Effect of electron resonant heating on the kinetic evolution and acceleration of the solar wind

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Abstract. We investigate the effects of electron cyclotron resonant heating on the kinetic evolution and acceleration of the fast solar wind. A previous study has shown that kinetic wave-particle interactions due to ion resonant heating, may account for the bulk acceleration of the solar wind, the preferential heating of the helium ions over the protons, as well as the occasionally observed double-peaked proton velocity distributions. The model followed the evolution of the particle distributions along an inhomogeneous field line under the effects of ion heating, Coulomb collisions, and an ambipolar electric field that was consistent with the distributions themselves. This study extends the model to take into account also the effect of electron cyclotron resonant heating. Our parametric study shows that the electron heating does not change the solar wind qualitative features described above. However, the wave-particle interaction increases the ambipolar electric field, thereby enhancing the solar wind velocity.

1. Introduction

The role of ion resonant heating in the global kinetic evolution of the solar wind has recently been investigated by *Tam and Chang* [1999] (TC99). The study addressed some qualitative features observed in the fast solar wind. For example, the preferential heating of the helium ions over the protons due to wave-particle interactions translates into a higher velocity downstream in the solar wind. That provides an explanation for the helium to be the faster major ion species in the solar wind, as observed, for example, by the Helios, WIND, and Ulysses spacecraft [*Marsch et al.*, 1982a; *Steinberg et al.*, 1996; *Feldman et al.*, 1996]. Moreover, the results of TC99 featured double peaks in the proton velocity distributions, which were occasionally observed by the Helios spacecraft [*Marsch et al.*, 1982b]. The formation of the double-peaked proton distributions in the theoretical study was explained as a result of the combined effects due to resonant heating in the corona by the inward propagating component of the left-hand polarized waves, and the mirror folding of the velocity distributions downstream in the solar wind.

While TC99 showed that wave-particle interactions play an important role in the acceleration of the solar wind, only resonances involving the major ion species (proton and helium) were considered. This study concentrates on another type of kinetic wave-particle interactions that may have a significant effect on the solar wind, namely electron cyclotron resonant heating (ECRH). Note that for plasma outflows in space, such as the solar wind, electrons may significantly affect the overall dynamics through their heat flux contributions. It has been shown that in the ionospheric daytime polar wind, which is another example of outflow in space plasmas, the electron heat flux is mainly carried by the photoelectrons, the suprathermal population. The presence of the photoelectrons, due to their heat flux contribution, significantly enhances the self-consistent ambipolar electric field, leading to higher ion outflow velocities [*Tam et al.*, 1995, 1998]. In the solar wind, wave-particle interactions may anisotropize the electron population, generating nonthermal features in their distributions and thereby enhancing the suprathermal electron components. Due to its effect on the electron heat flux, ECRH may modify the ambipolar electric field considerably, and in turn, significantly affect the kinetic evolution and acceleration of the solar wind.

In this study, we modify our previous solar wind model to take into account the effects of ECRH. For a more complete description, we include heating of all the particle species (ions and electrons) also in the direction parallel to the magnetic field. Note that in TC99, the ions were heated only in the transverse direction.

2. Model

We shall briefly review the model in TC99, and discuss how it is modified to incorporate the effects of ECRH. The ion resonant heating in TC99 involves low frequency electromagnetic waves whose wavevector component $k_\perp \ll k_\parallel \approx k$. Because we also consider ECRH here, the frequency of the waves that we are interested in extends to the electron gyrofrequency range. The right-hand polarized (RHP) and left-hand polarized (LHP) components of the waves resonate with a particle of parallel velocity ${v'}_\parallel$ in the solar wind frame when the following conditions are satisfied:

$$\omega' - k{v'}_\parallel \pm \Omega = 0 \; , \qquad (1)$$

where ω' is the wave frequency in the solar wind frame, Ω is the gyrofrequency of the particle, defined to be positive for the ions and negative for the electrons, and the top (bottom) sign applies for resonances with RHP (LHP) waves. Equation (1), combined with the cold plasma dispersion relation, determines the resonant frequencies and wavevectors for individual particles. However, in this study we consider electron resonances with only the RHP waves, and ion resonances with both the LHP and RHP waves, although as indicated in TC99, ion heating is mainly due to the LHP waves.

