A 16-Moment Fast Solar Wind Model

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Abstract. A 16-moment fast solar wind model based on a bi-Maxwellian velocity distribution is presented. Although the proton heat flux density is found to be significantly smaller than the classical Spitzer-Härm value, it still plays a significant role in shaping the proton temperature anisotropy in the fast solar wind. 0.3 AU and 1 AU.

1. Introduction

In situ measurements between 0.3 and 1 AU (Marsch et al., 1982) and spectral line observations in the inner corona (Kohl et al., 1998) indicate that protons and heavier ions have strong temperature anisotropy. The proton heat flux density, derived from in situ measurements between 0.3 and 1 AU is at least an order of magnitude smaller than the classical value (Marsch and Richter, 1984). Since the heat flux density can significantly influence the proton temperature profile, a better knowledge of the proton heat flux density is critical for the understanding of the heating and acceleration processes of the solar wind.

While it is clear that the classical expression for the proton heat flux density (Spitzer and Harm, 1953; Braginskii, 1965) is not valid for the solar wind, it is still not known whether the proton heat flux can be completely ignored in the inner corona. To adequately explore the magnitude of the proton heat flux density, transport equations including higher moments of the distribution function must be taken into account. The first bi-Maxwellian based 16-moment solar wind models developed by Demars and Schunk (1991) started at $28R_S$ and were typical of a slow solar wind. Hence, the key solar wind acceleration region — the first several solar radii was not explored.

In this paper, we present a bi-Maxwellian velocity distribution based 16-moment fast solar wind model. The 16-moment description is applied to the protons only while the electrons are assumed to be isotropic.

2. Model computation

The details of one-dimensional, time-dependent bi-Maxwellian based sixteen moment transport equations for the electron-proton solar wind with anisotropic proton temperature including the effect of the interplanetary spiral magnetic field are given by Li (1999). The electron heat flux density q_e, and the proton parallel and perpendicular heat flux densities $q_{p\|}$ and $q_{p\perp}$ are solved simultaneously with the electron density n, the proton velocity v, the electron temperature T_e, and the proton parallel and perpendicular temperatures, $T_{p\|}$ and $T_{p\perp}$. The mean proton temperature is given by $T_p = (T_{p\|} + 2T_{p\perp})/3$. The proton total heat flux density is defined as $q_p = (q_{p\|} + 2q_{p\perp})/2$.

We assume that protons are heated only in the direction perpendicular to the magnetic field, i.e. $Q_{p\|} = 0$. The following ad hoc heating and momentum addition functions (e.g. Withbroe, 1988; Hu et al., 1997)

$$\begin{aligned} Q_{p\perp} &= Q_{p1} e^{(R_s - r)/\sigma_p} + Q_{p2} \left[1 - e^{(R_s - r)/10R_S}\right]) \tfrac{R_s^4}{r^4}, \\ Q_e &= Q_{e0} e^{(R_s - r)/\sigma_e},\ D = D_0 e^{(R_s - r)/\sigma_d}, \end{aligned} \tag{1}$$

are used in our calculation, where Q_{e0}, σ_e, Q_{p0}, σ_p, D_0 and σ_d are constants. The additional heating function $Q_{p\perp}$ consists of two parts: one corresponds to a local heating at the coronal base and the other to an extended heating similar to that used by *McKenzie et al.* (1997).

The following coronal base conditions ($r = 1R_s$) are assumed in our model calculations: $n_e = 2.5 \times 10^8 \mathrm{cm}^{-3}, T_e = T_{p\|} = T_{p\perp} = 6 \times 10^5 K$. Shown in Figure 1 as solid lines is an example of a model calculation with a rapidly diverging flux tube similar to that given by Munro and Jackson (1977). The input parameters are chosen to yield a high speed wind which matches, as closely as possible, currently available empirical constraints in the inner corona (Fisher and Guhathakurta, 1995) and in interplanetary space (Marsch and Richter, 1989). The filled circles in Fugure 1 represent the observed upper and lower perpendicular temperatures of neutral hydrogen derived from line-width measurements of H I Lyα in polar coronal holes (Kohl et al., 1998). The triangles and stars represent the perpendicular and parallel proton temperatures observed by Helios (Marsch et al., 1982).

