ON THE ELECTRON TEMPERATURE AND CORONAL HEATING IN THE FAST SOLAR WIND CONSTRAINED BY IN-SITU OBSERVATIONS

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Abstract. The electron temperature profile in the polar coronal hole inferred by the ionic charge state data of the fast wind exhibits a local maximum of $\sim 1.5 \times 10^6$ K. This indicates the existence of electron heating in the source region of the fast solar wind. In this paper, a two-fluid solar wind model, which incorporates additional 'mechanical' heating, is used to investigate the heating of the electrons in the coronal hole. We find that the classical collision-dominated description for the electron conduction heat flux is not valid and needs to be severely limited in order for the electron temperatures predicted by the model to agree with constraints supplied by both the solar wind ionic charge state data and the solar wind plasma properties observed at 1 AU. The corresponding constraints on the coronal electron heating will also be discussed.

1. Introduction

Electron temperature is one of the important physical properties in the solar corona and the solar wind. The ionic charge state data of the fast wind measured by SWICS/Ulysses during its south polar pass have implied that the electron temperature in the south polar coronal hole has a maximum of around 1.5×10^6 K (Ko *et al.* 1997). At 1 AU, it was observed to have a mean value of $1.41 \pm 0.38 \times 10^5$ K (Newbury *et al.* 1998) with average heat flux of $2.8 \pm 0.9 \times 10^{-3}\,\mathrm{erg\,cm^{-2}s^{-1}}$ (Feldman *et al.* 1976). It is commonly accepted that electrons decouple from protons very low in the corona, and thus they need to be treated as separate fluids in modeling the solar wind. Quite a few efforts have been devoted to the heating and acceleration of the solar wind using multi-fluid models (e.g., Hansteen and Leer 1995; Olsen and Leer 1996; Esser *et al.* 1997). In this paper, we use a two-fluid model with the aim of fitting the electron temperature both in the inner corona and at 1 AU to gain some insights into the heat transport and coronal heating of the solar wind electrons.

2. The Two-Fluid Model

The transport equations adopted for the one-dimensional proton-electron two-fluid model are ($s = p, e$):

$$\frac{\partial}{\partial t}(\frac{\rho_s}{B}) + u_s(\frac{\rho_s}{B}) + \frac{\rho_s}{B}\frac{\partial u_s}{\partial r} = \frac{\delta}{\delta t}\frac{\rho_s}{B} \tag{1}$$

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$$\frac{\partial u_s}{\partial t} + u_s \frac{\partial u_s}{\partial r} + \frac{B}{\rho_s}\frac{\partial}{\partial r}(\frac{p_s + p_{w,s}}{B}) = \frac{\delta u_s}{\delta t} - \frac{p_s + p_{w,s}}{\rho_s}\frac{1}{B}\frac{dB}{dr} - \frac{GM}{r^2} + \frac{q_s}{m_s}E \quad (2)$$

$$\frac{\partial}{\partial t}(\frac{p_s}{B}) + \frac{5}{3}\frac{p_s}{B}\frac{\partial u_s}{\partial r} + u_s \frac{\partial}{\partial r}(\frac{p_s}{B}) + \frac{2}{3}\frac{\partial}{\partial r}(\frac{h_s}{B}) = \frac{\delta}{\delta t}(\frac{p_s}{B}) + \frac{2Q_s}{3B} + \frac{2}{3}u_s\frac{p_s}{B}\frac{1}{B}\frac{dB}{dr} \quad (3)$$

where ρ_s, u_s, p_s and h_s are the mass density, velocity, gas pressure (= $\rho_s kT_s/m_s$) and heat flux for species s. The magnetic flux tube geometry is given the form of super-radial expansion, $B_0/B(r) = f(r)(R_s^2/r^2)$, where B_0 is the magnetic field strength at one solar radius, R_s, and $f(r)$ takes the commonly adopted form from Kopp and Holzer (1976) with $f_{\max}, r_1$ and σ as free parameters. The Alfvén wave pressure is $p_{w,e} = 0$ for electrons, and for protons it is adopted from Habbal *et al.* (1994). The solar wind plasma is subject to the condition of quasi-neutrality $n_e = n_p$ and zero-current density $n_e u_e = n_p u_p$ where $n_s = \rho_s/m_s$ is the number density for species s. In conjunction with eq. (2) for electrons, we can solve for the electric field E. The source terms $\delta(\rho_s/B)/\delta t$, $\delta u_s/\delta t$, and $\delta(p_s/B)/\delta t$ represent the time rate of change due to electron-proton collisions, for which we adopt the forms in Schunk (1975).

Without the knowledge of specific heating mechanisms, the heating term Q_s in eq. (3) is generally given an *ad hoc* form of (e.g., Esser *et al.* 1997):

$$Q_p = Q_{p0}e^{-|(r-r_m)/H_m|} \text{ and } Q_e = Q_{e0}e^{-|(r-r_m)/H_m|} - n_e n_p P(T_e). \quad (4)$$

Note that radiative cooling $n_e n_p P(T_e)$ (following Rosner *et al.* 1978) is included in the heating term for electrons.

