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Apparent temperature anisotropies due to wave activity in the solar wind

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Abstract. The fast solar wind is a collisionless plasma permeated by plasma waves on many different scales. A plasma wave represents the natural interplay between the periodic changes of the electromagnetic field and the associated coherent motions of the plasma particles. In this paper, a model velocity distribution function is derived for a plasma in a single, coherent, large-amplitude wave. This model allows one to study the kinetic effects of wave motions on particle distributions. They are by in-situ spacecraft measured by counting, over a certain sampling time, the particles coming from various directions and having different energies. We compare our results with the measurements by the Helios spacecraft, and thus find that by assuming high wave activity we are able to explain key observed features of the measured distributions within the framework of our model. We also address the recent discussions on nonresonant wave–particle interactions and apparent heating. The applied time-averaging procedure leads to an apparent ion temperature anisotropy which is connected but not identical to the intrinsic temperature of the underlying distribution function.

Keywords. Interplanetary physics (Solar wind plasma) – Radio science (Waves in plasma) – Space plasma physics (Wave-particle interactions)

1 Introduction

It has been known for a long time that the solar wind is a turbulent plasma with wave activity occurring on a wide range of different scales (Belcher and Davis, 1971; Tu and Marsch, 1995; Horbury et al., 2005). Of course, any plasma wave has to fulfill the Vlasov-Maxwell equations, and it can therefore be understood as the space- and time-dependent self-consistent interplay between the periodic variations of the electromagnetic field and related motions of the particles, being represented by their velocity distribution function (VDF).

In the recent literature, the shaping of distribution functions due to wave activity has been widely discussed (Wang et al., 2006; Wu and Yoon, 2007; Wu et al., 2009; Wang and Wu, 2009). Obviously, the presence of wave forces (or their spectra) will lead to a deformation of the distribution function with respect to a Maxwellian shape and cause a velocity spreading after appropriate averaging over the wave effects. The plasma-physics definition of temperature is based on a statistical particle ensemble and usually defined in terms of the random kinetic energy (via the mean square of the particle velocity) in the particles' mean-velocity frame. This definition of temperature is not necessarily equal to the thermodynamic temperature, which may be called the "intrinsic temperature" of the particle ensemble. The mean square velocity fluctuation owing to wave activity is able to cause an effective broadening of the distribution function similar to real heating, and thus may mimic genuine heating. Therefore some authors have referred to this process as "apparent heating" (Wang et al., 2006), others as "nonresonant wave–particle interactions". The common ground of these wave effects is that they are reversible, and therefore not dissipative, and do not represent real heating. Collisions, however, might be able to dissipate coherent wave motion efficiently, and thus will lead to a real heating and an increase in the intrinsic temperature (Schekochihin et al., 2008; Howes, 2008). In the following, collisions are excluded from the treatment of the VDFs, in order to demonstrate the collisionless effects of waves and reveal the apparent heating due to wave activity.

Substantial ion temperature anisotropies have been observed in the solar wind and discussed by different authors (Marsch et al., 1981, 2004; Bale et al., 2009; Bourouaine et al., 2010). Typically the proton temperature is higher perpendicular to the magnetic field than parallel to it. These anisotropies have mostly been discussed as being the result

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of the cyclotron-resonant interaction with circularly polarized waves, a process which can be quantified by means of quasi-linear theory (e.g. Akhiezer et al., 1975b; Heuer and Marsch, 2007). On the other hand, such anisotropic distribution functions can become unstable if the anisotropy exceeds a certain threshold that depends on the plasma beta (Gary et al., 2000, 2001). For a typical solar wind beta of about 1, the beta dependence is not severe and the distribution function becomes unstable for $T_\perp/T_\parallel \gtrsim 2$. This instability can in turn excite and radiate ion-cyclotron waves. In this way, wave excitation can reduce the ion temperature anisotropy efficiently and yield moderate and stable values (Gary, 1993; Bale et al., 2009).

The general theory of this wave–particle interaction is well established, and in fact many traits of it were confirmed by observations (Marsch, 2006). However, the apparent heating effects are not well understood and have not yet been discussed in the context of ion–wave interactions below and near the ion inertial scale. Yet, they should be included in an appropriate description of space plasmas that are subjected to strong Alfvén/ion-cyclotron wave activity, such as it is typical for the solar wind in the inner heliosphere. To study possible physical causes of apparent wave heating is the aim of the present paper. First, we discuss the effect of a strong plasma wave on an intrinsically Maxwellian distribution function. Second, a concise form of the resulting model VDF is constructed, and thus we can discuss how such a distribution function would look like in a real plasma measurement made on a space probe.