Because of its rapid acceleration, the perpendicular cooling of the protons due to the radial expansion of the fast solar wind is only important in the inner corona (Hu et al., 1997; Li et al., 1999). Hu et al. (1997) demonstrated that the cooling effect of the spiral magnetic field is small too. Hence it is difficult to cool the proton parallel temperature in interplanetary space. This becomes even more difficult in the 16-moment model since the proton perpendicular heat flux density can conduct energy to or from the parallel degree of freedom because of the flow tube expansion. In 16-moment equations, $q_{p\perp}$ appears in the parallel energy equation too. Hence $q_{p\perp}$ can conduct thermal energy from the perpendicular to the parallel degree of freedom. In our model,

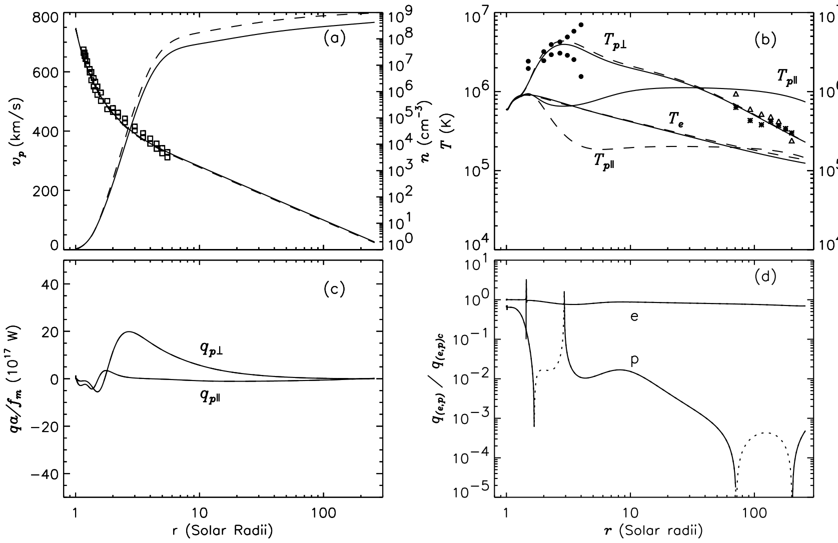

Figure 1. Parameters used in the model calculations are: $f_m = 6$,$r_a = 1.31R_s$,$\sigma_a = 0.51R_s$, $\sigma_e = 0.23R_s$, $Q_{e0} = 1.9 \times 10^{-6}$erg cm^{-3} s^{-1}, $\sigma_p = 0.42R_s$, $Q_{p1} = 8.2 \times 10^{-7}$erg cm^{-3} s^{-1}, $Q_{p2} = 1.64 \times 10^{-6}$erg cm^{-3} s^{-1}, $D_0 = 3.32 \times 10^{-15}$g cm^{-2} s^{-2}, $\sigma_d = 0.77R_s$. See text for details.

a higher $T_{p\perp}$ in the inner corona leads to a greater q_{perp} (see $T_{p\|}$ and $q_{p\perp}$ between 2 to 20 R_s in Figure 1b and 1c). That is why, as seen in Figure 1b, $T_{p\|}$ can increase from 2 R_s to about 50 R_s. This additional heating causes the proton parallel temperature to gain non-realistically high values beyond 0.3 AU. When both $T_{p\perp}$ and $T_{p\|}$ match observations in the fast solar wind, the total proton heat flux density can match observations as well (Li, 1999). The heat flux densities can change sign in the near Sun region, since proton temperatures reach a maximum in the region.

In order to show the effect of the 16-moment heat flux densities, we also compute a model by keeping the input parameters the same but neglecting the proton heat flux. The result is shown in Figure 1 as dashed lines. The electron density and temperature profiles are almost the same. The flow speed at 1AU increases by about 33 km/s while the mass flux at 1AU decreases by less than 3%. The most striking difference is in the parallel temperature. The proton parallel temperature is only about 20% of that in the 16-moment model starting from $10R_S$.

Shown in Figure 1d are the ratios between the electron and proton heat flux densities q_e and q_p computed from our model and the classical heat flux densities q_{ec} and q_{pc} defined by: $q_{ec} = 8 \times 10^{-7} T_e^{5/2} \frac{dT_e}{dr}$, $q_{pc} = 3.2 \times 10^{-8} T_p^{5/2} \frac{dT_p}{dr}$, with T_e and T_p taken from our 16-moment model. It is found that the electron heat flux density is very close to its classical value; the maximum relative difference is smaller than 25%. The small disturbances in Figure 1d are due to either the existence of a temperature maximum, where the classical heat flux density is zero, or a zero heat flux density. Hence the classical electron heat flux is still valid in our fast solar wind solutions. On the other hand, the classical Coulomb collision dominated concept of the proton heat flux completely breaks down in our model. Except at the coronal base, q_p is found to be much smaller than its classical value. The ratio q_p/q_{pc} can have negative values (dotted lines), implying that the collisionless proton heat flux does not necessarily conduct thermal energy from high to low temperature regions. In most of the computational domain, the 16-moment proton heat flux density is more than 2 orders of magnitude smaller than the classical heat flux density. Only at the coronal base is the proton heat flux density close to its classical value. However, the proton heat flux density is still important as far as the proton anisotropy is concerned. The electron heat flux density on the other hand is only slightly different from its classical value.

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