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Kinetic evolution and acceleration of the solar wind

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Abstract. We investigate the effects of kinetic wave-particle interactions on the solar wind using a global hybrid model. The model follows the evolution of the particle distributions along an inhomogeneous field line under the influence of wave-particle interactions, an ambipolar electric field that is consistent with the particle distributions themselves, and Coulomb collisions. This represents the "first results" of global evolutionary study of the solar wind that take into account these kinetic effects. The model can 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.

1. Motivation

Observations by the Helios, WIND, and Ulysses spacecraft have indicated that helium is generally the faster major ion species in the solar wind [*Marsch et al.*, 1982a; *Steinberg et al.*, 1996; *Feldman et al.*, 1996]. In addition, the observed proton velocity distributions were sometimes characterized by double peaks in the field-aligned direction. These distributions also demonstrated an anisotropy in the core region: $T_\perp > T_\parallel$, suggesting the presence of ion perpendicular heating in the solar wind [*Marsch et al.*, 1982b].

This study is motivated by these experimental indications. Our aim is to investigate the heating and acceleration of the solar wind under the influence of wave-particle interactions. Our model also includes the effect of Coulomb interactions, which may give rise to non-thermal features in the particle distributions [*Scudder and Olbert*, 1979; *Livi and Marsch*, 1987; *Tam et al.*, 1998].

Since the pioneering work by *Belcher and Davis* [1971] that associated Alfvén waves with the high-speed solar wind, a number of authors have investigated the heating of solar wind ions due to wave-particle interactions [e.g. *Hollweg and Turner,* 1978; *Dusenbery and Hollweg,* 1981; *Marsch et al.,* 1982c; *Isenberg,* 1984; *Leer et al.,* 1992; *Hu et al.,* 1997; *Czechowski et al.,* 1998; *Cranmer et al.,* 1999]. However, these models generally represent the wave-particle interaction effects in terms of local heating of the thermal portions of the ion populations. The present study, on the other hand, is based on a more global approach. This Letter describes the "first results" of a preliminary calculation in which we consider the evolution of solar wind distributions under the influence and interplay of global wave-particle interactions and collisional effects.

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2. Model

The resonant heating in this study involves low frequency electromagnetic waves whose wavevector component $k_\perp \ll k_\parallel \approx k$. In the solar wind frame, an ion with parallel velocity $v'_\parallel$ resonates with the left-hand polarized (LHP) and right-hand polarized (RHP) components of these waves when the following conditions are satisfied:

$$\omega' - kv'_\parallel \mp \Omega = 0 \ , \tag{1}$$

where the top (bottom) sign applies to LHP (RHP) waves, ω' is the wave frequency in the solar wind frame, and Ω is the cyclotron frequency of the ion. The effect of these wave-particle interactions can be incorporated into the steady-state collisional kinetic equation for the solar wind ions:

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

where $f_j(s, v_\parallel, v_\perp)$ is the distribution function for the ion 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 is a Coulomb collisional operator, and D is an operator that describes resonant heating.

The model we use to describe the effects included in Eq. (2) is a combination of two existing techniques in the literature: the self-consistent hybrid model applied to the polar wind [*Tam et al.*, 1995] and Monte Carlo modeling of ion resonant heating [*Retterer et al.*, 1983]. The self-consistent hybrid model has been described in detail by *Tam et al.* [1998]. 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 a drifting Maxwellian, and the ambipolar field are determined with a fluid approach. When combined with Monte Carlo modeling of ion resonant heating, the technique enables us not only to follow the global evolution of the solar wind particle distributions under the effect of wave-particle interactions, but also to determine the influence of the ambipolar electric field that is consistent with the distributions themselves.

3. Solar wind results

We have calculated the results for the solar wind flow between 1 $R_\odot$ and 1 AU. The flow is assumed to be current-free and quasi-neutral. In this calculation, we use a dipole

+ quadrupole + current sheet model for the interplanetary magnetic field [*Banaszkiewicz et al.*, 1998]:

$$B(r) \sim \frac{2}{(r/\mathrm{R}_\odot)^3} + \frac{4.5}{(r/\mathrm{R}_\odot)^5} + \frac{1}{1.538(r/\mathrm{R}_\odot + 1.538)^2}, \quad (3)$$

with $B = 3.1\times10^{-5}$ Gauss at 1 AU. We have also made some assumptions about the magnetic field wave spectra. First, note that Eq. (1) applies to both outwardly and inwardly propagating waves. Although the waves in the solar wind predominantly propagate away from the sun, it has been found that there is a considerable amount of wave power associated with inward propagation in both the high-speed and low-speed solar wind [*Tu and Marsch*, 1990]. Here, we shall utilize this information and assume the following relation for the power ratio between inwardly (e_-) and outwardly (e_+) propagating waves in the interplanetary space:

$$e_-/e_+ = 1 - e^{-(s/3)^2} \;, \quad (4)$$

where s is the radial distance from the sun in AU. Note that under this assumption, the inward propagating waves constitute only 10^{-6} of the total wave power at 1 $\mathrm{R}_\odot$.

