Velocity Distributions and Proton Beam Production in the Solar Wind

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Abstract. Helios, Ulysses, and Wind spacecraft have observed the velocity distribution functions (VDFs) of solar wind particles deviating significantly from Maxwellians. We review recent models using different approximations and mechanisms that determine various observed characteristics of the VDFs for the electrons, protons and minor ions. A new generation mechanism is proposed for super-Alfvénic proton beams and tails that are often observed in the fast solar wind. The mechanism is based on the proton trapping and acceleration by kinetic Alfvén waves (KAWs), which carry a field-aligned potential well propagating with super-Alfvén velocities.

Keywords: kinetic Alfvén waves, velocity distribution function, solar wind
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INTRODUCTION

The observed velocity distribution functions of the particles contain useful information on the solar wind processes (see review by Marsch [1] and references therein). These observations can be compared with the results of solar wind models where the VDF of the particles is found as a solution using the kinetic approach. Different approximations can be used in such kinetic models and they give different VDF characteristics that are compared to typical VDF measured by spacecraft. Comparisons of collisionless (exospheric) models, collision-dominated models (Euler 5 moments for the simplest approximation) and models based on the solution of the Fokker-Planck equation are useful to study the effects of Coulomb collisions.

The abundant presence of Alfvén waves and turbulence observed in the solar wind require also inclusion of wave-particle interaction terms in the collisional integral. Previous work was focused mostly on ion interaction with high-frequency (ion-cyclotron) Alfvén waves (see review by Hollweg and Isenberg [2] and references therein), for which there are observational evidences [3]. There are also observational evidences for low-frequency KAWs in the solar wind ([4], and references therein), but their influence on VDFs is studied insufficiently. In Section 4 we propose a new mechanism involving KAWs - proton trapping and acceleration by the field-aligned wave potential. We suggest that this process can be responsible for the formation of proton beams and tails observed in the solar wind (see [5] and two examples from Helios measurements in Fig. 1).

ELECTRONS

Typical electron VDFs are characterized by a thermal core, a suprathermal halo and a strahl population along the magnetic field direction [6]. Such distributions with suprathermal tails are well fitted by so-called Kappa distributions [7]. Considering the presence of suprathermal electrons in exospheric collisionless models based on the solution of Vlasov equation, Maksimovic et al. [8] have shown that the energetic electrons play an important role in the acceleration of the solar wind to high bulk velocities. Indeed, the presence of suprathermal electrons increases the electrostatic potential difference between the solar corona and the interplanetary space and thus increases the solar wind velocity [9]. This acceleration is especially large when it takes place at low radial distances in the coronal holes where the number density is lower than in other regions of the corona [10]. A similar acceleration appears also in the polar wind escaping from the giant planets when suprathermal particles are assumed to be present in their VDF at low radial distances [11].

Adding the effects of the Coulomb collisions, a kinetic solar wind model based on the solution of the Fokker-Planck equation was developed [12]. The authors showed that the suprathermal tails can be present even at low radial distances in the solar corona, due to the low effects of Coulomb collisions on the energetic particles. The model also showed the transformation of the velocity distribution function of the electrons in the transition region between the collision-dominated region in the corona and the collisionless region at larger radial distances [13]. The VDF became more and more anisotropic in the transition region.

The VDF obtained with the Fokker-Planck model is

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very different from a simple displaced Maxwellian used in the Euler (five moments) approximation. This VDF is obtained only in collision-dominated plasmas and characterizes only the thermal component. The solar wind model based on the solution of the Fokker-Planck equation reproduces the core and the halo components, as well as the strahl component due to the presence of the magnetic field.

PROTONS

Typical proton VDFs observed in the solar wind are characterized by an anisotropic core with $T_\perp > T_\parallel$ and a proton beam aligned with the magnetic field direction [5, 1]. Purely exospheric models give values in good agreement with the solar wind observations for the number density, bulk velocity and average temperatures [14]. Nevertheless, the VDFs of the particles are sharply truncated and give too high temperature anisotropies at large radial distances compared to the observations, due to the conservation of the magnetic moment. In addition to core protons and electrons, proton (and heavier ion) beams and/or high-energy tails are often observed in the fast solar wind (see Fig. 1, [1] and references therein).