2 Model distribution functions

2.1 Wave effects on the distribution function

To study the effects that waves have on the shape of a velocity distribution function, we have to determine the constants of individual particle motion in a given wave field, and then exploit the fact that any function of these constants of motion is a solution of the Vlasov equation (Davidson, 1983; Stix, 1992). Here, we discuss the influence of a single monochromatic wave only. It is supposed here to be transversal and left-hand circularly polarized, and its magnetic field can be assumed to have the form

$$\boldsymbol{B} = \begin{pmatrix} b\cos(kz-\omega t) \\ b\sin(kz-\omega t) \\ B_0 \end{pmatrix}, \tag{1}$$

with the constant field component B_0 along the z-axis and a wave amplitude b. The wave frequency is ω and the parallel wavenumber k, and its magnetic field is associated with an electric field which according to Faraday's law is given by

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}. \tag{2}$$

The equation of motion for a single particle with charge q and mass m in this electromagnetic field is determined by the Lorentz force:

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = \frac{q}{m}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v}\times\boldsymbol{B}\right). \tag{3}$$

It is useful and transparent to write this equation in the components of a cylindrical coordinate system (symmetry around the z-axis) as follows:

$$\frac{\mathrm{d}v_\perp}{\mathrm{d}t} = \Omega\left(\frac{\omega}{k} - v_\parallel\right)\frac{b}{B_0}\sin(\phi-\varphi), \tag{4}$$

$$\frac{\mathrm{d}v_\parallel}{\mathrm{d}t} = \Omega v_\perp \frac{b}{B_0}\sin(\phi-\varphi), \tag{5}$$

$$\frac{\mathrm{d}\varphi}{\mathrm{d}t} = -\Omega\left[1+\left(\frac{\omega}{k}-v_\parallel\right)\frac{1}{v_\perp}\frac{b}{B_0}\cos(\phi-\varphi)\right], \qquad v_\perp \neq 0, \tag{6}$$

where we made use of the abbreviation $\phi = kz - \omega t$ for the wave phase. The gyrofrequency is denoted by $\Omega = qB_0/(mc)$. A similar set of equations has already been used in a test-particle description to describe the nonlinear behavior of particles that are trapped in the wave fields (Matsumoto, 1979). Also nonresonant heating effects have been treated with similar equations under the assumption of low plasma betas both in the monochromatic parallel case and for a spectrum of oblique MHD waves (Hamza et al., 2006; Lu and Li, 2007; Li et al., 2007; Lu and Chen, 2009). However, the initial conditions in these cases break the condition of the coherent particle motion that is necessary to maintain the wave in a self-consistent way. Neglecting the coherence and violating the self-consistency may be an appropriate description for a minor particle species in the sense of a test-particle approach. But the description is insufficient for the dominating main species that carry the currents and charges maintaining the wave itself. Li et al. (2007) also consider consistent initial conditions that do reflect the coherent wave motion and find that these particles do not experience the nonresonant heating because they are not picked-up by the wave fields. A model for the coherent particle motion of the dominating species in a wave field at high plasma betas should be based on a Vlasov description to take the finite thermal width of the distribution into account. Numerical self-consistent simulations are another approach to this problem (e.g. Li and Habbal, 2005; Araneda et al., 2008, 2009; Maneva et al., 2010). In order to determine an adequate model distribution function, we first can determine two constants of motion for the kinematic system from Eqs. (4)–(6). These are the generalized momentum of the particle and its total kinetic energy in the wave frame:

$$M = v_\perp\cos(\phi-\varphi) + \frac{B_0}{b}v_\parallel\left[1-\frac{\omega}{\Omega}+\frac{kv_\parallel}{2\Omega}\right], \tag{7}$$

$$P = v_\perp^2 + \left(v_\parallel - \frac{\omega}{k}\right)^2. \tag{8}$$

Both M and P can be shown to be constant, simply by taking the derivatives with respect to t and using the equations of motion in Eqs. (4)–(6). It is known (Akhiezer et al., 1975a) that any distribution function which is a function of these constants of motion always fulfills the Vlasov equation. Therefore, we can make the ansatz

$$f = N \exp\left(-\frac{P}{v_{\mathrm{th}}^2}\right) \exp\left(\frac{2V_{\mathrm{w}}M}{v_{\mathrm{th}}^2}\right), \tag{9}$$

with the normalization factor N and constant coefficients v_{th} and V_{w}, which we can essentially define as the density, thermal velocity of the VDF and mean fluid-velocity amplitude of the particles in association with the wave motion.