The effect of these wave-particle interactions is incorporated into the steady-state collisional kinetic equations for

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the solar wind ions and electrons:

$$\left[v_\parallel \frac{\partial}{\partial s} - \left(g - \frac{q}{m}E_\parallel\right)\frac{\partial}{\partial v_\parallel} - {v_\perp}^2 \frac{B'}{2B}\left(\frac{\partial}{\partial v_\parallel} - \frac{v_\parallel}{v_\perp}\frac{\partial}{\partial v_\perp}\right)\right] f_j = C_j f_j + D_j f_j, \qquad (2)$$

where $v_\parallel$ and $v_\perp$ denote velocities in the spacecraft frame, $f_j(s, v_\parallel, v_\perp)$ is the distribution function for the species j, s is the distance along the magnetic field line, B is the magnetic field, q and m are the algebraic electric charge and mass of the species respectively, $E_\parallel$ is the field-aligned ambipolar electric field, g is the gravitational acceleration, $B' \equiv dB/ds$, C_j is a Coulomb collisional operator for the species j, and

$$D_j = \frac{\partial}{\partial v_\parallel} D_{j\parallel} \frac{\partial}{\partial v_\parallel} + \frac{1}{v_\perp}\frac{\partial}{\partial v_\perp}\left(v_\perp D_{j\perp}\frac{\partial}{\partial v_\perp}\right) \qquad (3)$$

is an operator that describes the resonant heating, with $D_{j\parallel}$ and $D_{j\perp}$ being quasilinear diffusion coefficients that represent heating in the parallel and perpendicular directions respectively. The diffusion coefficients may consist of contributions from LHP and RHP waves, and can be expressed as a sum of the two:

$$D_{j\parallel} = \eta_L D^L_{j\parallel} + \eta_R D^R_{j\parallel}\ , \quad \text{and} \qquad (4)$$

$$D_{j\perp} = \eta_L D^L_{j\perp} + \eta_R D^R_{j\perp}\ , \qquad (5)$$

where the subscripts in the notation $D^{L,R}_{j\parallel,\perp}$ denote the species and the direction of the resonant heating the diffusion coefficient emphasizes, and the superscript indicates the polarization of the waves resonating with the particles under condition (1). The parameters $\eta_{L,R}$ are factors that adjust the efficiency of the heating. The reasons for these adjustments were discussed by TC99, one of those being consistent with a recent study of wave dissipation near the corona [*Cranmer et al.*, 1999].

We use a model similar to that in TC99 to describe the effects included in Eq. (2) to (5). The model follows the global kinetic evolution of the solar wind particle distributions from 1 $R_\odot$ heliocentric distance to 1 AU, while taking into account the effects of wave-particle interactions, Coulomb collisions, and an ambipolar electric field that is consistent with the distributions themselves. It utilizes two techniques that had existed in the literature: the self-consistent hybrid model applied to the ionospheric polar wind [*Tam et al.*, 1995, 1998] and Monte Carlo modeling of ion resonant heating [*Retterer et al.*, 1983]. In the model, the global evolution of the ion distributions is based on kinetic calculations that, among other major effects, also take into account the Coulomb interactions, including those among the same ion species. The suprathermal electrons, which are the tail portion of the thermal electron distribution at the lower boundary, are also described by a similar approach, except that they are treated as test particles due to their low relative density. The bulk thermal electrons, assumed to be in the form of a drifting Maxwellian, and the ambipolar field are determined with a fluid approach. In this study, we extend the Monte Carlo modeling technique [*Retterer et al.*, 1983] also to the electron population, and take into account the global kinetic effect of ECRH.

Near the corona, the Coulomb collisional effect is very strong because of the high electron density. This collisional effect is velocity-dependent [*Scudder and Olbert*, 1979]; it is stronger in the core, and weaker in the tail of the electron distributions. Thus, there is a regime in the electron distributions dominated by Coulomb collisions, whose effect tends to hold the electron core together in the solar wind flow. We have compared the Coulomb collisional effect with that due to electron resonant heating, and estimated that the following criterion applies to the regime not dominated by Coulomb collisions: $m_e {v'}^2/2 \geq 5T_e$ at 1$R_\odot$, where T_e is the electron temperature. All the individual electrons that satisfy this criterion are treated as "suprathermal" electrons with the kinetic approach described above. The rest of the electron population is considered thermal electrons.