There are several possibilities to explain the origin of these beams (see [15] and references therein). Firstly, they can be injected in the solar wind by magnetic reconnection events at the coronal base. Secondly, the proton beams can be produced in the acceleration region at heliocentric distances 1.1-3 solar radii by the proton collisional runaway, or by the mirror force acting on the forward part of the proton velocity distribution. In particular, Coulomb collisions have been investigated by [16] to determine their influence on the generation of the proton tails and beams. Third, the beams can be produced gradually by the evolution of the proton velocity distributions under the action of wave-particle interactions in the extended region in the solar wind from the acceleration region to $r > 0.3$ AU where they are observed. So, in [15] a mechanism has been proposed for the proton beam formation based on the proton-cyclotron resonant interaction with cyclotron modes that can exist in the presence of alpha particles drifting with Alfvén velocity.

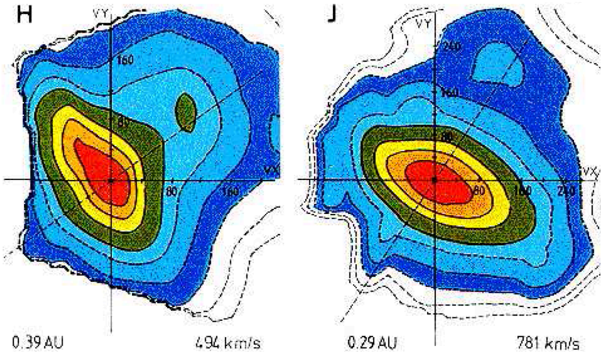

FIGURE 1. Contour plots of proton velocity distributions with beams in the solar wind (from Marsch [1]). Straight dash lines show the directions of the local magnetic field along which the proton beams propagate.

Recently Araneda et al. [17, 18] have studied parametric instabilities driven by Alfvén-cyclotron waves and their influence on solar wind ions. It was shown that product waves generated by these instabilities can lead to a selective heating and acceleration of different ion species, generating in particular a proton beam with drift speed of about the Alfvén speed. However, as there are pros and contras against all mentioned above mechanisms, we do not have a definite answer about the physical mechanism producing proton beams. In view of KAW activity observed in the solar wind [19, 20, 21], we propose the following scenario for the proton beam formation.

PROTON BEAM PRODUCTION BY KINETIC ALFVÉN WAVES

Recent investigations suggest that the wave-particle interactions in the solar wind are dominated not by ion-cyclotron waves with short wavelengths along the background magnetic field, but by waves with short cross-field wavelengths, i.e. in the wavelength range where kinetic Alfvén waves reside (see e.g. [22, 4], and references therein). Having this in mind, we propose a new generation mechanism for the proton beams based on the proton trapping and acceleration by KAWs. Our model implies a flux of MHD Alfvén waves converting into KAWs linearly and/or nonlinearly. When the proton gyroradius/cross-field wavelengths ratio becomes sufficiently large, the parallel potential well carried by the KAWs traps a fraction of core protons and accelerates them along the background magnetic field $\mathbf{B}_0$, as is illustrated in Fig. 2. The acceleration of trapped protons is caused by the accelerated KAW propagation under the condition that the normalized cross-field wave vector $k_\perp \rho_p$ increases ($\rho_p = V_{p\perp}/\Omega_p$ is the proton gyroradius, Ω_p is the proton cyclotron frequency, $V_{p\perp} = \sqrt{T_{p\perp}/m_p}$, $T_{p\perp}$ is the proton temperature in the plane $\perp \mathbf{B}_0$, m_p is the proton mass). There are several mechanisms in the solar wind, which can increase perpendicular wavenumber, like phase mixing in shear plasma flows, or in cross-field plasma inhomogeneities [22], or turbulent cascades [4]. We do not specify here the mechanism that increases $k_\perp \rho_p$, but study its consequences.

