conjunction with magnetic field data (for a description of the magnetometer see Frandsen et al., 1979). Forward shocks were identified by abrupt increases in bulk velocity, number density, proton temperature and magnetic field strength. The 41 events on the list which had the unambiguous signature of a forward shock and no data gap at shock passage, comprised the base for the present study. Number densities, bulk velocities and total proton temperatures determined using the ion data, as well as total electron temperatures determined from the electron data, were averaged over an approximately 5 min interval upstream and downstream of each shock and tabulated. The results of an analysis of these parameters is given next.

3) Experimental Results

a) Statistics

The statistics of particle heating at these 41 shocks are collected in Table 1. Inspection shows that this set of shocks is on the average weaker than the earth's bow shock. Whereas $\langle N(d/u) \rangle$ = 1.9 and $\langle V(d-u) \rangle$ = 76 km s^{-1} for this set, they are ~3 and ~100 km s^{-1} respectively for the earth's bow shock (see e.g. Hundhausen, 1970b; Montgomery et al., 1970; Scudder et al., 1973; Bame et al., 1979b). Electron heating at these interplanetary shocks is also weaker than at the bow shock. On average $\langle T_e(d/u) \rangle$ = 1.5 with a standard deviation of 0.5 as compared to $\langle T_e(d/u) \rangle$ = 3 for the earth's bow shock (Hundhausen, 1970b ; Scudder et al., 1973; Bame et al., 1979b). The electron heating at these shocks is also less than the proton heating averaged over the same shocks. This fact is demonstrated by comparing the rows in Table 1 giving the statistics for $T_e(d/u)$ and $T_e(d-u)$, with those giving $T_p(d/u)$ and $T_p(d-u)$ respectively. This result is also similar to that obtained at the earth's bow shock (Montgomery et al., 1970).

b) Parameter Correlations

The associations of electron and proton heating with each other as well as with the density and velocity changes at interplanetary shocks can best be displayed by scatter plots of pairs of parameters. Since the ratio of number

Table 1

Statistics of Particle Heating at 41 Interplanetary Shocks Observed Between August 1978 and December 1979

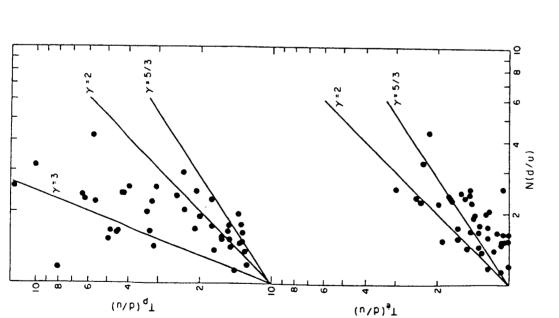| Parameter	Units	Average	Standard Deviation	Low 5%	High 5%
$N(d/u)$	---	1.9	0.6	1.2	3.1
$V(d-u)$	km s^{-1}	76	53	17	225
$T_e(d/u)$	---	1.5	0.5	1.0	2.5
$T_e(d-u)$	10^5K	0.8	0.9	0.0	2.7
$T_p(d/u)$	---	3.3	2.5	1.3	10.0
$T_p(d-u)$	10^5K	1.6	2.2	0.1	9.2

The entries in the last two columns give the second lowest and second highest parameter values from the full set of 41 shocks.

density measured just downstream to that just upstream, $N(d/u)$, is a measure of the shock strength, we explore first how well it orders the data. If particle heating at interplanetary shocks obeys a polytrope law then $\ln[T(d/u)]$ = $(\gamma - 1)\ln[N(d/u)]$ where γ is the ratio of specific heats. Such a law is used sometimes as a guide for interpreting theoretical simulations of collisionless shocks (see e.g. Forslund et al., 1982) and has been found useful for organizing data showing electron heating across high speed stream interaction zones at 1AU (Feldman et al., 1978). The averages listed in Table 1 would then provide estimates of γ for electron and proton heating separately, $(\gamma_e - 1)$ = 0.6 and $(\gamma_p - 1) = 1.9$.

Plots of the ratio of upstream to downstream electron and proton temperatures, $T_e(d/u)$ and $T_p(d/u)$, respectively, against the ratio of proton number density, $N(d/u)$, are given in Figure 1. The solid lines represent polytrope laws having γ = 5/3, 2 and 3 representing adiabatic heating in 3, 2, and 1 dimensions, respectively. Inspection of the plots shows only weak positive correlations between either temperature ratio and the number density ratio. It also shows that a polytrope law does not describe adequately the parametric dependences of particle heating at interplanetary shocks. This conclusion is reinforced by examining the slopes, m, y intercepts, b, and correlation coefficients, r, of the linear regressions between $\ln[T_e(d/u)]$ and $\ln[N(d/u)]$ and between $\ln[T_p(d/u)]$ and $\ln[N(d/u)]$ listed in Table 2. Not only are both correlation coefficients low, $r \sim 0.5$, but the y intercepts are nonzero and the slopes differ substantially from those estimated from the averages given in Table 1.