We use the same assumptions as in TC99 on the interplanetary magnetic field [*Banaszkiewicz et al.*, 1998], the wave power spectrum [*Bavassano et al.*, 1982], and the ratio between inward and outward propagating wave power. In particular, the wave power spectrum is extrapolated to the electron gyrofrequency range. Note that solar wind spectra have commonly been observed to feature a dissipation range above the local proton gyrofrequency, where the slopes of the spectra are significantly steeper. The reason for the steepening is due to wave dissipation by the particles before the waves can propagate to the distances of observations. Thus, the dissipation range is a result of particle heating that occurs at a lower heliocentric distance. Here, we use half-Maxwellian particle distributions at 1 $R_\odot$, implicitly assuming no significant heating below, or otherwise, the particle distributions there would be highly non-thermal. For short heating scale height (0.5 $R_\odot$, see below), our extrapolation scheme of the non-dissipation slope in the spectrum is consistent with this assumption. To investigate the uncertainties introduced by the approximation, we perform a parametric study of the effects of ECRH by including at least two order of magnitudes in the wave power that heats the electrons.

3. Parametric Study

We study how the solar wind changes with different values of the parameter η_R. As in TC99, we assume:

$$\eta_L = 1.25 \times 10^{-2} \exp\left[(1-r)/0.5\right], \qquad (6)$$

where r is heliocentric distance in the unit of $R_\odot$. Here, we shall present results of the solar wind for three different cases: (a) $\eta_R = 0$; (b) $\eta_R = 0.1\,\eta_L$; (c) $\eta_R = \eta_L$. Note that ECRH increases from (a) to (c). Except for η_R, all the parameters and boundary conditions in the three cases are the same: at the lower boundary, the proton and helium densities are respectively 1.5×10^7 and 2×10^6 cm^{-3}, and the electron temperature is 2×10^6 K. By comparing Cases (b) and (c) with (a), one can identify the net effects due to ECRH.

Electron cyclotron resonant heating, as expected, enhances the electron temperature, as shown in Fig. 1. Note that the global kinetic effects carry the heated electrons downstream, leading to an increase in the electron parallel temperature $T_{e\parallel}$ throughout the flow from (a) to (c). The increase improves the agreement with observations [*Pilipp et al.*, 1990]. The resonant heating also increases the total electron heat flux, as Fig. 2 indicates. Above a few $R_\odot$, the electron heat flux profiles follow closely to a power law with indices ranging from −2.03 to −2.06. These indices agree with the estimates based on a number of fast solar wind events observed by the Helios spacecraft [*Pilipp et al.*, 1990]. However, the heat flux in (c) is about half an order

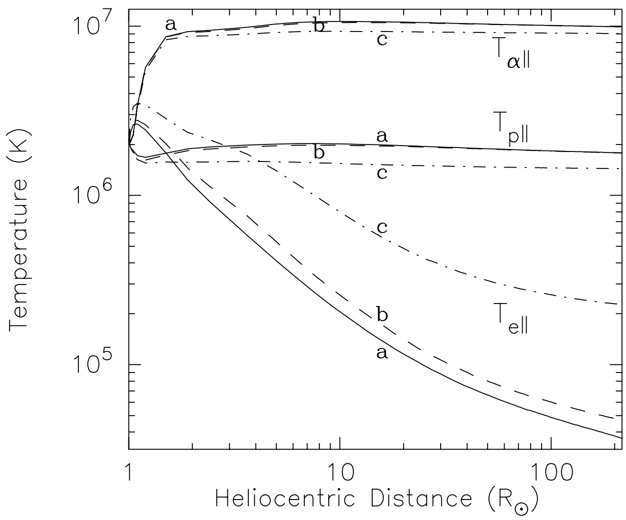

Figure 1. Parallel temperatures profiles for the protons (subscript p), helium ions (subscript α), and the total electron population (subscript e) in the three solar wind cases (labeled a, b, and c).

