Electron temperature in the ambient solar wind: Typical properties and a lower bound at 1 AU

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Abstract. Our understanding of what controls the solar wind electron temperature is far from complete. Previous studies from the Vela and IMP spacecraft have suggested that twice the proton temperature or an assumed average of ~150,000 K are reasonable estimations of total electron temperature at 1 AU. Eighteen months of continuous ISEE 3 solar wind data are analyzed in this paper and are found to have a mean electron temperature of 141,000 ± 38,000 K, in good agreement with past measurements. No correlation is found between electron temperature and other solar wind parameters, including proton temperature. However, a very distinct lower bound on the electron temperature is found; this bound increases with proton temperature and is observed by both ISEE 3 and Ulysses spacecraft. The bound is also found to vary with bulk solar speed of the solar wind and with distance from the Sun. Solar wind plasma observed following stream interactions are often associated with temperatures near this bound, and enhanced electromagnetic wave activity in the 18-100 Hz range is coincident with intervals where this apparent temperature coupling is observed, suggesting the possible presence of wave-particle interactions. Possible explanations for the existence of this electron temperature bound are explored, but no definitive answer has been found at this time.

1. Introduction

The condition of quasi-neutrality leads to correlations between average densities and velocities of protons and electrons in the ambient solar wind. However, correlations between proton and electron temperatures are not expected to be found in this medium. The protons expand nearly radially from the Sun at supersonic speeds, and their bulk velocity greatly exceeds their thermal speed. Thus the protons lose "contact" with the solar corona. In contrast, the electrons have thermal velocities that greatly exceed the solar wind bulk velocity, so the electrons move principally along magnetic field lines and maintain contact with the solar corona as they drift outward with the solar wind protons. Also, the high thermal conductivity of electrons rapidly "smoothes out" any spatial or temporal fluctuations in electron temperature which may be created by interplanetary shocks or stream interactions, whereas proton temperatures remain at disturbed levels for longer periods.

Solar wind electron measurements are generally more difficult to make than measurements of their proton counterparts. They can be drastically affected by a spacecraft's potential (Scime et al., 1994a), and electron measurements are not always made by spacecraft which are observing the solar wind, despite the fact that knowledge of the electron temperature is indispensable in order to characterize the properties of the plasma. Thermal pressure and the sound speed (and hence plasma β and sonic and magnetosonic Mach numbers) are strongly dependent on electron temperature, as are the Rankine-Hugoniot shock jump conditions. An obvious question arises: What is the best estimation for electron temperature in the solar wind when no spacecraft observations are available? In this situation an educated guess must be made, since electrons make a major contribution to the upstream solar wind conditions, but there are conflicting suggestions as to what sort of guess to make. Previous studies near 1 astronomical unit (AU) have suggested either a constant electron temperature of ~150,000 K or an electron temperature that is twice the concurrent proton temperature (e.g., Feldman et al., 1977; Montgomery, 1971).

In this study, observations made by the ISEE 3 solar wind monitor near 1 AU are used to examine the relationship between electron temperature and other solar wind parameters. We reaffirm the constancy of average electron temperature and find that the best educated guess for the average electron temperature is indeed a constant ~141,000 K, in agreement with Feldman et al. [1977]. We show that relating electron
temperature to twice the proton temperature is generally a poor approximation. In addition, we find important but puzzling exceptions which suggest that there is occasional coupling between protons and electrons. This apparent coupling is exhibited in the form of a distinct lower bound to the electron temperature, which increases with proton temperature. The nature of this bound is further examined with ISEE 3 data and with observations made by the Ulysses spacecraft during its journey in the ecliptic plane.

The relative constancy of the solar wind electron temperature near 1 AU was established with the Vela 4B satellite. Twenty hours of data sampled over a 2 month observation period suggested the basic characteristics of solar wind electron behavior [Montgomery et al., 1968]. Electron temperatures \( T_e \) were observed over a range of 70-8000 eV, which for the prevailing proton temperatures \( T_p \). Electron temperatures were also observed to fluctuate much less than proton temperatures, and electron temperature anisotropies were significantly less (and never greater) than corresponding proton anisotropies. Thermal energy conducted by the electron component flowed in the direction of maximum proton temperature, that is, along the interplanetary magnetic field (IMF). Also, the magnitude of the thermal energy flow was observed to depend strongly on the electron temperature.

Hundhausen and Montgomery [1971] showed that the high conductivity of electrons allows their temperatures in the solar wind to remain relatively constant. The energy equation for solar wind electrons is dominated by the heat conduction term which rapidly smoothes out any spatial or temporal fluctuations in the electron temperature. As the solar wind expands, electron temperature cools slowly with radial distance, and the solar wind electrons remain in good thermal contact with the solar corona along the IMF.

