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ABSTRACT

Solar wind thermal electron distributions exhibit distinctive trends which suggest that Coulomb collisions and geometric expansion in the interplanetary magnetic field play key roles in electron transport. We introduce a simple numerical model incorporating these mechanisms, discuss the ramifications of model results, and assess the validity of the model in terms of ISEE-3 and Ulysses observations. Although the model duplicates the shape of the electron distributions, and explains certain other observational features, observed differences in total electron temperature indicate the importance of additional heating mechanisms.

Solar wind electron distributions generally include two populations: a thermal "core" component and a suprathermal "halo" component. While the halo is often strongly anisotropic, the core distributions usually have only modest anisotropies, with the parallel-to-perpendicular temperature ratio most often in the range 1.0 to 1.5. Analysis of a large data base of ISEE-3 electron observations near 1 AU [1] revealed that the electron core anisotropy, $T_{\parallel}/T_{\perp}$, varies systematically as a function of density, with denser plasmas more nearly isotropic. Further, $T_{\parallel}$ is relatively constant, while $T_{\perp}$ is much more variable, such that the most anisotropic distributions have a high $T_{\perp}$ and thus a high total temperature. A subsequent study [2] identified intervals where core $T_{\parallel}$ exceeded $T_{\perp}$ and showed that this condition was associated with slow, dense, plasma and with interplanetary magnetic field (IMF) orientations which were nearly transverse to the flow.

Figure 1 summarizes these observations, for an ISEE-3 data set of 31,000 electron spectra measured near the L1 point. Data are plotted vs. core temperature ratio, $T_{\parallel}/T_{\perp}$, and include (top panel) an observation frequency distribution, (second panel) median core density, (third panel) medians of the two temperature components, and (bottom panel) the median departure of the ecliptic IMF direction from the Parker spiral based on the observed proton bulk speed. Note the following: (1) most distributions have a small $T_{\parallel} > T_{\perp}$ anisotropy, with decreasing likelihood for higher anisotropies and for $T_{\perp} > T_{\parallel}$; (2) $T_{\parallel}/T_{\perp}$ varies inversely with density; (3) $T_{\parallel}$ is much more variable than is $T_{\perp}$; (4) radial (transverse) IMF is associated with high (low) temperature ratios. These observations motivated development of a model for core electron transport [1,2,3]. This model is not intended to provide a complete description of electron transport; it explicitly neglects the interplanetary electrostatic potential and the electron heat flux, among other things. Its purpose is to demonstrate the important roles of collisions and adiabatic expansion in the modification of core electron distributions. We use the model to make predictions for the in-ecliptic and high-latitude phases of the Ulysses mission, and show Ulysses results which qualitatively support some of these predictions.

To construct the collision-expansion model for electron transport, we start with the double adiabatic invariants [4] referred to henceforth as the CGL relations:

$$\frac{d}{dt} \left(\frac{P_{\parallel} B^2}{\rho^2} \right) = 0 \quad (1)$$

$$\frac{d}{dt} \left(\frac{P_{\perp}}{\rho B} \right) = 0 \quad (2)$$

where $P_{\parallel}$ and $P_{\perp}$ are plasma pressure parallel and perpendicular to the magnetic field B , ρ is mass density, and d/dt is the convective derivative. The expressions are often used to describe proton behaviour in slowly changing magnetic fields in the absence of dissipation and heat flux. By neglecting the ambipolar electric field of the solar wind and by assuming that the electron heat flux is carried by the halo electrons only, one can also apply the CGL relations to thermal electrons. Figure 2 shows the expansion of a plasma parcel, depicted as a spherical shell, moving radially outward from the Sun with imbedded radial (top) and spiral (bottom) IMF. The direction of geometric expansion is shown as a solid arrow, similar expansion also

occurs normal to the plane of the figure. For radial IMF, the expansion is everywhere perpendicular to $\mathbf{B}$; such expansion results in cooling only of $T_{\perp}$. In the spiral field case, the expansion of the plasma cools both components, with the relative cooling rate of $T_{\perp}$ increasing as the field wraps up (note, however, that the expansion out of the plane of the figure always cools $T_{\perp}$ exclusively). Thus one might expect large $T_{\perp}/T_{\parallel}$ anisotropies to develop in the nearly radial field of the inner solar system, and then be mitigated by the increasing pitch of the IMF at greater distances from the Sun.

