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ACCELERATION OF WEAKLY COLLISIONAL SOLAR-TYPE WINDS

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ABSTRACT

One of the basic properties of the solar wind, the high speed of the fast wind, is still not satisfactorily explained. This is mainly due to the theoretical difficulty of treating weakly collisional plasmas. The fluid approach implies that the medium is collision dominated and that the particle velocity distributions are close to Maxwellian. However, the electron velocity distributions observed in the solar wind depart significantly from Maxwellian. Recent kinetic collisionless models (called exospheric) using velocity distributions with a suprathermal tail have been able to reproduce the high speeds of the fast solar wind. In this Letter we present new developments of these models by generalizing them over a large range of corona conditions. We also present new results obtained by numerical simulations that include collisions. Both approaches calculate the heat flux self-consistently without any assumption on the energy transport. We show that both approaches—exospheric and collisional—yield a similar variation of the wind speed with the basic parameters of the problem; both produce a fast wind speed if the coronal electron distribution has a suprathermal tail. This suggests that exospheric models contain the necessary ingredients for powering a transonic stellar wind, including the fast solar wind.

Subject headings: acceleration of particles — methods: numerical — solar wind — stars: winds, outflows — Sun: corona

1. INTRODUCTION

In spite of the success of the fluid models in explaining the supersonic solar wind, it is still not known how the fast wind is accelerated to speeds up to 800 km s^{-1} and how the energy is transported. This is mainly due to a major theoretical difficulty of treating such weakly collisional plasmas. In fact, the Knudsen number, which is defined as the ratio of the particle mean free path to the density scale height, is close to unity at Earth's orbit and larger than 10^{-3} in the fast wind acceleration region. In this case, the classical heat conduction formulation (Spitzer & Harm 1953) breaks down (Shoub 1983), and the low level closing of the infinite hierarchy of MHD equations is hard to justify (see Parks 2004).

Furthermore, the electron velocity distribution functions (VDFs) in the solar wind are not Maxwellian. They exhibit high-energy (nonthermal) tails that have been modeled by a halo Maxwellian population (Feldman et al. 1975) or, more recently, by the power-law part of a generalized Lorentzian or Kappa function (Maksimovic et al. 1997b). These tails can develop even in moderately collisional plasmas as a result of the rapid increase of the particle free paths with speed ($\propto v^4$). The existence of such electron VDFs in the upper chromosphere has been suggested to be the reason for the rapid rising of the temperature in the chromosphere-corona transition region through the mechanism of gravitational velocity filtration (Scudder 1992). Indeed, there is an increasing amount of observational evidence showing that nonthermal VDFs may exist in the corona and even in the high chromosphere (Owocki & Ko 1999; Pinfield et al. 1999; Esser & Edgar 2000; Chiuderi & Chiuderi Drago 2004; Doyle et al. 2004). Some theoretical works on the possible generation mechanisms of such nonthermal electron distributions in the chromosphere (Roberts & Miller 1998; Viñas et al. 2000) and the corona (Vocks & Mann 2003) have been published. Others have been trying to show that Kappa distributions can be a natural, and quite general, state of weakly collisional plasmas and not merely a convenient mathematical way of describing nonthermal VDFs (Collier 1993; Ma & Summers 1999; Treumann 1999; Leubner 2002; Collier 2004).

Investigating the effects of nonthermal VDFs in the corona requires a kinetic approach. The simplest one is the exospheric model that has recently provided transonic wind solutions using non-Maxwellian VDFs for the electrons (Zouganelis et al. 2004). However, the collisionless assumption may appear as a strong intrinsic limitation of these models. Kinetic simulations, taking into account binary collisions between particles (Landi & Pantellini 2003), suggest that collisions might be an important ingredient for accelerating the wind to supersonic speeds, even though this latter work does not consider nonthermal electron VDFs. We should note that these models include neither the effects of plasma instabilities nor any kind of wave-particle interaction that are sometimes invoked to be a fundamental ingredient in the wind acceleration process (see, e.g., Lie-Svendsen et al. 2001). Given that the real importance of these effects is not yet established, they will be neglected in this work.