Extended observations of solar wind plasma reaffirmed the initial Vela electron observations. Montgomery [1971] focused on the thermal properties of electrons and protons relative to solar wind bulk speed. For low solar wind speeds an electron-to-proton temperature ratio of \( T_e/T_p \approx 4 \) was found to be a good average, while the overall \( T_e/T_p \) averaged for typical bulk speeds (\( \sim 400 \) km/s) was determined to be 2. The IMF 6, 7, and 8 spacecraft provided further opportunity to study electrons in the solar wind. Feldman et al. [1977] summarized a large variety of solar wind plasma properties at 1 AU based on 3 years of IMP data. In particular, the mean electron temperature was found to be \( 1.4 \pm 0.4 \times 10^5 \) K. Electrons were again verified to be generally isotropic, and the average ratio of \( T_e/T_p \) was 2.0 \( \pm 1.3 \).

Occasionally, the assumption that the solar wind electron temperature is twice the concurrent proton temperature appears in the literature. In this paper we will show that a constant \( T_e = 141,000 \) K is a better approximation near 1 AU, regardless of other concurrent solar wind plasma conditions. We also examine the lower bound of observed electron temperature as a function of proton temperature and find that this lower bound is particularly distinct and varies with bulk speed and with radial distance. Possible physical (and instrumental) mechanisms that could result in such a bound are explored but cannot be explained conclusively at this time.

2. Instrumentation and Data Analysis

2.1. ISEE 3 and Ulysses

In this paper we utilize the plasma and magnetic field observations made by the ISEE 3 solar wind monitor and by Ulysses. Although not contemporaneous, the ISEE 3 and Ulysses data sets provide complementary samples of the solar wind. ISEE 3 monitored the solar wind from 1 to 4 AU, Ulysses measured the heliocentric distance (1 AU), and the early phase of the Ulysses mission provides a radical cut of solar wind observations in the ecliptic plane from 1 to 3.4 AU. ISEE 3 was placed in a halo orbit about the sunward Lagrangian point, where it continuously observed the solar wind from August 1978 through September 1982 (after which time it was moved to the Earth's geomagnetic tail). This orbit, \( \sim 235 \) R\(_S\) sunward of the Earth, minimizes magnetic connection to the Earth and is far more favorable than an Earth orbit for solar wind plasma measurements. Energetic particles from the bow shock, foreshock, and magnetosphere are observed to be streaming away from the Earth whenever a satellite is magnetically connected to the shock, a common occurrence for an Earth-orbiting spacecraft [e.g., Klimas, 1985]. This can result in an artificially high measurement of total electron temperature. The orbit of ISEE 3 significantly reduced this contamination (but did not entirely eliminate it) [Stanberry et al., 1988; Feldman et al., 1989].

Los Alamos' Solar Wind Experiment (SWE) on ISEE 3 consisted of two electrostatic analyzers: one for electron measurements and the other for proton measurements. Particles entered spherical section apertures and were analyzed according to their energy-to-charge ratio by applying voltage sweeps across the plates. Two-dimensional plasma electron data are composed of 15 energy level count rate samples ranging from 8.5 to 1440 eV. Each level was measured at 16 azimuthal angles which span 360° about the spacecraft spin plane (nearly aligned with the ecliptic plane). A two-dimensional electron distribution measurement representing a 3 x spacecraft spin was made every 84 s. To correct for effects due to the ISEE 3 spacecraft potential, every 70 min a second set of 15 energy levels (ranging from 1.9 to 186 eV) was used to measure the energy spectrum of photoelectrons. Proton data were obtained in 32 contiguous energy per charge (E/q) levels at 22 azimuths spaced at 2.78° intervals centered on the sunward direction. A complete two-dimensional measurement of the proton distribution was made in two spacecraft spins (6 s) and repeated at 24 s intervals. The Los Alamos ISEE 3 plasma electrostatic analyzers are described in detail by Reme et al. [1978].

Magnetic field data are used to aid in the identification of interplanetary shocks, coronal mass ejections, and stream interactions. The Jet Propulsion Laboratory vector helium magnetometer on ISEE 3 provided measurements of the three components of the IMF, which were sampled six times per second. A description of experimental details is given by Frandsen et al. [1979].

Plasma wave data from ISEE 3 are also used to identify potential intervals where plasma instabilities may be active. The Plasma Wave Experiment consisted of two electric dipoles used to measure magnetic wave levels from 17 Hz.
te 1 kHz in eight channels and electric levels from 17 Hz to 90 kHz in 16 channels [see Scarf et al., 1978].

Ulysses plasma data are from the Los Alamos experiment, Solar Wind Observations Over the Pole of the Sun (SWOOPS), which is a three-dimensional (3-D) electrostatic analyzer covering the energy range 1.6-862 eV in 20 logarithmic steps. An electron energy spectrum is measured in 2 min, and every third distribution is fully three-dimensional. All Ulysses observations used in this paper are based on 3-D measurements. In this paper we consider SWOOPS data recorded during the spacecraft’s journey in the ecliptic plane from the Earth to 4 AU (November 18, 1990, through August 25, 1991). The density of plasma observed from 4 to 5.4 AU was generally too low to make accurate measurements of the electron distribution [B. Goldstein, private communication, 1997], and we also avoid intervals where electron and proton densities are noticeably different (not a significant portion of the 1-4 AU data set). SWOOPS is discussed in detail by Bame et al. [1992].