Measurements by the Helios spacecraft indicated that the solar wind wave power decreases with both frequency and radial distance [*Bavassano et al.*, 1982; *Denskat and Neubauer*, 1982]. The decrease can generally be described by power laws. In this study, we assume a magnetic field power spectrum based on these experimental results. We also extrapolate the power law relations to higher frequencies, and radial distances beyond the measurement range (0.29 – 0.87 AU). To determine the frequencies of the waves that resonate with the individual ions, we solve Eq. (1) and the cold plasma dispersion relations for the LHP and RHP waves in the solar wind frame. The Doppler-shifted frequencies in the spacecraft frame are then obtained, and used to determine the wave power.

However, the LHP and RHP waves constitute only a fraction of the total waves observed. Moreover, a recent study has suggested that most of the waves generated from the sun and resonating with the ions dissipate within 1.5 $\mathrm{R}_\odot$ [*Cranmer et al.*, 1999]. Thus, we make adjustment to the available wave power by including an efficiency factor (1.25% at 1 $\mathrm{R}_\odot$) in the calculation. We let this factor fall off exponentially with a scale length of 0.5 $\mathrm{R}_\odot$ to reflect the dissipation of these wave components as they propagate along the magnetic field line from the sun.

In this study, we consider only the resonant heating perpendicular to the magnetic field. The operator D in Eq. (2) is thus given by:

$$D = \frac{1}{v_\perp}\frac{\partial}{\partial v_\perp}\left(v_\perp D_\perp \frac{\partial}{\partial v_\perp}\right), \quad (5)$$

where $D_\perp$ is a diffusion coefficient that emphasizes only the resonance conditions equivalent to Eq. (1).

The proton and helium densities in this calculation are respectively 1.5×10^7 and 2×10^6 cm^{-3} at the lower boundary. The ambipolar electric field in our results corresponds to a potential drop of about 900 V from the sun to 1 AU. Because the electric field preferentially accelerates the protons, this potential directly affects the ion differential velocity. As discussed by *Tam et al.* [1998] in their polar wind study, the ambipolar potential can be significantly affected by the overall electron heat flux. The total electron heat flux profile in this calculation follows closely to a power law with an index of −2.03 from a few solar radii to 1 AU. Such a power law index agrees with the estimates based on a number of high-speed solar wind events observed by the Helios spacecraft [*Pilipp et al.*, 1990]. The total electron heat flux at 1 AU, 9.06×10^{-6} Jm^{-2}s^{-1}, also falls within the experimental limits deduced from the Ulysses measurements [*McComas et al.*, 1992].

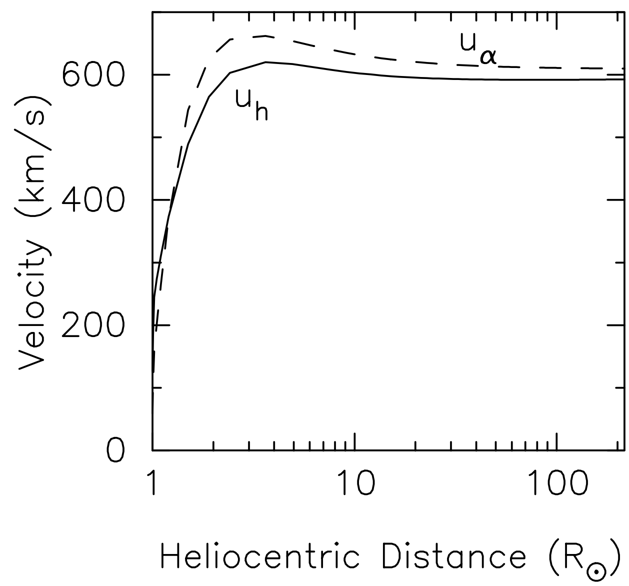

Figure 1. Solar wind ion velocities, u_α for the helium ions and u_h for the protons.