In this Letter we present new simulations based on Landi & Pantellini (2003) using Kappa distributions for the electrons and compare the results to those of exospheric models. We show that both models yield similar wind speeds under a wide range of conditions. A common characteristic of both exospheric models and kinetic simulations is that, unlike fluid models, no assumption on energy transport has to be made: the heat flux is completely self-consistent. A detailed comparison of the results from both exospheric models and collisional kinetic models is presented and discussed.

2. EXOSPHERIC MODELS AND KINETIC SIMULATIONS

In exospheric or kinetic collisionless models of stellar atmospheres, the plasma is assumed to be completely collisionless beyond a given altitude, called the exobase. In principle, the collisionless nature of the plasma above the exobase allows the computing, for each particle species, of the VDF at any arbitrary height as a function of the VDF at the exobase, by means

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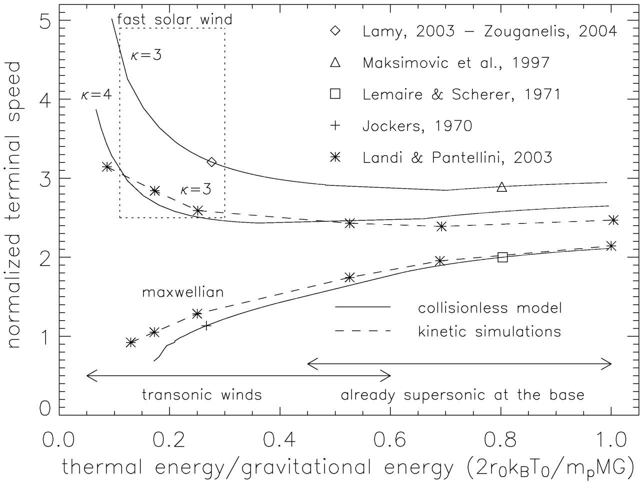

FIG. 1.—Terminal speed normalized to the thermal speed either at the exobase (exospheric model) or the lower boundary (kinetic model with collisions) as a function of the dimensionless parameter α for different models.

of Liouville's theorem and the requirement of energy and magnetic moment conservation. However, the task is not trivial because the electric field profile needed to ensure local quasi-neutrality and zero current is an unknown of the problem that has to be determined self-consistently. The electric field arises because of the small electron-to-proton mass ratio that makes it easier for an electron, compared to a proton of the same energy, to escape from the star. In short, the electric force must be directed toward the star for the electrons and away from the star for the protons. This field is thus responsible for the strong outward acceleration of the protons (see, e.g., Maksimovic et al. 1997a).

The first models of this kind (Jockers 1970; Lemaire & Scherer 1971) were based on Maxwellian VDFs for the electrons and were unable to reproduce the observed velocities of the fast solar wind, unless extremely high, and unrealistic, coronal temperature were assumed. Years later, it became possible to reproduce the high speeds of the fast solar wind by assuming Kappa distributions at the exobase (Maksimovic et al. 1997a); this is because the suprathermal electrons tend to increase the flux of escaping electrons and therefore produce a larger accelerating electric potential for the protons. These early models assumed that the total proton potential energy (gravitational+electrostatic) is a monotonic decreasing function of the radial distance to the star. As a consequence, the exobase was implicitly assumed to be located close to the subsonic-supersonic transition level.

This model has been generalized by Lamy et al. (2003) and Zouganelis et al. (2004) by relaxing the requirement of the proton potential energy being monotonic. These authors found complete transonic solutions describing both the subsonic and the supersonic regimes of the fast solar wind. The basic outcome is a high value of the terminal bulk speed (700–800 km s^{-1}), compatible with observed fast solar wind speeds, by assuming a Kappa VDF for the high-energy electrons at the exobase without any assumption on energy transport. It is noteworthy that this result is not an artifact of the use of Kappa functions. Zouganelis et al. (2004) were able to obtain similar results assuming a sum of two Maxwellians, which is the most commonly used model to represent the electron VDFs in the solar wind.