Unlike the ISEE 3 data, the 3-D Ulysses distributions have been corrected for spacecraft charging effects with a technique by Scime et al. [1994a] which corrects electron trajectories that are deflected by the sheath of photoelectrons. This correction dramatically improves the gyrotropy of the observed electron distributions, which in turn affects the moment calculations, particularly density and bulk speed. The existence of quasi-neutrality is much clearer in the corrected data set, as is the condition of zero net current from the Sun [cf. Scime et al., 1994a, Figures 9 and 11]. The effect on plasma temperature, although not nonexistent [Scime et al., 1994b], is not as dramatic at 1 AU. As we show in Section 3, the temperatures measured by uncorrected ISEE 3 and corrected Ulysses (around 1 AU) are not significantly different.

2.2. Plasma Distributions and Reduction

Solar wind electron distributions are generally described by a superposition of two separate populations: a relatively cool core population (denoted by the subscript c) and a diffuse, hot halo population (subscript h) [Feldman et al., 1975]. The bulk of the electron distribution resides at low energies in the core. Occasionally, a focused, hot strahl component (subscript s) is superimposed on the halo, streaming outward from the Sun along the IMF [Rosenbauer et al., 1977]. The presence of a strahl is interpreted as evidence of direct magnetic connection to the hot, coronal source of electrons, whereas the roughly isotropic halo distribution results from the scattering of strahl electrons over spatial scale lengths of the order of many astronomical units [Scudder and Oster, 1979a, b].

The total velocity distribution function is the sum of these three component distributions: $f_T(v) = f_c(v) + f_h(v) + f_s(v)$. The core distribution $f_c(v)$ has been modeled as a connecting bi-Maxwellian function. Diffuse halo electrons have been modeled as a bi-Maxwellian function and as the product of a modified Lorentzian energy function and an expansion to the fourth order of Legendre polynomials. Strahl populations have been fit by a bi-Maxwellian function with an origin offset in velocity space (and the constraint that the strahl electrons must move antisunward). The data reduction method for ISEE 3 electrons is discussed in more detail by Feldman et al. [1982].

Plasma parameters used in this study (namely, velocity, density, and temperature) are standard integrated moments of the observed electron and proton fluxes [Feldman et al., 1975]. Maximum and minimum temperatures are calculated separately for each of the three distribution components based on the symmetry axes of the distributions without reference to the concurrent IMF vector. The temperature along the major axis of the temperature ellipsoid for a particular distribution is referred to as $T_L$ (generally, but not always, parallel to the IMF), and the temperature normal to that axis is $T_T$ [Philips et al., 1989]. The perpendicular, parallel, and total temperatures are determined by the temperature of the component distributions, normalized according to component density $n$:

$$T_L = T_L A(n_c/n_c) + T_H A(n_h/n_h)$$

(1)

$$T_T = T_L A(n_c/n_c) + T_H A(n_h/n_h) + T_S A(n_s/n_s)$$

(2)

The total temperature is defined to be

$$T_T = \frac{1}{2} T_L + \frac{1}{3} T_T$$

(3)

which is a reasonable assumption given the low degree of anisotropy in solar wind electron distributions. This study utilizes 5 min averages of ISEE 3 data collected during the period of time when both the proton and electron SWE instruments were operational, from August 16, 1978, through March 4, 1980.

2.3. Determination of “Ambient” Solar Wind

In order to characterize ambient solar wind, it is necessary to separate solar wind observations from anomalous phenomena. The most notable effects on electron temperature are found in association with coronal mass ejections (CMEs) and interplanetary (IP) shocks.

2.3.1. Coronal mass ejections. CMEs are easily identified by the presence of bidirectional electron heat flux [Bame et al., 1981]. Gosling et al. [1987] provide a thorough analysis of the characteristics of CME plasma observed by ISEE 3 and find that total electron temperatures in a CME are slightly cooler than average solar wind. The lower temperatures generally seen in coronal mass ejections are qualitatively explained by the greater expansion of a CME compared to the surrounding ambient plasma. Another statistical study reported more variable behavior of electron temperature in CMEs [Richardson et al., 1997].

A total of 54 CME events was identified during the August 1978 to February 1980 interval. Event durations range from less than an hour to more than 40 hours and typically last 12 hours. CME-associated plasma accounts for ~5% of all data collected by ISEE 3 during this period.

2.3.2. Interplanetary shocks. IP shocks are identified by simultaneous jumps in magnetic field, plasma density,
velocity, and temperature. Figure 1 contains a typical IP shock observed by ISEE 3 at 0300 UT on January 9, 1979. The electron temperature is rapidly cooled to its original preshock value, apparently "oblivious" to the large fluctuations occurring simultaneously in the proton parameters and the magnetic field magnitude. Because of the dominance of the electron thermal conductivity term in the electron energy equation, electrons will promptly cool to ambient temperatures [Hundhausen and Montgomery, 1971].

Thomsen et al. [1987] have studied heating at the bow shock and find that the electrons gain only a fraction of the energy lost by the bulk motion of the ions (as also seen in Figure 1). This temperature jump can be qualitatively (quantitatively, at low Mach numbers) explained in terms of the path the electrons take while crossing the shock [Goodrich and Scudder, 1984; Friedman et al., 1990].