The rate of energy transfer due to the perpendicular resonant heating is about 5×10^{-6} J/s near 1 $\mathrm{R}_\odot$. The protons and helium ions both receive about 50% of the energy. Because of their lower density, the helium ions on average receive significantly more energy than the protons. Most of this energy is transferred to the field-aligned direction due to the mirror force, thereby preferentially accelerating the helium ions. Figure 1 shows the solar wind ion velocities in our results. Notice that the helium ions initially have a smaller velocity than the protons because of the similar temperatures of the two species at 1 $\mathrm{R}_\odot$ (which we shall discuss below). But, due to the reason discussed above, the helium ions overtake the protons in velocity within 2 $\mathrm{R}_\odot$, and remain the faster ion species throughout the solar wind flow, in agreement with observations [*Marsch et al.*, 1982a; *Steinberg et al.*, 1996; *Feldman et al.*, 1996]. In our results, the ion differential velocity at 1 AU is about 17 km/s, same order as the local Alfvén speed, v_A, which is about 23 km/s. We should point out that the ion heating is mainly due to resonances with the LHP waves. The RHP waves can resonate with the ions only when $v'_\parallel$ is at least twice of v_A. Because v_A is much larger than the ion thermal speed near the sun, where the majority of resonant heating occurs, the RHP waves do not have a significant effect on the ion velocities.

In the calculation, we have imposed a thermal electron temperature of 2×10^6 K at the lower boundary. Initial proton and helium velocity distributions are chosen at the boundary such that the resulting parallel temperatures are comparable to the electron temperature. These temperature profiles, together with those of the ion perpendicular temperatures are shown in Fig. 2. Downstream in the solar wind flow, the helium parallel temperature becomes about 4 times larger than that of the protons, consistent with observations by the Helios spacecraft [*Marsch et al.*, 1982a]. However, both of these temperatures are about 2 to 3 times larger than the observed values. We find that due to the global kinetic nature of the solar wind flow, the parallel temperatures of the ions for a given bulk speed depend critically on the Alfvén velocity in the region where the majority of heating occurs. The higher the Alfvén velocity, the more uniform the heating is among the ions, and the lower the ion temperatures are. Provided that Eq. (3) has correctly estimated the magnetic field near 1 $R_\odot$, the discrepancy in the ion parallel temperatures between our results and the observations suggests that a significant amount of heating may occur below 1 $R_\odot$, where v_A is considerably higher.

The proton distributions in our results demonstrate the presence of double peaks in the field-aligned direction, a feature occasionally observed by the Helios spacecraft [*Marsch et al.*, 1982b]. The formation of the double peaks in our calculations is mainly due to the combined effect of mirror folding, and resonant heating associated with the inward propagating component of the LHP waves. These distributions at large radial distances also have low perpendicular temperatures, as a result of the mirror effect. These temperatures are lower than the observed values. However, these results have not taken into account the LHP and RHP waves which can be generated locally by the solar wind plasma, or those which propagated there and/or by mode-conversion [*Johnson et al.*, 1995], to interact with the solar wind. We incorporate a small amount (efficiency factor = 0.1%) of these locally generated wave components into our calculations to heat the ions at a few isolated locations. We found that such local heating has little effect on the overall solar wind ion velocity and parallel temperature profiles. However, the shape of the ion velocity distributions changes significantly. One can clearly see the signature of local perpendicular heating in a typical proton velocity distribution shown in Fig. 3. The heating below the core velocity is mainly due to resonance with the LHP waves, while that above the core velocity is associated with the RHP waves. The inclusion of local resonant heating in the calculation leads to velocity distributions that are more consistent with the Helios observations. (See, for example, Fig. 8 in *Marsch et al.* [1982b] for comparison.)

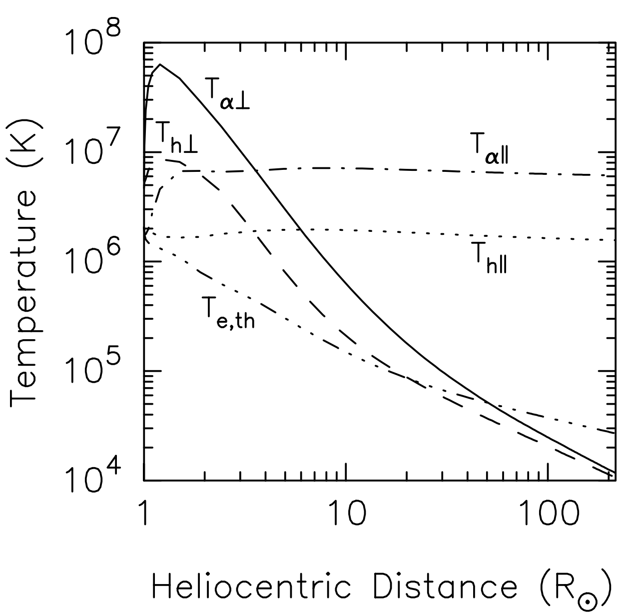

Figure 2. Temperature profiles for the protons (subscript h), helium ions (subscript α), and thermal electrons (subscript e, th).