Landi & Pantellini (2003) have presented self-consistent kinetic simulations of a stationary solar type wind using Maxwellian VDFs for the protons and the electrons. The model is spatially one-dimensional and spherical symmetric, but particles' velocities are three-dimensional. In order to allow for binary collisions, the following rule has been introduced: two particles crossing each other at relative velocity u at a distance r from the star may undergo an isotropic elastic collision with probability $\propto u^{-4}r^{-2}$. The u^{-4} dependence of the collision probability mimics the velocity dependence of the scattering cross section for Coulomb collisions, whereas the r^{-2} dependence accounts for the spherical geometry of the problem. The transport properties of such a plasma have been shown to be similar to those of a Fokker-Planck plasma (Pantellini & Landi 2001; Landi & Pantellini 2001). These kinetic simulations have shown that the existence of a transonic wind requires a minimum collisionality near the sonic point. In other words, the coronal density must exceed a threshold density for the wind acceleration to be sufficiently strong for the distant wind to be supersonic. It was also shown that the electron heat flux departs from the classical value (Spitzer & Harm 1953) in most of the acceleration region. In the next section we present new results from this model using Kappa VDFs for the electrons and the real value of the proton to electron mass ratio, unlike Landi & Pantellini (2003), who used a reduced mass ratio of 400 for computational reasons.

3. RESULTS

In both the exospheric models and the kinetic simulations, we use a Kappa VDF $f_\kappa(v) \propto (1 + v^2/\kappa v_\kappa^2)^{-(\kappa+1)}$. The equivalent Kappa temperature T_κ (defined from the second moment of the VDF, as the ratio between pressure and density) is related to the thermal speed v_κ by $T_\kappa = [\kappa/(2\kappa - 3)]m_e v_\kappa^2/k_B$, where k_B is the Boltzmann constant and m_e is the electron mass. For speeds smaller or comparable to v_κ, the Kappa VDF is close to a Maxwellian, having the same most probable speed v_κ. In contrast, for $v \gg v_\kappa$, the Kappa VDF decreases with v as a power law $f_\kappa \propto v^{-2(\kappa+1)}$. In the limit $\kappa \rightarrow \infty$, $f_\kappa(v)$ reduces to a Maxwellian VDF ($\propto e^{-v^2/v_\kappa^2}$). Note that when electron distributions measured in the solar wind are fitted with Kappa functions, the parameter κ ranges from 2 to 5 (Maksimovic et al. 1997b).

Besides the shape of the VDF, the physical state of the corona at heliocentric distance r_0 (exobase) is characterized by a key parameter, proportional to the ratio of the thermal energy of a proton to its gravitational energy

$$\alpha \equiv \frac{2v_{\rm th0}^2}{v_{\rm esc}^2} = \frac{2r_0 k_B T_0}{m_p MG} \propto r_0 T_0, \tag{1}$$

where M is the mass of the star and T_0 is the temperature at the base of the wind, assumed for simplicity to be the same for electrons and protons. In this case, the wind profiles can only depend on α and on the shape of the VDF.

Figure 1 summarizes our results. It shows the terminal bulk speed normalized to the proton thermal speed at the exobase as a function of α for different values of κ. Results are shown for the exospheric model (*solid lines*) and kinetic simulations (*dashed lines*). The rectangle in the upper left part of the figure covers the parameter space compatible with observational data for the fast solar wind. When α is large, the corona "explodes" and the wind starts at nearly supersonic velocity. This is the case studied by Lemaire & Scherer (1971) with a Maxwellian VDF and by Maksimovic et al. (1997a) with a Kappa VDF. For smaller values of α, the gravitational force holds most of the protons back, up to a radial distance where their potential

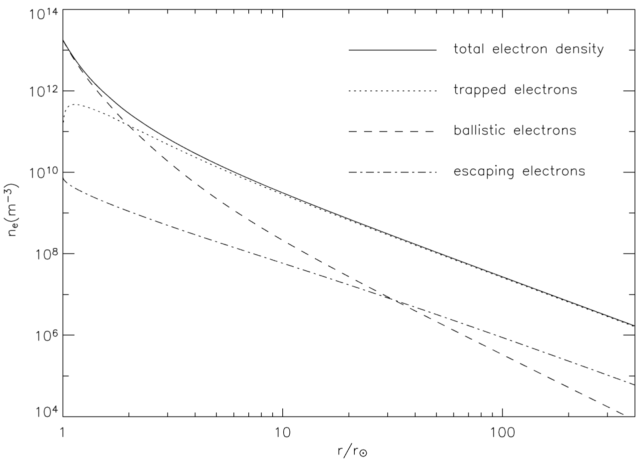

FIG. 2.—Electron density profile (*solid line*) for $\kappa = 2.5$. The other lines show the contributions of the different electron populations. Note that trapped electrons (*dotted line*) become predominant beyond a few solar radii.

energy goes through a maximum and where the wind is already supersonic. This case has been studied by Jockers (1970) with a Maxwellian VDF and by Lamy et al. (2003) and Zouganelis et al. (2004) with a Kappa VDF, a sum of two Maxwellians, and a sum of a Maxwellian and a Kappa function. The transition between a transonic and a supersonic wind takes place at $\alpha = 0.5$ in the traditional Parker model and at a slightly different value in the present models.