We define the end of the shocked plasma interval to be the approximate time when plasma parameters return to undisturbed levels. Because of the large difference in conductivity between protons and electrons, the point where plasma is no longer disturbed differs for the various solar wind parameters, making it difficult to determine the "end" of shocked plasma. For example, in Figure 1 the interval of shocked plasma was defined to be from 0300 UT on January 9 through 0400 UT on January 10, although the electron parameters relax in a shorter time period. Variations in the ambient solar wind and the proximity of a shock to other solar wind phenomena add to this difficulty. In the case of a shock associated with the arrival/departure of a CME, the period of time from the shock ramp to the advent/conclusion of the CME event was defined to be the interval of shocked plasma. Since our primary concern is to remove shocked plasma from the data set rather than to thoroughly study the characteristics of the shocked plasma itself, we used somewhat liberal judgment to identify regions of shocked plasma. Undoubtedly, a small amount of unshocked plasma was removed from the data set in the process, but this is negligible given the large size of the ISEE 3 solar wind data set.

In all, 59 IP shocks were identified with ISEE 3, including four reverse shocks. Of these shocks, 60% were associated with CMEs [Gosling et al., 1987]. The duration of shocked plasma lasted between 6 and 60 hours and averaged ~18 hours. This shocked plasma accounts for ~9% of the total ISEE 3 solar wind data set.

2.3. Ambient solar wind. The ISEE 3 solar wind observations that remain after the intervals of shocked plasma and CMEs have been removed are defined as "ambient." The ambient data set includes observations of other solar wind phenomena, including stream interactions. A histogram of bulk speed for the ambient plasma data set is displayed in Figure 2. For the purposes of comparison, ambient solar wind is defined to be "high-speed" when proton velocity \( V_p > 475 \text{ km/s} \), "low-speed" when \( V_p < 350 \text{ km/s} \), and "intermediate" for \( V_p \) in between these limits.

3. Electron Temperature Average Properties

Once the ambient solar wind plasma has been isolated, the statistical distribution of electron temperatures can be compared with the entire ISEE 3 data set, the shocked plasma, and the CME plasma. Figure 3 contains such a comparison, and Table 1 lists the mean electron and proton temperatures with standard deviations for these classifications of solar wind. Apart from a slightly narrower distribution, there is no significant change between the ambient plasma data set and the entire ISEE 3 data set. The shocked plasma has a hotter, wider distribution compared with the entire data set, and the CME plasma is distinctly colder. These results conform with shock and CME expectations and agree with previous observations from other spacecraft [e.g., Feldman et al., 1977; Gosling et al., 1987]. After the passage of an IP shock the electron temperature is elevated; in a CME the electrons are cooler than in the ambient solar wind.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** An interplanetary shock observed by the ISEE 3 solar wind monitor. \( V_p \) promptly returns to its original preshock level despite large fluctuations in the proton and magnetic parameters.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Histogram of ambient solar wind bulk speed as observed by ISEE 3. Solar wind is classified as "fast" when \( V_p > 475 \text{ km/s} \), "slow" if \( V_p < 350 \text{ km/s} \), and "intermediate" if \( V_p \) lies between these limits.
In Section 1 we posed the question, What is the optimum educated guess one can make for total electron temperature in the solar wind? To answer this question, Figure 4 presents plots of electron temperature distributions versus various other solar wind parameters. The mean electron temperature remains constant regardless of proton temperature, bulk velocity, and density. In addition, the 5% and 95% levels of the T_e distributions remain constant, indicating that the overall distribution of electron temperatures is essentially unchanged. Table 2 also lists mean temperatures and standard deviations for the high, low, and intermediate-velocity solar wind.

Figure 5a compares the distribution of electron and proton temperatures as a function of bulk speed. The overall distributions of electron temperature is much narrower in comparison with the proton temperature distribution. Figure 5b shows that the apparent dependence of the T_e/T_p ratio on bulk speed is simply a reflection of the relationship between T_e and bulk speed [Burlaga and Ogilvie, 1973].

As seen in Table 2, the mean ratio of electron temperature to proton temperature is ~2 for typical solar wind speeds. This is in agreement with reports by Montgomery [1971] and Feldman et al. [1977]. However, given the large degree of proton temperature deviation and the relative constancy of electron distributions, the assumption that electron temperature is generally twice the concurrent proton temperature is not the most accurate. The best educated guess one can make for electron temperature in the solar wind at 1 AU is a constant value of 144,000 K with a standard deviation of 38,000 K. This is not to say that the electron temperature is strictly constant, rather only that it is not influenced by other concurrent parameters in the ambient solar wind. This independence makes it difficult to improve upon our educated guess for electron temperature.