Table 2

Correlations Between Pairs of Fluid Parameters at 41 Interplanetary Shocks Observed Between August 1978 and December 1979

$$Y = mX + b$$

Y Parameter	Units	X Parameter	Units	m	b	r
$\ln T_e(d/u)$	---	$\ln N(d/u)$	---	0.27	0.16	0.51
$\ln T_p(d/u)$	---	$\ln N(d/u)$	---	1.23	0.22	0.53
$T_e (d/u)$	---	$T_p (d/u)$	---	0.14	1.03	0.75
$T_e (d-u)$	10^5K	$T_p (d-u)$	10^5K	0.29	0.31	0.72
$V(d-u)$	km s^{-1}	$N(d/u)$	---	74.6	-69.0	0.82
$T_e(d-u)$	10^5K	$V(d-u)$	km s^{-1}	0.015	-0.36	0.89
$T_p(d-u)$	10^5K	$V(d-u)$	km s^{-1}	0.035	-1.06	0.83
$\ln T_e(d/u)$	---	$\ln V(d-u)$	km s^{-1}	0.31	-0.94	0.76
$\ln T_p(d/u)$	---	$\ln V(d-u)$	km s^{-1}	0.70	-1.87	0.73

Figure 1. Scatter plots of the ratio of downstream to upstream proton temperatures (above) and electron temperatures (below) against the ratio of downstream to upstream proton number density for 41 forward interplanetary shocks observed at ISEE 3 between August 1978 and December 1979. The solid lines represent polytrope laws with ratios of specific heats, $\gamma = 3$, 2 and 5/3.

Electron and proton heating are more strongly correlated with each other as well as with the difference in bulk velocity across the shocks, V(d-u), than they are with the density jump across the shocks. Scatter plots showing the correlation between electron and proton heating are shown in Figures 2 and 3. Both temperature ratio and temperature difference correlations are roughly equal, r = 0.75 and 0.72 respectively. Although these correlations are significantly better than those between ℓnT and ℓnN, the data in Figures 2 and 3 show substantial scatter. Comparison of the data with the solid lines, which represent equal fractional heating in figure 2 and equal amounts of heating in figure 3, shows that interplanetary shocks heat the protons more than they heat the electons. This condition holds true also for the earth's bow shock (Montgomery et al., 1970).

Electron and proton heating at interplanetary shocks are best correlated with the difference in bulk velocity across the shocks. This velocity difference is also a measure of shock strength as defined by the ratio of downstream to upstream densities, N(d/u). This fact is evident by the good correlation between V(d-u) and N(d/u) shown in Figure 4. The parameters of the linear regression are given in the fifth row of Table 2 showing r = 0.82.

Scatter plots showing the correlations between T_e(d-u) and V(d-u) as well as between T_p(d-u) and V(d-u) are shown in Figures 5 and 6. The parameters of the respective linear regressions are given in rows 6 and 7 of Table 2. Although not shown here, plots of T_e(d/u) against V(d-u) and of T_p(d/u) against V(d-u) show similar correlations. An important property of these correlations is that the shocks having the larger velocity differences are relatively more effective in heating protons than they are in heating electrons. This effect can be seen by comparing Figures 5 and 6 and is quantified in the last 2 rows of Table 2. Specifically the slope for the correlation between ℓnT$_p$(d/u) and ℓnV(d-u) is larger than that for the correlation between ℓnT$_e$(d/u) and ℓnV(d-u).