The right second term in the expression for M compensates the frame-shift of $v_\parallel$ by ω/k in the definition of P, if the condition

$$V_{\mathrm{w}} = -\frac{b}{B_0} \frac{\omega/k}{1-\omega/\Omega} \tag{10}$$

is fulfilled, and if we can ignore the weak effects due to a small spread in the parallel direction ($kv_\parallel \ll \Omega$). Interestingly enough, this relation then corresponds to the wave polarization relation found by Sonnerup and Su (1967) for a circularly polarized wave with a vanishing parallel bulk drift. In their classical solution, they showed that the transversal velocity is determined by

$$\boldsymbol{V}_{\mathrm{t}} = -\frac{\omega/k}{1-\omega/\Omega} \frac{\boldsymbol{B}_{\mathrm{t}}}{B_0} \tag{11}$$

for vanishing drifts in the z-direction. We define the transversal magnetic field vector as $\boldsymbol{B}_{\mathrm{t}} = (B_{\mathrm{x}}, B_{\mathrm{y}}, 0)$, with the first two components as obtained from Eq. (1). The dispersion relation of the waves was also given in that work and can be written as

$$k^2 + \sum_j \frac{1}{\ell_j^2} \frac{\omega}{\omega - \Omega_j} = 0, \tag{12}$$

whereby the small displacement current in Maxwell's equations was neglected. The index j numbers all participating species (in the case considered later only protons and electrons), and $\ell_j = c/\omega_j$ is the corresponding inertial length, with the species' plasma frequency $\omega_j = \sqrt{4\pi n_j q_j^2/m_j}$.

We find that after normalization the non-gyrotropic model VDF of the particles in response to the wave forces reads

$$f_{\mathrm{w}}(v_\perp, v_\parallel, \varphi) = \frac{n_0}{\pi^{3/2} v_{\mathrm{th}}^3} \exp\left(-\frac{V_{\mathrm{w}}^2 + \omega^2/k^2}{v_{\mathrm{th}}^2}\right) \times \\ \times \exp\left(-\frac{v_\perp^2 + v_\parallel^2}{v_{\mathrm{th}}^2}\right) \exp\left(\frac{2v_\perp V_{\mathrm{w}}}{v_{\mathrm{th}}^2} \cos(\phi - \varphi)\right). \tag{13}$$

The first exponential stems from the normalization and does not change the structure of the distribution function, but depends on the particles sloshing velocity amplitude, V_{w}, and wave phase speed, ω/k. It is interesting to note, that this model distribution function is equal to a Maxwellian distribution in cylindrical coordinates, yet which is shifted by $\boldsymbol{V}_{\mathrm{t}}$ in the transversal direction and can be written in this shifted Maxwellian form as

$$f \sim \exp\left(-\frac{(v_{\mathrm{x}} - V_{\mathrm{x}})^2 + (v_{\mathrm{y}} - V_{\mathrm{y}})^2}{v_{\mathrm{th}}^2}\right), \tag{14}$$

with the cartesian speed components V_{x} and V_{y} reflecting the rigid displacement of the whole VDF in the wave field. This is an ansatz commonly used to initialize consistently numerical simulations (Araneda et al., 2008), and represents the sloshing motion of particles in the wave field (e.g. Markovskii et al., 2009).

A VDF that has an additional intrinsic temperature anisotropy is supposed to be represented by a modified bi-Maxwellian distribution. The appropriate choice for a VDF in a wave field including an intrinsic temperature anisotropy is given by

$$f_{\mathrm{a}} \sim \exp\left(-\frac{V_{\mathrm{w}}^2}{v_{\mathrm{th}\perp}^2} - \frac{\omega^2/k^2}{v_{\mathrm{th}\parallel}^2}\right) \exp\left(-\frac{v_\perp^2}{v_{\mathrm{th}\perp}^2} - \frac{v_\parallel^2}{v_{\mathrm{th}\parallel}^2}\right) \times \\ \times \exp\left(\frac{2v_\perp V_{\mathrm{w}}}{v_{\mathrm{th}\perp}^2} \cos(\phi - \varphi)\right), \tag{15}$$

where different thermal speeds in the perpendicular and parallel direction are chosen to account for the intrinsic anisotropy. It is important to note, however, that this distribution function is not an exact solution of the Vlasov equation anymore. Without wave activity, this distribution function obtains the usual bi-Maxwellian form. We do not apply this modified bi-Maxwellian VDF in the following since we focus our considerations on the role of apparent temperature anisotropies only.