Note that the points in Figure 1 are *based on* the publications that they refer to but are not the explicit results of these publications. They are mainly illustrating the different validity range of these works. All exospheric curves (*solid lines*) were obtained using the model by Zouganelis et al. (2004). The simulation curves (*dashed lines*) were obtained using the model by Landi & Pantellini (2003) generalized to allow for Kappa electron VDFs as a boundary condition at the lower boundary of the simulation domain.

Solutions of the exospheric problem are simple for the case in which the wind is already supersonic at the base, since in this case the proton potential energy (gravitational+electrostatic) is a monotonic decreasing function of the radial distance. Any proton injected at the base is then doomed to escape to infinity, and both the terminal speed and the asymptotic temperatures can be calculated analytically (Meyer-Vernet & Issautier 1998). If the wind velocity at the base is subsonic (the solar wind case), a local maximum appears in the proton potential energy profile. Only a fraction of the protons injected at the base are then able to escape to infinity, and the acceleration is found to be weaker than in the case of a supersonic start at the base, at least for Maxwellian electron VDFs (Zouganelis et al. 2004).

When Kappa VDFs are used for the electrons, a larger acceleration is attained, as we can see in the curves based on Maksimovic et al. (1997a) and on Lamy et al. (2003) and Zouganelis et al. (2004) for $\kappa = 3$. For small values of α (subsonic at the exobase), the speed increases as α decreases, which means that the acceleration can be stronger for a lower temperature. This basic difference from the Maxwellian case is presumably due to the fact that the acceleration is mainly sustained by the excess of suprathermal electrons of the Kappa distribution and less dependent on the thermal energy.

The dashed curves in Figure 1 stem from kinetic simulations with collisions. When Maxwellian electron VDFs are injected at the lower boundary of the simulation, the results are remarkably similar to those obtained using Maxwellian distributions in the exospheric model. This means that neglecting collisions in the exospheric models has no significant consequences on the terminal bulk speed. When injecting Kappa electron VDFs at the lower boundary, the curves from the kinetic simulations with collisions are slightly different from those obtained with the corresponding exospheric model, but the qualitative behavior is similar (normalized terminal speed decreasing with α). In this case there is always some value of κ for the exospheric model giving the same results, in a large range of α, as the kinetic simulations with a lower κ. As we can see, the kinetic simulations with $\kappa = 3$ give almost the same results as the exospheric model for $\kappa = 4$ for fast solar wind–compatible parameters (although this does not imply a general rule). This suggests that collisions tend to reduce the wind acceleration for a given Kappa distribution.

However, the agreement between exospheric collisionless models and kinetic simulations with collisions is rather surprising. Indeed, the main criticism usually raised against exospheric models is their neglect of collisions. The relative agreement between the exospheric model and the kinetic model including collisions may be explained by the presence of trapped electrons in exospheric models. These electrons do not have enough energy to escape from the Sun and their inclination to the magnetic field lines is large enough that they are reflected by the magnetic mirror force before reaching the exobase. Trapped particles do not therefore exist at the exobase, despite the fact that they rapidly become the dominant component of the total electron density on the way from the exobase to the maximum of the proton potential energy and beyond. Figure 2 shows that at large radial distances, the trapped electrons represent more than 90% of the total electron density.

When completely withdrawing the trapped electrons from exospheric models, no supersonic wind solution can be found numerically. This is presumably due to the electron density being too small to ensure local plasma neutrality, together with a reasonable configuration of the proton potential energy. In other words, if all electrons do escape (except the small population of ballistic ones, falling back to the exobase), quasi-neutrality and zero electric current tend to become incompatible requirements of the model.