It is well known that the classical description of the electron heat conduction (Spitzer and Härm 1953) in the solar wind is not valid when $\lambda_e/L_T \gtrsim 10^{-2}$, where $\lambda_e = (kT)^2/8\pi n_e e^4$ is the electron mean free path for e-e and e-p collisions and $L_T = |(1/T_e)(dT_e/dr)|^{-1}$ is the temperature scale height (e.g., Hollweg 1976). We find that this 'collision-dominated' description breaks down very close to the coronal base (cf. Figure 1b). We thus choose to describe the heat flux for protons and electrons as:

$$h_s = \begin{cases} \max\left(-k_s \frac{\partial T_s}{\partial r}, -\phi_s \frac{3}{2} p_s v_{th,s}\right) & \text{if } \frac{\partial T_s}{\partial r} > 0 \\ \min\left(-k_s \frac{\partial T_s}{\partial r}, \phi_s \frac{3}{2} p_s v_{th,s}\right) & \text{if } \frac{\partial T_s}{\partial r} < 0 \end{cases} \quad (5)$$

where k_s is the classical heat conductivity as derived by Schunk (1975). ϕ_s is a factor multiplied by the 'free-streaming' heat flux $h_{FS} = \frac{3}{2}p_s v_{th,s}$ where $v_{th,s} = \sqrt{5p_s/3\rho_s}$ is the thermal speed. The above transport equations are solved using a higher-order semi-implicit Godunov-type finite volume scheme. For the detailed numerical procedure, see Groth *et al.* (1999).

Figure 1a shows the proton and electron temperature profiles from our model in which we try to fit the model parameters with the observed values. Figure 1b compares λ_e with L_T in this model. We can see that $\lambda_e/L_T \gtrsim 10^{-2}$ for $r \gtrsim 2.2R_s$.

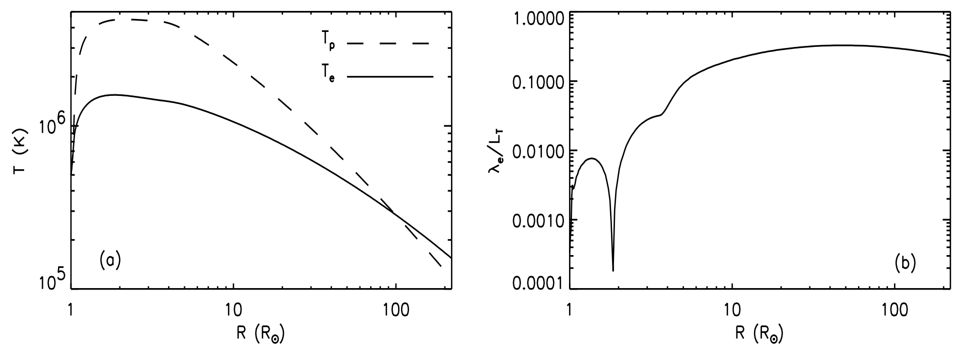

Figure 1. (a) Proton and electron temperature profiles. The input parameters for this particular model are: $f_{\max}$ = 10, r_1 = 1.5R_s, σ = 0.7R_s, $n_p(1R_s)$ = $n_e(1R_s)$ = $10^8 \mathrm{cm}^{-3}$, $T_p(1R_s)$ = $T_e(1R_s)$ = 5 × 10^5 K, Q_{p0} = 3 × 10^{-4}erg cm^{-3}s^{-1}, Q_{e0} = 1.1 × 10^{-4}erg cm^{-3}s^{-1}, H_m = 0.4R_s, r_m = 1.0R_s, ϕ_p = 2.0, ϕ_e = 0.17. The resulting solar wind parameters are: in the inner corona, $T_{p,\max}$ = 4.49 × 10^6 K, $T_{e,\max}$ = 1.55 × 10^6 K; and at 1 AU, $T_{p,E}$ = 1.18 × 10^5 K, $T_{e,E}$ = 1.56 × 10^5 K, n_E = 3.1 cm^{-3}, u_E = 818 km s^{-1}, $n_E u_E$ = 2.54 × 10^8cm^{-2}s^{-1}, $h_{p,E}$ = 6.1 × 10^{-4}erg cm^{-2}s^{-1}, $h_{e,E}$ = 3.4 × 10^{-3}erg cm^{-2}s^{-1}. (b) λ_e/L_T as a function of r in our model.

Therefore, the classical electron heat conduction already breaks down low in the corona. In this particular model, the heat flux for electrons takes the form of the 'free-streaming' flux (cf. eq. [5]) starting at $\sim$ 3.7 R_s and beyond.