Figure 3 shows the evolution of the electron temperature components and total temperature, for CGL-based transport, starting from 0.1 AU with a scalar temperature of 1.5×10^6 K; density is assumed to vary as r^{-2} . The heavy dot represents a typical electron temperature at 1 AU. For collisionless transport in a radial field (top), the CGL relations reduce to constant $T_{\perp}$, $T_{\parallel} \propto r^{-2}$, and an unrealistically high temperature ratio of 100:1 at 1 AU. For a spiral field (middle panel), the wrap-up of the IMF reduces the temperature at 1 AU, but still results in an unrealistic 32:1 temperature ratio. The bottom panel shows the extreme opposite case, one in which we assume that the distributions are collision-dominated such that no anisotropies can develop. In this limit, the CGL relations reduce to the polytropic relation $P \propto n^{5/3}$, which for $n \propto r^{-2}$ yields a temperature gradient of $T \propto r^{-4/3}$. Note that this cited gradient for adiabatic transport applies only in the isotropic case; gradients in total temperature are substantially flatter if anisotropies develop.

The profiles in Figure 3 show the collisional and collisionless extremes of CGL-based transport. In fact, core electron distributions are marginally collisional, with collisional isotropization serving to mitigate the anisotropies generated by geometric expansion. The collision frequency used in the model, which incorporates electron isotropization by Coulomb collisions with electrons, protons, and alphas, will not be cited explicitly for the sake of brevity; the reader is referred to *M* for this expression. It resembles more familiar collision frequencies in that it is directly proportional to n and inversely proportional to $T^{1/2}$ (actually to $T^{-1/2}$), but also incorporates terms involving the anisotropy. We implement the collisional relaxation by assuming that total electron temperature is conserved in the relaxation process.

$$\frac{dT_{\perp}}{dt} = -\frac{1}{2} \frac{dT_{\parallel}}{dt} = 2.55\nu(T_{\parallel} - T_{\perp}) \quad (3)$$

where ν is the electron-electron collision frequency and 2.55 is the scaling factor incorporating electron scattering by protons and a 5% (by number) alpha population [3]. We then prescribe a constant radial convection speed V , require that $n \propto r^{-2}$, and use a standard Parker spiral treatment to calculate $\mathbf{B}$ as a function of heliocentric distance r , solar rotation rate Ω , and heliocentric latitude θ . We can then express the variation of the two temperature components with r as follows:

$$\frac{dT_{\parallel}}{dr} = -T_{\parallel} \frac{2r\Omega^2 \cos^2 \theta}{V^2 + r^2\Omega^2 \cos^2 \theta} - \frac{2(2.55\nu)(T_{\parallel} - T_{\perp})}{V} \quad (4)$$

$$\frac{dT_{\perp}}{dr} = -T_{\perp} \frac{2V^2 r^{-1} + r\Omega^2 \cos^2 \theta}{V^2 + r^2\Omega^2 \cos^2 \theta} + \frac{2.55\nu(T_{\parallel} - T_{\perp})}{V} \quad (5)$$

These equations are integrated numerically from an initial assumed scalar temperature T_0 at 0.1 AU.