Ulysses, of course, observes cooler plasma as a function of heliospheric distance. In the vicinity of 1 AU, electron measurements by Ulysses (which have been corrected for sheath focusing effects [Stone et al., 1994a]) agree with ISEE 3 and IMP electron observations (well within a standard deviation). Using 19 days of ambient plasma observations from 1.15 to 1.34 AU, Ulysses measured the fol-

Table 1. Temperature Means and Standard Deviations

<table>
<thead>
<tr>
<th></th>
<th>(T_e ± σ) x 10^5 K</th>
<th>(T_p ± σ) x 10^5 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>All ISEE 3 observations</td>
<td>1419 ± 4.4</td>
<td>1031 ± 6.33</td>
</tr>
<tr>
<td>Ambient solar wind</td>
<td>1450 ± 3.80</td>
<td>930 ± 7.40</td>
</tr>
<tr>
<td>Shocked plasma</td>
<td>1535 ± 3.69</td>
<td>1610 ± 4.47</td>
</tr>
<tr>
<td>CMEs</td>
<td>1221 ± 4.19</td>
<td>540 ± 5.01</td>
</tr>
</tbody>
</table>

CME, coronal mass ejection.
Figure 4. Independence of $T_e$ from other solar wind parameters (from ISEE 3 ambient solar wind observations): Mean $T_e$ and the 5% and 95% levels of the $T_e$ distribution are plotted versus bins of (a) proton temperature, (b) proton density, (c) proton velocity, and (d) magnetic field strength. The horizontal lines indicate the mean $T_e$ determined from the ISEE 3 ambient data set (141,000 K).

Lower average temperatures: $T_e = (14.7 \pm 2.8) \times 10^4$ K, $T_e = (11.1 \pm 3.1) \times 10^4$ K, and $T_e = (7.5 \pm 2.0) \times 10^4$ K.

For comparison, IMPs measured $T_e = (14 \pm 4) \times 10^4$ K, $T_e = (12.5 \pm 2.9) \times 10^4$ K, and $T_e = (6.9 \pm 1.1) \times 10^4$ K [Feldman et al., 1977]. At greater heliocentric distances, differences between shreds-corrected and uncorrected temperature calculations are more pronounced [Scime et al., 1994b].

4. Lower Bound of $T_e/T_p$

In Section 3 it has been established that, on average, electrons are independent of other properties of the solar wind. Because of the low-electron, high-thermal conductivity and very high thermal velocities of electrons, one might expect no (or only a very weak) correlation between electron and proton temperatures in the ambient solar wind. However, upon closer examination we have found such a correlation. The electron temperature has a lower bound which increases with proton temperature. This correlation is most clearly seen within a plot of electron temperature versus proton temperature from the ISEE 3 ambient solar wind data set (Figure 6). With over 18 months of observations a wide range of $T_e$ versus $T_p$ parameter space is sampled in Figure 6. The very sharp lower bound on $T_e$ is unexpected and seems to suggest that electron and proton temperature can, at times, be coupled. The minimum observed $T_e$ increases linearly as a function of $T_p$, such that

$$T_e = c + dT_p + e$$

where $c$, $d$, and $e$ are the slope and intercept fitting parameters, respectively.

The fitting parameters in equation (4) are observed to change with solar wind conditions. Figure 7 shows how $c$, $d$, and $e$ vary inversely with solar wind bulk speed. The slope of the $T_e/T_p$ bound ranges from $-0.47$ in the slow solar wind to $-0.25$ for high speeds. The data displayed in Figures 7a are simply the superposition of the slow, intermediate, and fast solar wind data sets (Figures 7b, 7c, and 7d); thus the $T_e/T_p$ bound for the entire data set corresponds to the bound in the fast solar wind data set. In all cases the slope of the bound is less than unity. Protons are generally much hotter than the simultaneous measurement of electrons for the observations which define this bound. In Sections 4.1-4.6 we examine possible explanations for this phenomenon and further investigate the nature of the plasma that corresponds to the data points which form the lower bound illustrated in Figures 6 and 7.

<table>
<thead>
<tr>
<th>$V_p$ km/s Range</th>
<th>$(T_e \pm \sigma) \times 10^4$ K</th>
<th>$(T_p \pm \sigma) \times 10^4$ K</th>
<th>$T_e/T_p \pm \sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>14.1 \pm 3.8</td>
<td>9.9 \pm 7.4</td>
<td>2.3 \pm 1.7</td>
</tr>
<tr>
<td>High-speed</td>
<td>$V_p \geq 475$</td>
<td>14.2 \pm 3.6</td>
<td>17.8 \pm 8.9</td>
</tr>
<tr>
<td>Middle-speed</td>
<td>$330 &lt; V_p &lt; 475$</td>
<td>14.6 \pm 3.8</td>
<td>9.5 \pm 5.4</td>
</tr>
<tr>
<td>Low-speed</td>
<td>$V_p &lt; 330$</td>
<td>12.9 \pm 3.7</td>
<td>4.5 \pm 2.7</td>
</tr>
</tbody>
</table>
4.1. Instrumental Effects

The very distinct nature of the bound in Figure 6 raises the suspicion that the phenomenon could be an instrumen-
tal artifact rather than a physical effect. However, we have
been unable to find an instrumental explanation for the lower
bound on $T_e$. We have examined a large number of individ-
ual distribution functions observed during the apparent $T_e$:
$T_p$ coupling conditions as well as during average solar wind
conditions and see no abnormalities that could account for
our observations. Three examples of slices from the 2-D
electron plasma distributions are displayed in Figure 8: one
observed at the $T_e$ lower bound (Figure 8a) and two observed
during more “typical” solar wind conditions (Figures 8b and
8c). Slices are arbitrarily taken along a 90° angle to the GSE
x direction and not in reference to the IMF. The 2-D distri-
butions (not displayed) are quite isotropic in all cases. To-
tal electron temperatures and densities are quite close in the
December 3C, 1978, and August 29, 1978, distributions, and
the August 14, 1978, distribution shows “normal” solar wind
with similar temperature but higher density. In particular, the
distributions show that photoelectrons have been adequately
removed from the electron data.