This is in agreement with kinetic simulations showing that collisions are necessary to accelerate the wind to supersonic velocities. Collisions are responsible for the transformation of ballistic particles into trapped ones. In exospheric models, trapped particles were historically added in order to avoid discontinuities in the VDFs at the interface between trapped and untrapped orbits in phase space, but they seem to be crucial for the acceleration of the wind to supersonic velocities. Their presence in exospheric models implies that the latter are not collisionless in a rigorous sense.

Note that a similar problem arises in the environment of space probes (Laframboise & Parker 1973). In that case, the small size of the probe makes the medium both fully collisionless (there are no trapped particles) and nonneutral; there is a nonzero space charge, albeit not exactly the canonical Debye sheath (see Meyer-Vernet 1993). In contrast, in the solar wind case, the plasma has to be neutral because the scales are much greater than the Debye length, and for this reason, the presence of trapped electrons is essential.

In simulations, collisions have been seen to serve to convert the electron heat flux into plasma bulk energy. We have compared the heat flux given by exospheric models and by kinetic simulations and found a qualitative agreement. As was pointed out by Landi & Pantellini (2003), the nonclassical term $q_{\rm NC} \propto (3/2)nvk_{\rm B}T_e$ of the electron heat flux introduced by Hollweg (1974) dominates the classical Spitzer-Harm term for the supersonic wind. With both the exospheric model and the simulations, we find a heat flux still several times greater than the above value. This suggests that the classical formulation is not the relevant one for such a semicollisional medium, which is not surprising as the Spitzer-Harm term was calculated upon the assumption of a collision-dominated plasma (Knudsen number much smaller than unity).

4. CONCLUSIONS

Exospheric models are aimed at explaining the strong acceleration of the fast solar wind in a self-consistent way with a minimum number of assumptions. In particular, no assumption on how energy is transported through the acceleration region needs to be included in the model. The model is admittedly oversimple in that it is one-dimensional, time-stationary, collisionless, and by construction free of any wave activity. However, the basic ingredients for powering stellar winds appear to be present, suggesting that propulsion by plasma waves is not necessarily needed to produce powerful transonic winds. Over the last three decades, various exospheric models were able to reproduce both the slow and the fast solar wind, albeit in restricted wind regimes only. For the first time, we generalize all previous models to a much wider range of parameters by varying both the temperature and the abundance of suprathermal particles. The generalization covers a large class of coronal conditions, including the solar corona case. For high-temperature coronas or large stellar radii or small stellar mass, the corona "explodes" and the wind starts supersonic at the exobase (nonsolar case). The solar case is different as the solar wind starts subsonic and becomes supersonic beyond a distance of some solar radii. Treating this case makes exospheric models much more complicated than before (an accurate numerical description has been recently given by Zouganelis et al. 2004).

We have also compared these models with kinetic simulations that include Coulomb-like collisions. These simulations have been made for the first time using non-Maxwellian functions. Rather unexpectedly, the results of exospheric models and kinetic simulations are in good agreement despite the wide difference in both the physics (collisionless vs. collisional) and the methodology. The agreement between the two approaches is likely due to the fact that a small amount of collisionality is implicit in exospheric models in that particle trajectories that are not accessible from the exobase are populated "by hand." The existence of trapped electrons in exospheric models is a necessary condition for the wind to be supersonic, just as collisions in kinetic simulations are necessary to produce a supersonic wind.

Exospheric models are able to reproduce the strong acceleration of the fast solar wind from the subsonic to the supersonic regime, provided the electron VDF has a suprathermal tail. The similarity of results from exospheric models and kinetic simulations with collisions suggests that the main role of collisions is to feed particles into trajectories that are not accessible from the exobase (the trapped particle trajectories). Indeed, a small number of collisions are implicitly included in exospheric models through the by-hand populating of the trapped particles populations. Even the high terminal speeds obtained in exospheric models do not seem to be a consequence of the collisionless nature of these models, the main reason for the strong acceleration being the presence of suprathermal electrons (e.g., Kappa distribution or a sum of two Maxwellians). Suprathermal electrons are found to collide very rarely because of the v^4 dependence of the collisional mean free path. Collisions can therefore modify the shape of the VDF at low energy, but the high-energy suprathermal tails are basically unaffected by collisions and so is the overall wind acceleration. Despite their intrinsic limitations, exospheric models are found to be a very convenient tool to explore the physics of weakly collisional solar-type winds.

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