Figure 4 shows model results, in this case emphasizing the roles of the IMF spiral and convection speed in regulating the electron distributions. T_0 is assumed to be 1.5×10^6 K and density to be 3 cm^{-3} at 1 AU. The two temperature components are shown as functions of r for bulk speeds of 250 and 750 km s^{-1} . For radial $\mathbf{B}$, as might be expected over the poles of the Sun (top panel), the only effect of convection speed is to increase the time available for collisional relaxation. The slower plasma stays nearly isotropic and cools rapidly, while the faster plasma develops a large anisotropy and cools more slowly. The same qualitative effects could be created by changing the plasma density and thus also the collision frequency: the denser plasma would be more isotropic and cool more rapidly. For spiral $\mathbf{B}$, as at low solar latitudes (bottom), the effects of changing bulk speed are twofold: a higher speed allows less time for collisions, and also creates a less tightly wound IMF spiral. Note that for $V = 250 \text{ km s}^{-1}$ the spiral and radial IMF cases are nearly identical, this is because the slow speed enables collisional isotropization to dominate the distributions such that the magnetic field orientation is of little consequence. For $V = 750 \text{ km s}^{-1}$, however, the radial and spiral field cases are markedly different, due to the paucity of collisions and to expansion parallel to the IMF as the field wraps up.

In both the high and low speed, spiral field, cases of Figure 4, $T_{\perp}$ ultimately exceeds $T_{\parallel}$. When the IMF pitch exceeds 55° , $T_{\parallel}$ cools more rapidly than $T_{\perp}$ and begins to mitigate the prevailing $T_{\perp} > T_{\parallel}$ anisotropy of the inner solar system. The point at which the reverse anisotropy ensues depends on a variety of factors, including speed, density, initial temperature, and latitude /2/. Note however, that the $T_{\perp} > T_{\parallel}$ anisotropy in the outer solar system is never very pronounced, due to the expansion component normal to the plane of the IMF spiral, and that the anisotropy ultimately becomes largest for faster (or less dense) solar wind due to the lesser influence of collisional isotropization.

The collision-expansion model is successful in explaining some aspects of the ISEE-3 observations at 0.99 AU. For example, the relatively cool and isotropic distributions characteristic of dense, slow interstream flows, despite their origin in the hot coronal streamer belt, can be attributed to the dominance of collisions and the resulting sharp temperature gradient. The existence of $T_{\perp} > T_{\parallel}$ anisotropies during periods of high density, low speed, and anomalously transverse IMF are also predicted by the model /2/, though the agreement between model and observations is far from perfect. Figure 5 shows median observed temperature components (top) and electron density (bottom) at 0.99 AU as functions of temperature ratio. The observations are from ISEE 3, and the model incorporated the following initial conditions at 0.1 AU: $V = 400 \text{ km s}^{-1}$, $T_{\parallel 0} = 1.5 \times 10^6 \text{ K}$. Density was varied to produce the model results shown in Figure 5 as solid traces. This single initial condition reproduces the relative behavior of the two temperature components (top), and is somewhat successful in explaining the dependence of temperature ratio on plasma density (bottom).

The model makes predictions about the variation of electron temperature and anisotropy with heliocentric distance and latitude. We chose two sets of initial conditions for purposes of illustration. The first set represents an interstream flow, originating in the coronal streamer belt and characterized by high coronal temperature, high plasma density, and low convection speed. The initial conditions at 0.1 AU are: $T_{\parallel 0} = 2.0 \times 10^6 \text{ K}$, $V = 350 \text{ km s}^{-1}$, and $n_{\parallel 0}$ such that $n = 10 \text{ cm}^{-3}$ at 1 AU. The second set of conditions, representing a high speed stream, is as follows: $T_{\parallel 0} = 1.5 \times 10^6 \text{ K}$, $V = 500 \text{ km s}^{-1}$, and $n_{\parallel 0}$ such that $n = 2 \text{ cm}^{-3}$ at 1 AU. Figure 6 shows model calculations as contours of total temperature (left) and anisotropy