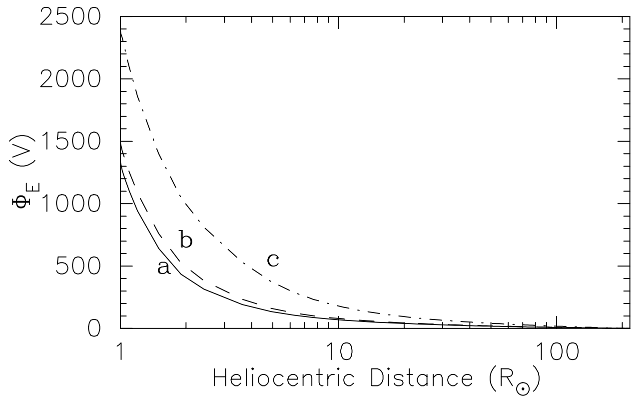

Figure 3. Profiles of the ambipolar electric potential for the three solar wind cases.

larger than the upper limit observed by Ulysses at 1 AU [*Scime et al.*, 1994; and references therein], suggesting that an η_R between those of (b) and (c) may be more consistent with observations. As discussed by *Tam et al.* [1998] in their ionospheric polar wind study, the increase in the overall electron flux may enhance the self-consistent ambipolar electric field. A collisionless solar wind study by *Maksimovic et al.* [1997] has also shown that the electric field increases as the tail of the electron distributions is enhanced. Figure 3 shows that indeed the ambipolar electric potential drop from the sun to 1 AU increases significantly from (a) to (c), as a result of ECRH enhancing the total electron heat flux.

Due to the increase in the ambipolar electric field, the proton velocity u_p also significantly increases from (a) to (c). As shown in Fig. 4, u_p at 1 AU increases from about 650 to 750 km/s, improving the agreement between the model and the Ulysses observations [*Feldman et al.,* 1996]. The same trend is also found in the helium ion velocity u_α. Therefore, ECRH can be considered as an acceleration mechanism of the solar wind, although its contribution in accelerating the ions seems less than those by ion resonances. Because ECRH accelerates the ions mainly by means of its effect on the ambipolar electric field, we expect the protons rather than the helium ions to gain more speed because of their higher charge-to-mass ratio. Indeed, when we compare the ion velocities of the three solar wind cases, we find that the ion differential speed, $u_\alpha - u_p$, is smaller as the amount of electron resonant heating increases, as shown in Fig. 5. The observations by WIND [*Steinberg et al.*, 1996] indicated that the ion differential speed at 1 AU is typically about 18 km/s, which we estimate to be about 0.3 of the Alfvén velocity. These values suggest that an η_R slightly below that of (c) would render results that agree well with the observations.

As for the ion parallel temperatures, shown in Fig. 1, those in (c) are significantly lower than in the other two cases. The reason is due to the global kinetic effect of the solar wind flow. Note that because of a higher ambipolar electric field, the ions are traveling faster in (c). That reduces their resident time near the corona, where the majority of ion resonant heating occurs. Thus, the amount of resonant heating received by the ions is smaller in (c). Due to the global kinetic nature of the solar wind

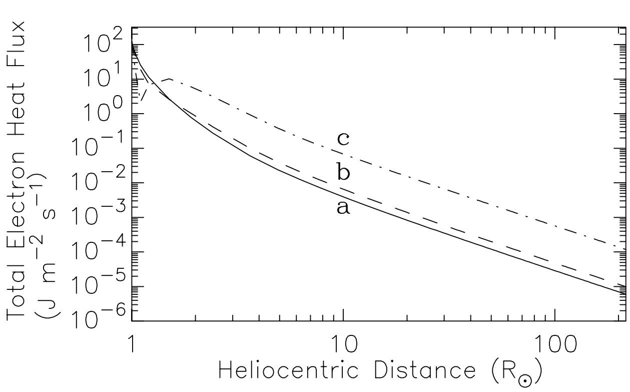

Figure 2. Total electron heat flux profiles for the three solar wind cases (labeled a, b, and c).