3. Discussion

The main goal of this work is to look for coronal conditions in the fast wind source region (i.e., the physical parameters in the context of our two-fluid model) that can simultaneously satisfy the observed $T_{e,\max}$ in the coronal hole and $T_{e,E}$ at 1 AU. We find that the classical description of the electron heat conduction flux is not valid starting very low in the corona. Taking this form for the entire range will overestimate the electron heat flux and the electron temperature profile will be too flat to satisfy the observed values at both the inner corona and 1 AU (Hu *et al.* 1997). Furthermore, the electron heat flux at large r needs to be nearly an order of magnitude smaller than the 'free-streaming' flux ($\phi_e \sim 0.17$). This agrees with the observation that ϕ_e = 0.22 ± 0.07 at 1 AU (Feldman *et al.* 1976). Figure 2 shows $T_{e,\max}$, $T_{e,E}$ and $h_{e,E}$ as a function of ϕ_e, with other parameters fixed at values stated in Figure 1. Other observable solar wind quantities are very weak functions of ϕ_e. It is obvious that in order to fit the observed $T_{e,\max}$, $T_{e,E}$ and $h_{e,E}$ simultaneously, ϕ_e must be around 0.2. Note that increasing (or decreasing) the electron heating (i.e., Q_{e0}, H_m, r_m) moves all these curves up (or down), and we cannot find any values of Q_{e0}, H_m, r_m that fit with the observations if $\phi_e > 0.2$.

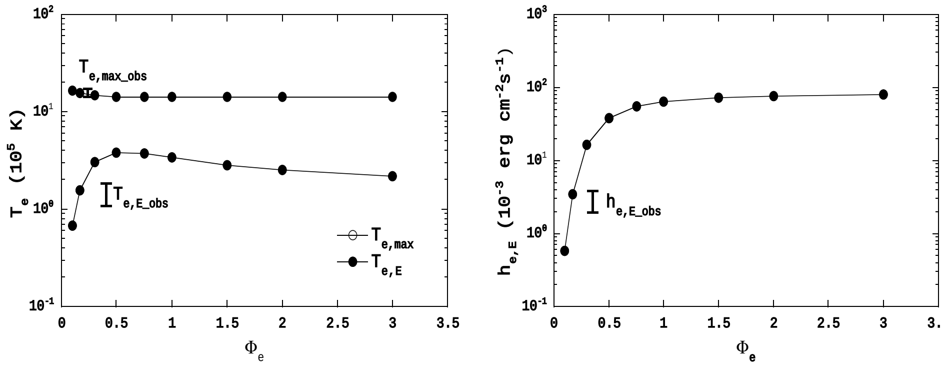

Figure 2. $T_{e,\max}$, $T_{e,E}$ and $h_{e,E}$ as a function of ϕ_e. The ranges of their observed values are also shown.

We also find that the implied $T_{e,\max}$ from the data requires an electron heating source other than heat conduction and electron-proton collisions. Our models show that $T_{e,\max} \propto Q_{e0}^{0.46} H_m^{1.7} r_m^{1.8}$ which is a strong function of these heating parameters. This would put a rather tight constraint on the possible magnitude of the electron heating in coronal heating models.

Olsen and Leer (1996) have shown from their 8-moment 2-fluid model that the electron heat conductivity can be well described by the Spitzer-Härm term. They also discussed that the 8-moment approximation breaks down if $h_s/h_{FS} \gtrsim 1$ which is the case here for $r > 9\,R_s$ if we take h_e to be the classical heat conduction flux. The prime result of our work is that the model cannot produce an electron temperature profile that fits both the inner coronal value and that at 1 AU without having some sort of heating *and* much lower heat conduction fluxes than the classical values. Various coronal line ratios (e.g., Wilhelm *et al.* 1998; David *et al.* 1998) indicate that the coronal electron temperature is no higher than $\sim 8 \times 10^5$ K for $r \lesssim 1.6\,R_s$ and is lower outward. This obviously contradicts with that inferred by the solar wind ionic charge states. We find that this discrepancy is hard to reconcile at this moment. The argument lies mainly on the observed Si charge states which indicate a freezing-in temperature $> 1.4 \times 10^6$ K. Owocki and Ko (1999) have shown that these Si ions are relatively insensitive to the non-thermal tail of electrons in the coronal temperature range. Thus, a non-thermal distribution of electrons may not explain this discrepancy between solar wind particles and coronal UV measurements.

When the classical description of the heat flux breaks down, the heat transport becomes non-local. Thus our prescription of the heat flux is not strictly valid because of the local nature of the 'free-streaming' flux. Non-local heat transport of electrons due to a steep temperature gradient has been widely studied in laser fusion studies (e.g., Krasheninnikov 1993). In general, the heat flux under a steep temperature gradient is found to be a small fraction of the free-streaming flux. This is in agreement with our results. Although solar wind electrons have no strong effect on the bulk flow properties, we stress that it is necessary to incorporate adequate electron heat transport into the solar wind models to correctly model the heating of solar wind electrons.

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