(right) for the interstream flow (top) and high-speed stream conditions (bottom). The view is “meridional” in a quarter plane through the solar poles and extending to 5 AU. Note that for the interstream flow, which due to its high density and low speed is highly collision-dominated, there is little variation in temperature with latitude (the contours are nearly circular). The temperature ratio reaches a maximum of only about 1.4 in the inner solar system, then gradually decreases. For the high speed stream, the lower rate of collisional isotropization allows large anisotropies to develop. This is especially pronounced at high latitudes, where the model produces nearly radial magnetic fields and predicts temperature ratios as high as 6:1 at 4-5 AU. The onset of the $T_{\perp} > T_{\parallel}$ anisotropy occurs relatively close to the Sun (1.2 AU in the equatorial plane) for the interstream flow, but the $T_{\perp} > T_{\parallel}$ anisotropy never becomes very pronounced due to the dominance of collisions. For the high-speed stream, the $T_{\perp} > T_{\parallel}$ anisotropy is delayed to 2.8 AU in the equatorial plane, but ultimately becomes more pronounced due to the lower collision rate.

Ulysses in-ecliptic electron temperature results out to 3.76 AU are presented elsewhere in these proceedings /5/. Although the results should be considered preliminary, the Ulysses measurements support an overall core electron temperature gradient which can be expressed as $T \propto r^{-0.70}$. This gradient is considerably flatter than predicted by the collision-expansion model for low-speed, high-density flows, and is slightly flatter than that predicted for high-speed, low-density solar wind. Heating mechanisms not incorporated in the model, such as core-halo interactions and compression due to solar wind stream dynamics, are evidently at work. However, certain aspects of the Ulysses results qualitatively support the importance of collisions and expansion in a spiral IMF. Figure 7 (top) shows the percent occurrence of various core electron maximum-to-minimum temperature ratios (definitive identification of $T_{\perp}$ and $T_{\parallel}$ will require further analysis) for Ulysses 3-d measurements between 1.15 and 3.76 AU. Data are sorted into three subsets, shown in the legend, based on density normalized by r^{-2} to 1 AU. Note that as density increases, the core electrons tend to become more isotropic. This is a distinctive signature of the effect of collisions in isotropizing the distributions. In the bottom panel, we limit the data to the medium density ($4 < nr^{-2} < 8$ cm^{-3}) subset, and plot the anisotropy occurrence in three ranges of heliocentric distance. Note that the distributions become more nearly isotropic with increasing distance. Thus the trends in anisotropy qualitatively support the key roles of collisions and geometric expansion in regulating electron distributions.

but the observed gradient in total temperature indicates that heating mechanisms, not incorporated in the model, are probably at work.

The simple collision-expansion model presented here is not intended to be a comprehensive model for transport of solar wind thermal electrons. Other mechanisms neglected by the model may also contribute to the regulation of electron distributions. However, we believe that the model provides a zeroth order understanding of the interplay of collisions and expansion in a spiral magnetic field, which together control the development and mitigation of anisotropies. We anticipate further comparison of model predictions with Ulysses observations at various heliocentric distances and latitudes.

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FIGURE CAPTIONS

Fig. 1. Overview of ISEE-3 observations at 0.99 AU. From /3/.

Fig. 2. Schematic of the geometric expansion of an outwardly propagating gas in a radial (top) and spiral (bottom) magnetic field. From /3/.

Fig. 3. Evolution of core electron temperature components and total temperature based on the CGL relations for (top) radial IMF and no collisions, (middle) spiral IMF and no collisions, and (bottom) collision-dominated transport in any field configuration. From /3/.

Fig. 4. Radial profiles of core temperature components for marginally collisional transport, for $V = 250$ and 750 km s^{-1} , for radial field (top) and spiral field (bottom). From /3/.

Fig. 5. Temperature components (top) and core electron density (bottom), as functions of core temperature ratio, showing median ISEE-3 observations and model predictions. From /3/.

Fig. 6. Meridional view, with Sun at lower left, showing model contours of core electron temperature (left) and temperature ratio (right) for interstream (top) and high-speed (bottom) solar wind conditions. From /3/.

Fig. 7. Ulysses observations from 1.15 to 3.76 AU, showing percent occurrence of maximum-to-minimum temperature ratio for three density subsets (top), and for three heliocentric distance ranges (bottom).

FIG. 1

Radial B

Spiral B

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG 6.

FIG. 7