Kinetic Alfvén wave (KAW) is the extension of MHD Alfvén wave in the range of short cross-field wavelengths comparable to the ion gyroradius ρ_i ($k_\perp \rho_i \sim 1$), and/or electron inertial length δ_e ($k\delta_e \sim 1$). Consider a harmonic KAW with wave frequency ω and wave vector $\mathbf{k} = (k_\perp; 0; k_z)$, $k_\perp \gg k_z$, in the two-fluid hydrogen plasma model [23]. In the solar wind at distances $r > 20$, where $\rho_T^2/\delta_e^2 > 1$, the wave dispersion is determined by the thermal effects, and we can use an approximate expression for the KAW phase velocity:

$$V_k \equiv \frac{\omega}{k_z} \simeq V_A \sqrt{1 + k_\perp^2 \rho_T^2}, \qquad (1)$$

where $\rho_T^2 = \left(1 + T_{e\parallel}/T_{p\perp}\right)\rho_p^2$, $\rho_p = V_{p\perp}/\Omega_p$ is the proton gyroradius, $V_{p\perp(\parallel)} = \sqrt{T_{p\perp(\parallel)}/m_p}$ is the perpendicular (parallel) proton thermal velocity, $V_A = B_0/\sqrt{4\pi n m_p}$ is the Alfvén velocity, $\Omega_p = eB_0/(m_p c)$ is the proton cyclotron frequency, $\delta_e = V_A/\Omega_p \sqrt{m_e/m_p}$ is the electron inertial length.

KAWs possess a parallel electric potential φ_k given by

$$\frac{e}{T_e}|\varphi_k| = \frac{V_A}{V_{p\perp}} \frac{k_\perp \rho_p}{\sqrt{1 + k_\perp^2 \rho_T^2}} \frac{B_{k\perp}}{B_0}, \qquad (2)$$

where $B_{k\perp}$ is the wave magnetic amplitude. For small $k_\perp \rho_p \to 0$ the parallel electric potential $\varphi_k \to 0$ and the wave phase velocity $V_k \to V_A$, as in classic Alfvén waves. With increasing $k_\perp \rho_p$ KAWs' potential φ_k increases (hence proton trapping) and propagates with growing velocity V_k (hence proton acceleration). For particular $k_\perp \rho_p$ all the protons in the velocity range

$$\frac{|V_z - V_k|}{V_{p\parallel}} < \sqrt{\frac{4e}{T_p}|\varphi_k|} \qquad (3)$$

are trapped. This trapping condition follows from the requirement that the kinetic energy of trapped protons should be less than the potential depth $2e|\varphi_k|$.

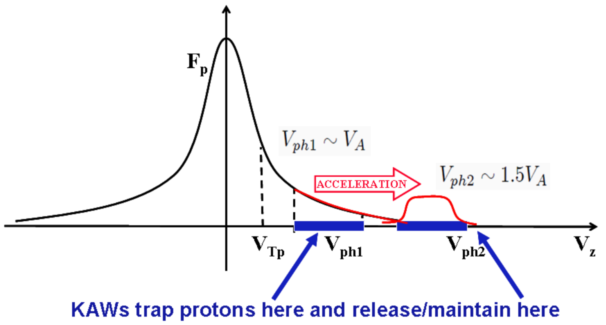

FIGURE 2. A sketch of the proton trapping and acceleration by KAWs. Low-dispersive KAWs (phase speed V_{ph1}) trap protons with velocities $V_z \sim V_{ph1}$ and accelerated them by the increasing phase speed up to $V_z \sim V_{ph2}$, where the KAWs' energy is exhausted.

Using particular solar wind models in the above expressions, it is possible to proceed with numerical simulations, which is the subject of our ongoing study. Here, we demonstrate the efficiency of the proposed mechanism by the following numerical example:

(1) consider a KAW with $k_\perp \rho_p = 0.3$ and $B_k/B_0 = 0.1$ in a plasma with $\beta_p \left(= V_{p\parallel}^2/V_A^2\right) = 0.25$;

(2) such KAWs trap protons with velocities $V_z \gtrsim V_{Tp}$ and number density $n_b \lesssim 0.1 n_0$;

(3) with $k_\perp \rho_p$ increasing to $k_\perp \rho_p = 1.12$, the trapped protons are accelerated to $V_b = \langle V_z \rangle \simeq V_k \simeq 1.5 V_A$;

(4) the above estimations are energetically and kinematically self-consistent and compatible with solar wind observations.