Spacecraft charging effects, which are associated with low
plasma densities, could theoretically induce errors which
would increase $T_e$. To eliminate this possibility, we repeated
our study, limiting the data set to proton densities >5/cm$^3$
and to intermediate bulk speeds, and the intermediate $T_e$
lower bound found in Figure 7c was still reproduced (Fig-
ure 9). (The high-speed $T_e$ lower bound seen in Figure 7d
is only resolved at a low $v_p$ when $v_p$ > 5/cm$^3$. By limit-
ning the density, most high speed streams are eliminated. As
discussed in Section 4.4, there is a correlation between the
high-$v_p$ $T_e$ bound and high-speed solar wind streams.)

Figure 5. (a) Electron and proton temperatures versus bulk
speed from ISEE 3 ambient solar wind observations, with
5% and 95% distribution levels. (b) The dependence of
$T_e/T_p$ on $v_e$ is due to the relationship between $T_e$ and $v_p$.

Figure 6. $T_e$ versus $T_p$ for ambient ISEE 3 solar wind measured from August 11, 1978 to February 17,
1980. Each data point corresponds to a 5 min average of solar wind data. Note the distinct cutoff relation
creating a lower bound on $T_e$ as a function of $T_p$. 
4.2. Statistical Sampling

We also need to examine the possibility that the lower bound is a statistical effect. One could imagine that for average solar wind proton temperatures, a large number of observations would be available, and statistically there would be some observations at especially low $T_e$. Within a higher $T_p$ bin, there would be fewer observations, and hence there is statistically less of an opportunity to observe very low electron temperatures. Given this scenario, the mean $T_e$ could...
remain constant across all $T_e$ bins, but the tails of the $T_e$ distribution would increase as $T_e$ increases and as the number of data points in each $T_e$ bin decreases. This could explain the lower bound seen in Figure 6.

The bins in the histograms in Figure 4 are too large to display the bound, so the plausibility of this statistical explanation is explored in Figure 10, which contains statistical representations of Figures 6 (the entire ambient data set) and 7d (high-speed solar wind data set) and displays the mean, median, 5% level, 95% level, maxima, and minima of the distributions of electron temperature within bins of proton temperature. Figures 10a and 10c display the number of data points in each $T_e$ bin. Note that when the bin count is below ~100 data points, mean and median levels diverge, and the bin sampling is too low for accurate statistics. If we restrict our analysis to the $T_e$ range where the bin count is sufficiently high ($T_e < 350,000$ K), we observe a constant mean/median $T_e$ and roughly equidistant 5% and 95% distribution levels from the mean. This suggests that the bulk of the $T_e$ distribution is unchanged as $T_e$ increases. If the lower bound is merely a result of statistical probability, one would expect that the high-speed solar wind data set (which has nearly an order of magnitude fewer data points in its $T_e$ bins) would have a steeper minimum $T_e$ curve than that for the entire ambient solar wind data set. This is clearly not the case: In Figures 10b and 10d the minimum curve (the temperature bound) is the same.

4.3. Observations with Ulysses

The same effect on the lower bound of $T_e$ is found in the Ulysses data set. Ambient solar wind data observed by Ulysses in the ecliptic plane from 1 to 4 AU are plotted in Figure 11 in the $T_e$ versus $T_p$ format. Each data point corresponds to an average over an hour of plasma observations. When the data set is subdivided according to distance from the Sun, a different picture of the lower bound emerges: When Ulysses was close to 1 AU, the slope $\tau_p$ and intercept of the lower bound $T_{ei}$ are nearly identical to those observed by ISEE 3 (compare Figure 11b with Figure 6). As Ulysses travels towards Jupiter, $\tau_p$ appears to steepen and $T_{ei}$ decreases (which is consistent with the fact that the solar wind cools as it travels away from the Sun). Solar wind bulk speed does not vary with heliocentric distance, so this suggests a second variable governing the lower bound. The lack of sampling of $T_e$ versus $T_p$ parameter space makes it difficult to reliably quantify this variation in the bound as a function of radial distance.