4) Summary and Conclusions

Detailed comparisons between the foregoing results and the many theories of particle heating at collisionless shocks is not possible since these theories depend importantly on parameters which were not included in the present study. Specifically they depend on the upstream β (ratio of particle pressure to magnetic field pressure), the shock-normal-magnetic field angle, the Mach number, and the conductivity of both the upstream-ambient, and downstream-shocked plasmas. However electron heating at a large set of interplanetary shocks is reported here for the first time. Comparison of the measured heating with the γ = 2 line in Figure 1 indicates that if such heating is confined to two dimensions as many theories predict (see e.g. Tidman and Krall, 1971; Lemons and Gary, 1978; Forslund et al., 1982), then heat conduction must be an important electron cooling mechanism. This conclusion is consistent with that reached previously (Hundhausen and Montgomery, 1971). Finally, the relatively larger efficiency for heating protons at the stronger interplanetary shocks is consistent with theories of ion reflection (Forslund and Shonk, 1970; Auer et al., 1971; Leroy et al., 1982) although to date, no evidence for such reflection has been found (Gosling et al., 1983). This lack of evidence may indicate that few if any of the interplanetary shocks observed at ISEE-3 were supercritical.
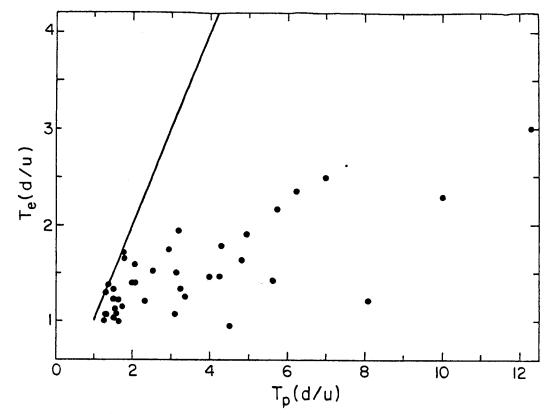
Figure 2. A scatter plot showing the correlation between the ratios of downstream to upstream electron and proton temperatures at 41 forward interplanetary shocks observed at ISEE 3 between August 1978 and December 1979. The solid line represents equal ratios of downstream to upstream electron and proton temperatures.
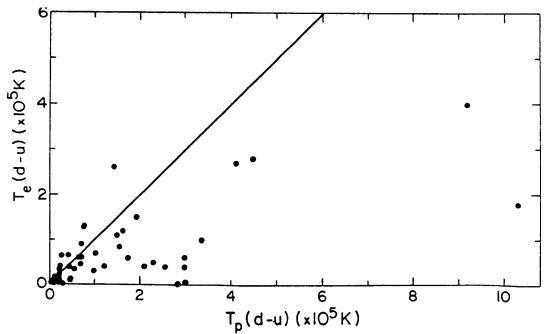

Figure 3. A scatter plot showing the correlation between the amounts of electron and proton heating at 41 forward interplanetary shocks observed at ISEE 3 between August 1978 and December 1979. The solid line represents equal electron and proton heating.
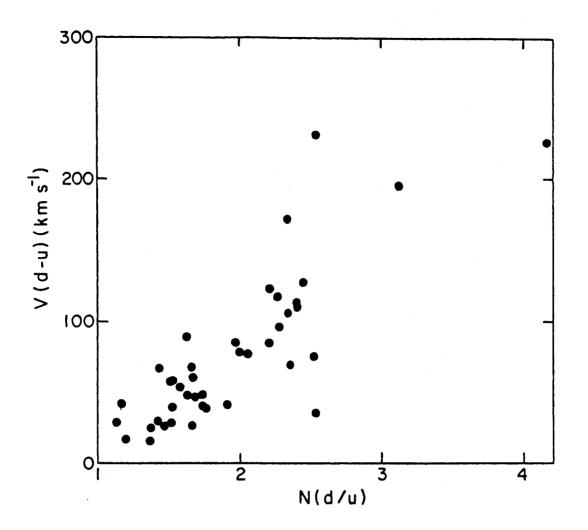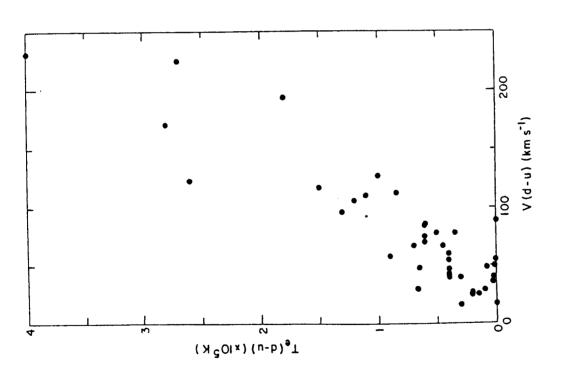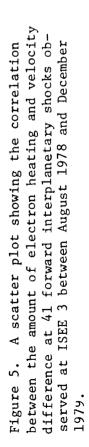
Figure 4. A scatter plot showing the correlation between the velocity differences and ratios of downstream to upstream proton densities at 41 forward interplanetary shocks observed at ISEE 3 between August 1978 and December 1979.

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Figure 6. A scatter plot showing the correlation between the amount of proton heating and velocity difference at 41 forward interplanetary shocks observed at ISEE 3 between August 1978 and December 1979.
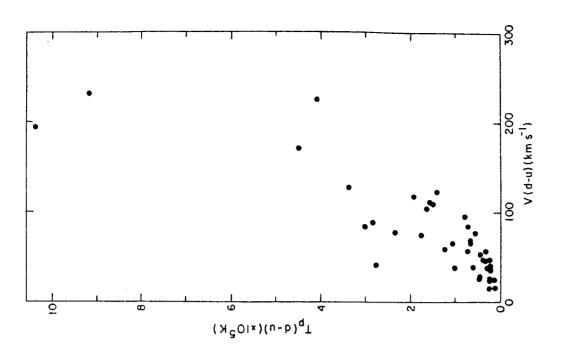

Figure 5. A scatter plot showing the correlation between the amount of electron heating and velocity difference at 41 forward interplanetary shocks observed at ISEE 3 between August 1978 and December 1979.

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