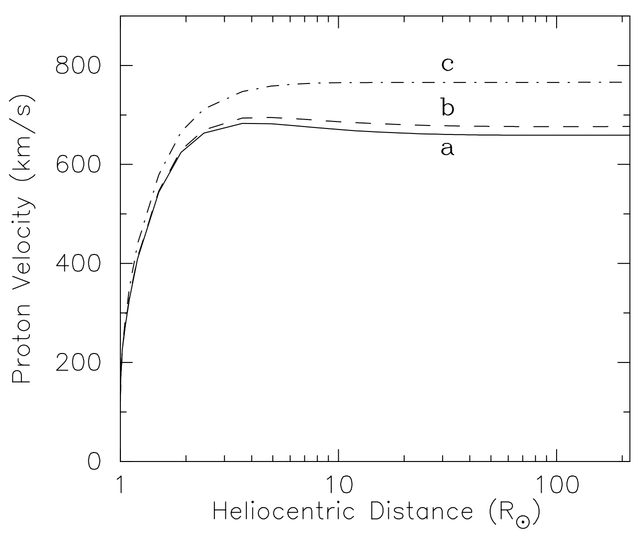

Figure 4. Proton velocity profiles for the three cases.

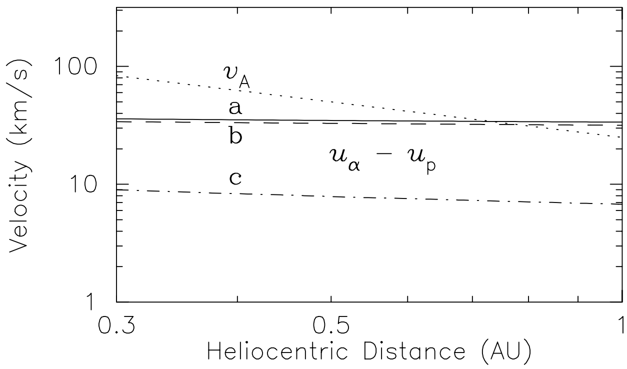

Figure 5. Ion differential speed, $u_\alpha - u_p$, for the three cases; v_A is the local Alfvén speed.

flow, the ion temperatures downstream in that case are also smaller. These ion temperatures, nevertheless, are still about 2 times higher than the corresponding observed values [*Marsch et al.*, 1982b]. As suggested by TC99, the lower observed values may be due to resonant heating below 1 $R_\odot$, which the present study does not take into account. We should note that like the ion temperatures shown in Fig. 2 of TC99, the temperatures in Fig. 1 reflect only the effect of resonant heating near the corona. Under this approximation, the perpendicular temperatures of the ions in the two studies are of the same order, while that of the electrons, for example in (c), is about 25% of $T_{e\parallel}$ near 1 AU, about half of the observed values [*Pilipp et al.*, 1990]. We have shown in our previous study that inclusion of local resonant heating downstream in the solar wind does not change the parallel temperatures or velocities by a significant extent, but can increase the perpendicular temperatures, rendering distributions which are consistent with Helios observations [*Marsch et al.*, 1982b].

By comparing the results of the three solar wind cases from the figures, one can conclude that the presence of ECRH, despite its significant modification on the solar wind quantities such as the ion temperatures, does not change the qualitative behavior of the outflow. Among other solar wind qualitative features, the double-peaked proton velocity distributions exist in all three cases.

4. Conclusion

We have investigated the effects of electron cyclotron resonant heating on the global kinetic evolution of the solar wind. Our model describes the kinetic evolution of the solar wind particle distributions under the effects of wave-particle interactions, Coulomb collisions, and an ambipolar electric field that is consistent with the distributions themselves. The results based on our parametric study show that electron resonant heating increases the electron temperature and heat flux, leading to a larger ambipolar electric field in the solar wind. The effect of electron resonant heating on the ions are mainly through the ambipolar field. Electron heating leads to higher ion velocities with the protons being preferentially accelerated. That results in a decrease in the ion differential speed in the solar wind. Ion temperatures are also lower in the presence of electron heating.

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