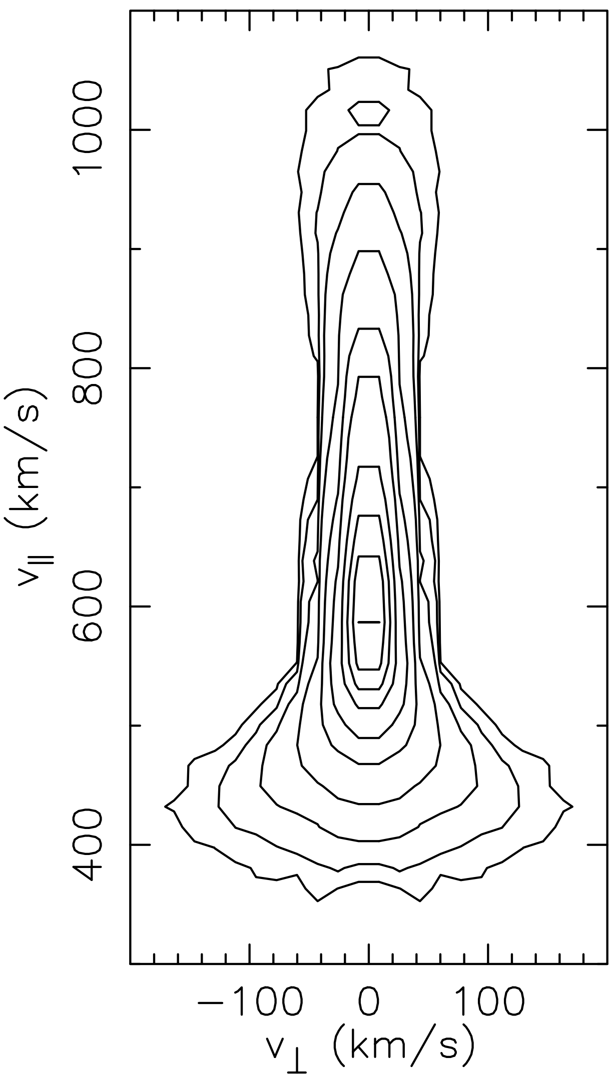

Figure 3. Contour plot of the proton velocity distribution at 0.45 AU. Resonant heating due to locally generated waves is included.

4. Conclusion

We have investigated the effects of kinetic wave-particle interactions on the global evolution of the solar wind. We have demonstrated that the resonant effect associated the LHP waves can dominate that of the electric field, giving rise to a solar wind flow where the helium is the faster ion species compared with the proton. The velocity difference between the ion species in our results is in agreement with the Helios observations within the earth's orbit. The resonance between the protons and the inward propagating component of the LHP waves can lead to the formation of double-peaked velocity distributions, which have occasionally been observed in the solar wind. Locally generated waves can significantly modify the shape of the ion distributions, and may account for the distributions observed by the Helios spacecraft.

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References

Banaszkiewicz, M., W. I. Axford, and J. F. McKenzie, An analytic solar magnetic field model, *Astron. Astrophys.*, **337**, 940, 1998.

Bavassano, B., M. Dobrowolny, F. Mariani, and N. F. Ness, Radial evolution of power spectra of interplanetary Alfvénic turbulence, *J. Geophys. Res.*, **87**, 3617, 1982.

Belcher, J. W., and L. Davis, Jr., Large-amplitude Alfvén waves in the interplanetary medium, 2, *J. Geophys. Res.*, **76**, 3534, 1971.

Cranmer, S. R., G. B. Field, and J. L. Kohl, Spectroscopic constraints on models of ion cyclotron resonance heating in the polar solar corona and high-speed solar wind, *Astrophys. J.*, **518**, 937, 1999.

Czechowski, A., R. Ratkiewicz, J. F. McKenzie, and W. I. Axford, Heating and acceleration of minor ions in the solar wind, *Astron. Astrophys.*, **335**, 303, 1998.