Figure 8. Slices of 2-D electron plasma distributions from ISEE 3. From the $T_e$ lower bound on (a) December 30, 1978, 11:36 UT ($n_e = 714$ km/s, $T_e = 59.7 \times 10^3$ K, $T_p = 16.6 \times 10^3$ K, and $n_b = 3.09$ cm$^{-3}$): From more typical solar wind, on (b) August 29, 1978, 09:34 UT ($n_e = 530$ km/s, $T_e = 13.9 \times 10^3$ K, $T_p = 16.7 \times 10^3$ K, and $n_b = 3.4$ cm$^{-3}$) and (c) on August 16, 1978, 20:06 UT ($n_e = 326$ km/s, $T_p = 7.1 \times 10^3$ K, $T_e = 17.5 \times 10^3$ K, and $n_b = 8.4$ cm$^{-3}$).
4.4. Occurrence in High-Speed Streams

Solar wind plasma observations which correspond to the data points along the $T_e-T_p$ lower bound are not typical plasma: on average, proton temperatures are not significantly greater than electron temperatures in the solar wind at 1 AU. In addition to the bulk speed and heliocentric distance dependencies noted previously, plasma observations near the $T_e$ lower bound also generally coincide with a somewhat lower-than-average proton density of $\approx 3.3/\text{cm}^3$ (where $7.7/\text{cm}^3$ is a typical solar wind density [Feldman et al., 1977]). These plasma characteristics are most commonly observed in association with high-speed streams in the solar wind ($39 \pm 0.6/\text{cm}^3$ [Feldman et al., 1976]). When bound data are compared with the ISEE 3 temporal profile, it becomes obvious that periods when prolonged conditions of lower-bound $T_e$ are observed most often occur in high-speed streams (Table 3). In particular, there appears to be a correlation between lower bound data and proton cooling following a stream interface.

A solar wind stream interface is identified by an increase in plasma density followed by a sharp density decrease, a
sharp increase in proton temperature, and a small increase in bulk flow speed occurring on the rising speed portion of a high-speed stream. This characteristic flow pattern is consistent with a coronal structure in which a high-speed plasma stream overtakes and compresses slower moving plasma ahead of it while simultaneously overrunning and rarefying the plasma behind it (Barliaga, 1974; Gosling et al., 1972). Protons generally behave adiabatically at stream interfaces (Newbury et al., 1997), and electrons at the stream interface are significantly heated in the compression zone. The electron temperature which results from this heating reflects the competition between heat loss due to conduction and heat gain due to compression (Feldman et al., 1978a, b).

In Figure 12a this characteristic plasma flow pattern is illustrated with an ISEE 3 observation of a stream interface followed by a high-speed stream. In this example a particularly large amount of heating is experienced at the stream interface by both protons and electrons, and wide ranges of \( T_p \) and \( T_e \) are observed. Particularly intriguing is the way in which protons and electrons cool following the stream interface. Figure 12b contains a hodogram of \( T_p \) versus \( T_e \) for the 6-day interval displayed in Figure 12a. Once the protons reach a maximum temperature of \( \sim 800,000 \text{ K} \), electrons and protons simultaneously cool in such a way as to lie generally along the \( T_e \) lower bound for high-bulk-speed plasma (as in Figure 7d). About 50% of the data points which make

![Figure 11](image.png)

**Table 3.** Occurrence and Duration of Plasma Observations Corresponding to \( T_e \) Lower Bound

<table>
<thead>
<tr>
<th>High Speed Stream Near CME Following an IP Shock</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of lower bound data set</td>
<td>47.2</td>
</tr>
<tr>
<td>Number of intervals</td>
<td>20</td>
</tr>
<tr>
<td>Average duration of bound interval, hours</td>
<td>13.3</td>
</tr>
</tbody>
</table>

IP, interplanetary.
Figure 12. (a) Plasma parameters observed by ISEE 3 during a stream interface and high-speed stream. The profile is typical for such an interaction, although the degree of proton and electron heating is especially large in this example. (b) Hodogram of $T_e$ versus $J_e$ during the interval displayed in (a). Note how the plasma appears to cool along the $T_e$ lower bound displayed in Figure 7d.

up the high‐bulk‐speed bound are observed following high‐speed stream interfaces. (As listed in Table 3, other extended periods of $T_e$ bounded data points were observed within 24 hours of the passage of a CME or an IP shock, and ∼15% of lower‐bound data do not appear to be associated with any particular solar wind phenomenon.) Observations following less dramatic, but still identifiable, interactions with mid‐speed streams can be seen at the intermediate‐bulk‐speed bound. This correlation with stream interactions is highly suggestive, but we have no explanation for a possible mechanism involving stream interactions and resulting in the $T_e$ lower bound at this time.

4.5. Coincidence with Wave Activity

Perhaps most suggestive of a physical source for this effect is the presence of enhanced electromagnetic wave activity during the intervals when the electron temperature limit is observed. Intense activity in the 17.8‐100 Hz channels of the B field antenna from the ISEE 3 plasma wave experiment is consistently present, suggesting that some type of plasma instability may be in action. Whether or not that instability relates to the electron temperature bound is another matter. This whistler mode turbulence is commonly associated with IP shocks and with high‐speed streams in the solar wind (Connerney et al., 1982; Lengel‐Frey et al., 1996), and a number of potential sources have been suggested.