Heavier ions should undergo a similar trapping/acceleration by KAWs, but more complicated by their larger gyroradius as compared to the protons.

IONS

Solar wind ion distribution functions have been measured by WIND for ^{20}Ne, ^{16}O and ^{4}He [24]. Because such ions are present in low quantities, the observations are averaged over several days. Such distributions are also observed to be characterized by suprathermal tails and have been fitted by Kappa functions. Moreover, the ions in the high speed solar wind are characterized by a temperature more than proportional to their mass [25].

Different processes have been suggested to explain such high temperatures and were presented in [25]. Ion-cyclotron waves for instance is a possible scenario. The velocity filtration effect, as suggested initially by [26], is an alternative interesting mechanism leading to temperatures more than proportional to the ion mass. As shown in [27] with a model of the corona in hydrostatic equilibrium, VDFs of particles characterized by an enhancement of suprathermal particles lead to a filtration effect that predicts ion coronal temperatures more than proportional to the mass of the ions, with a small correction for the charge state.

Whatever is the heating process in the solar corona, Pierrard et al. [28] have shown that sufficiently high temperatures of the ions in the low corona can cause their acceleration to bulk velocities larger than that of the protons, as it is indeed often observed for the Helium ions in the high speed solar wind. This process is efficient for light ions that are highly ionized.

DISCUSSION AND CONCLUSIONS

As it has been stated before (see e.g. [2], and references therein), the variety of particle velocity distributions observed in the solar wind cannot be explained by a single mechanism. Kinetic plasma models including Coulomb collisions with proper boundary conditions are capable in reproducing solar wind speeds and number densities compatible with observations. But such salient features as temperature anisotropies and ion beams propagating with super-Alfvén velocities require an additional energy source. An obvious source for that is provided by Alfvén waves carrying sufficient energy fluxes for additional cross-field ion heating and beam production. We therefore include wave-particle interactions and suggest a new mechanism for the proton beam production via proton trapping and acceleration by KAWs.

Our scenario for the proton beam formation in the solar wind is as follows. At first stage, in the vicinity of the solar wind base (or at some distance from the Sun inside 0.3 AU), a part of the Alfvén wave flux develops high cross field wave numbers $k_\perp \rho_p \gtrsim 0.1$. Such Alfvén waves carry a significant parallel electric potential (2) and trap protons in the velocity interval given by (3). If the normalized wave number $k_\perp \rho_p$ continues increasing, the trapped proton fraction is accelerated by the accelerated wave propagation since the KAW phase velocity increases with increasing $k_\perp \rho_p$, in accordance with (1). In such a way the trapped proton fraction detaches from the main proton component and forms the super-Alfvénic proton beam. The number density and energy content in this beam depends on the energy content in KAWs. In principle, the observed proton beams can be generated by KAWs with magnetic amplitudes smaller than those used in our numeric example ($B_k/B_0 = 0.1$). In that case, instead of a single high-amplitude KAW, a sequence of lower-amplitude KAWs (e.g. resulting from different parts of Alfvén wave spectrum) should develop at different distances high enough wavenumbers $k_\perp \rho_p \gtrsim 0.1$ to produce a chain of acceleration events whose cumulative result will be again the super-Alfvénic proton beams of the same intensity as in the case of single high-amplitude KAW.

The observational evidences for KAWs in solar wind have been found mainly in wave data ([4] and references therein). Concerning particle data we suppose that the same KAWs producing proton beams should also be able to generate heavier ion beams with super-Alfvénic velocities. KAWs should influence also electron distributions, producing local deviations from Maxwellian in the range of resonant velocities spanned by the wave phase velocities. These are subjects for our ongoing study.

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