Denskat, K. U., and F. M. Neubauer, Statistical properties of low-frequency magnetic field fluctuations in the solar wind from 0.29 to 1.0 AU during solar minimum conditions: HELIOS 1 and HELIOS 2, *J. Geophys. Res.*, **87**, 2215, 1982.

Dusenbery, P. B., and J. V. Hollweg, Ion-cyclotron heating and acceleration of solar wind minor ions, *J. Geophys. Res.*, **86**, 153, 1981.

Feldman, W. C., B. L. Barraclough, J. L. Phillips, and Y.-M. Wang, Constraints on high-speed solar wind structure near its coronal base: a Ulysses perspective, *Astron. Astrophys.*, **316**, 355, 1996.

Hollweg, J. V., and J. M. Turner, Acceleration of solar wind He^{++} 3. Effects of resonant and nonresonant interactions with transverse waves, *J. Geophys. Res.*, **83**, 97, 1978.

Hu, Y. Q., R. Esser, and S. R. Habbal, A fast solar wind model with anisotropic proton temperature, *J. Geophys. Res.*, **102**, 14661, 1997.

Isenberg, P. A., Resonant acceleration and heating of solar wind ions: anisotropy and dispersion, *J. Geophys. Res.*, **89**, 6613, 1984.

Johnson, J. R., T. Chang, and G. B. Crew, A study of mode conversion in an oxygen-hydrogen plasma, *Phys. Plasmas*, **2**, 1274, 1995.

Leer, E., T. E. Holzer, and E. C. Shoub, Solar wind from a corona with a large helium abundance, *J. Geophys. Res.*, **97**, 8183, 1992.

Livi, S., and E. Marsch, Generation of solar wind proton tails and double beams by Coulomb collisions, *J. Geophys. Res.*, **92**, 7255, 1987.

Marsch, E., K.-H. Mühlhäuser, H. Rosenbauer, R. Schwenn, and F. M. Neubauer, Solar wind helium ions: observations of the Helios solar probes between 0.3 and 1 AU, *J. Geophys. Res.*, **87**, 35, 1982a.

Marsch, E., K.-H. Mühlhäuser, R. Schwenn, H. Rosenbauer, W. Pilipp, and F. M. Neubauer, Solar wind protons: three-dimensional velocity distributions and derived plasma parameters measured between 0.3 and 1 AU, *J. Geophys. Res.*, **87**, 52, 1982b.

Marsch, E., C. K. Goertz, and K. Richter, Wave heating and acceleration of solar wind ions by cyclotron resonance, *J. Geophys. Res.*, **87**, 5030, 1982c.

McComas, D. J., S. J. Bame, W. C. Feldman, J. T. Gosling, and J. L. Phillips, Solar wind halo electrons from 1 – 4 AU, *Geophys. Res. Lett.*, **19**, 1291, 1992.

Pilipp, W. G., H. Miggenrieder, K.-H. Mühlhäuser, H. Rosenbauer, and R. Schwenn, Large-scale variations of thermal electron parameters in the solar wind between 0.3 and 1 AU, *J. Geophys. Res.*, **95**, 6305, 1990.

Retterer, J. M., T. Chang, and J. R. Jasperse, Ion acceleration in the suprauroral region: a Monte Carlo model, *Geophys. Res. Lett.*, **10**, 583, 1983.

Scudder, J. D., and S. Olbert, A theory of local and global processes which affect solar wind electrons: 1. the origin of typical 1 AU velocity distribution functions — steady state theory, *J. Geophys. Res.*, **84**, 2755, 1979.

Steinberg, J. T., A. J. Lazarus, K. W. Ogilvie, R. Lepping, and J. Byrnes, Differential flow between solar wind protons and alpha particles: First WIND observations, *Geophys. Res. Lett.*, **23**, 1183, 1996.

Tam, S. W. Y., F. Yasseen, T. Chang, and S. B. Ganguli, Self-consistent kinetic photoelectron effects on the polar wind, *Geophys. Res. Lett.*, **22**, 2107, 1995.

Tam, S. W. Y., F. Yasseen, and T. Chang, Further development in theory/data closure of the photoelectron-driven polar wind and day-night transition of the outflow, *Ann. Geophys.*, **16**, 948, 1998.

Tu, C.-Y., and E. Marsch, Evidence for a "background" spectrum of solar wind turbulence in the inner heliosphere, *J. Geophys. Res.*, **95**, 4337, 1990.

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