Figure 13 presents an example of this wave activity, as observed by ISEE 3. Also shown in Figure 13 are the total magnetic field and the $T_e/T_B$ ratio for the same interval, which corresponds to the end of a high‐speed stream when electron and proton observations lie near the lower bound seen in Figure 6. Downward wave activity is observed in the 17.8‐56.2 Hz channels at this time. Often this wave activity is associated with gyrofrequency [Lengel‐Frey et al., 1996], but this does not appear to be the case during this interval. The magnetic field strength (and hence the gyrofrequency) varies little, whereas the wave activity does.

Two common sources of whistlers, the electron heat flux instability and the whistler anisotropy instability, depend on anisotropic electron distributions [Gary et al., 1994]. However, a cursory examination of ISEE 3 electron distribution functions during intervals where the $T_e$ lower bound is observed does not suggest that this is the case. Since the most common proton instabilities in the solar wind are nonresistant with the electrons (electromagnetic ionization, for example), they are independent of electron temperature and also do not appear to apply to the problem at hand [Schwartz, 1980; Gary, 1993].

The presence of wave activity suggests the influence of a plasma instability, but clearly, a more detailed examination of plasma distribution functions must be made in order to determine potential sources of free energy and to determine which instability might arise. If one assumes that the bound described by equation (4) is due to microinstabilities and that
electron heat flux is the primary source of free energy, the bound is indeed due to heating of $T_e$ (rather than a cooling of $T_i$). With particle scattering in a stochastic process, which leads to an increase of the temperature of a species. This will be the subject of a future study.

4.6. Collisions

Finally, we should also ask if particle collisions between electrons and protons could possibly explain the observed lower bound. Previous studies have shown the influence of electron-electron collisions on isostropping the core temperatures of electrons [Phillips et al., 1989; Phillips and Gosling, 1990]. However, a major portion of $T_e$ lower bound observations occurs during the transition regions of high-speed streams where density is low. Phillips and Gosling [1990] have shown that electron-electron collisions have little effect on isostropping temperatures in such regions. Any proton-electron collisions would be even less likely to occur than would electron-electron collisions; thus a collisional explanation for the observed $T_e$ versus $T_p$ coupling would not be expected in such a low-density environment.

5. Conclusions

In this study of IEEE 3 solar wind observations near 1 AU, 16 continuous months of solar wind data were analyzed in order to examine average and extreme properties of solar wind electron temperatures. After removing plasma from the data set that corresponds to known coronal mass ejections and interplanetary shocks, the remaining “ambient” plasma was found to have a mean total electron temperature of 141,000 ± 38,000 K. This result is in agreement with measurements from past spacecraft near 1 AU [e.g., Feldman et al., 1977; Montgomery, 1971].

No correlation is found between average electron temperature and other solar wind parameters. Distributions of electron temperatures are nearly identical for fast, intermediate, and slow solar wind speeds. Correlation of the $T_e/T_p$ ratio with solar wind speed is merely a reflection of the dependence of proton temperature on solar wind speed. The assumption that electron temperature is generally twice the concurrent proton temperature is not accurate, especially given the large variations in proton temperatures that are observed and the relative constancy of the mean electron temperature. The best estimate one can make for electron temperature in the solar wind at 1 AU is a constant value of 141,000 ± 38,000 K, independent of the velocity or density of the solar wind ions.

However, an unexpected correlation between electron and proton temperatures has been discovered: There is an apparent lower bound to electron temperature which varies with proton temperature in the ambient solar wind. Although an instrumental explanation cannot be proved or disproved at this time, there are several reasons to believe that this lower bound on $T_e$ is physical. The slope of the bound is dependent on solar wind bulk speed: It increases as the solar wind speed increases. The lower bound is verified with a second spacecraft, Ulysses. When Ulysses was near 1 AU, the $T_e$ bound is nearly identical to that observed by IEEE 3 but appears to evolve with radial distance as Ulysses travels in the ecliptic plane to Jupiter. There is also a distinct correlation between cooling plasma in a high-speed stream following a solar wind stream interface and periods when prolonged $T_e$ bound conditions are observed. Finally, observational periods where this $T_e$ bound is observed are also coincident with intervals of enhanced electromagnetic, whistler-type wave activity in the 18-100 Hz frequency range.

This phenomenon is especially puzzling since the most common proton instabilities in the solar wind are nonresonant with electrons and are thus independent of electron temperature. Also, the common electron instabilities which generate whistler waves depend on anisotropic distributions, which are not observed during periods of temperature coupling. This correlation between electron and proton temperatures indicates that we do not understand the basic mechanisms that regulate the temperature of the solar wind. This phenomenon could potentially be a universal plasma effect that has not previously been appreciated. Other regions of space contain plasmas that are significantly hotter than electrons, such as the central plasma sheet ($T_e < 7.5 T_B$, [Baumjohann et al., 1989]) and deep within the magnetotail ($T_e < 11 T_B$, [Phan et al., 1994]). (In the past this correlation has been attributed to shock heating [e.g., Thom- sen et al., 1985]). At this time, we know of no mechanism for coupling the electron and ion temperatures in this way but are continuing to investigate this question.

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