2.2 Wave effects on particle measurements

The solar wind is permeated by magnetic field fluctuations and waves (Tu and Marsch, 1995) of all kind. A particle detector that is able to determine the velocity distribution function of particles (e.g., such as flown onboard the Helios spacecraft) counts particles in different energy and direction channels, and thereby integrates the net particle fluxes into the various single channels over the so-called sampling time T. In a first approximation, we may interpret this time as kind of an exposure time (like in photography), and thereby neglect time-dependent sampling effects on the instrument's pointing direction (to different solid looking angles), or on the accessibility of the particles to the different energy channels during the measurement cycle. Effects of the proper motion of the detector with respect to the solar wind flow are also neglected for the first estimation. A possibility to handle the effects arising from this relative motion would be to treat the waves as frozen in the solar wind and being with the fixed spatial structure convected over the space probe. This assumption is called Taylor hypothesis and is valid only for $\boldsymbol{k}\cdot\boldsymbol{V}_{\mathrm{SW}}\gg\omega$, where $\boldsymbol{V}_{\mathrm{SW}}$ denotes the solar wind flow velocity. Since the Alfvén speed is typically about a factor of 10 less than the flow speed of the solar wind in the spacecraft reference frame, this Doppler effect would even increase the sampling problem because waves with lower wavenumbers appear at higher frequencies for the detector. These lower wavenumber structures typically have a higher power than waves at higher wavenumbers. Therefore, the relative motion of the solar wind with respect to the spacecraft amplifies the wave effect on the measured distribution function additionally.

Such a model instrument would not be able to take snapshots of the VDF but integrate the sloshing distribution over time T, and would therefore obtain a spread in the VDF due to the wave activity. In the following, we determine theoretically the influence of this final integration time on the actual measurement.

The relevant spectral range is limited to frequencies that are higher than the sampling frequency, $2\pi/T$, because slower motions would be more or less resolved. They would merely lead to a rigid shift of the full distribution function without deformation. The analysis software of a plasma instrument would set the origin of the reference frame to the shifted center of the VDF, so that no change would be detectable. On the upper frequency side, the acting part of the wave spectrum should be limited by the gyrofrequency, because the waves are supposed to be strongly damped in the case of Alfvén-cyclotron waves at this scale, and thus beyond it the observed spectral energy goes down significantly. The slope of the spectral energy density follows Kolmogorov's law at lower frequencies (Tu and Marsch, 1995). Numerical simulations show that at wave numbers around $k\approx 0.8/\ell_{\mathrm{p}}$ the Alfvén/ion-cyclotron spectral slope usually breaks because of the onset of dissipation at these scales (Ofman et al., 2005). Here, we only assume a monochromatic wave with $\omega=2\pi/T$.

Given all these assumptions, the time-averaging process of the VDF under the influence of waves, f_{w}, may be expressed mathematically as

$$\bar{f}=\frac{1}{T}\int\limits_{0}^{T} f_{\mathrm{w}}\mathrm{d}t. \tag{16}$$

We can now insert our model function of Eq. (13), in which the last exponential factor can be expanded (Abramowitz and Stegun, 1972) and represented by a sum over modified Bessel functions according to the relation:

$$e^{a\cos b}=I_0(a)+2\sum_{m=1}^{\infty}I_m(a)\cos(mb). \tag{17}$$

The time dependence of the averaged distribution function $\bar{f}$ is hidden in the wave phase, $\phi(t)$. The coordinates of the distribution function (i.e., z, $v_\perp$, and $v_\parallel$) have no time dependence in this context. The expression for f_{w} in Eq. (13) delivers a value of the VDF at each position in phase space and at each time. Without any restriction, the spatial position can be taken $z=0$. Then the time-averaged distribution function can be written as

$$\bar{f}=N\exp\left(-\frac{v_\perp^2+v_\parallel^2}{v_{\mathrm{th}}^2}\right)\left[I_0\left(\frac{2v_\perp V_{\mathrm{w}}}{v_{\mathrm{th}}^2}\right)+\right.$$
$$\left.+\frac{2}{T}\sum_{m=1}^{\infty}I_m\left(\frac{2v_\perp V_{\mathrm{w}}}{v_{\mathrm{th}}^2}\right)\frac{\sin(m\omega T+m\varphi)-\sin(m\varphi)}{m\omega}\right] \tag{18}$$

We find that the sum is always zero for all possible positions in φ if $\omega=2\pi/T$. So we can simplify the above formula and write

$$\bar{f}_1=N\exp\left(-\frac{v_\perp^2+v_\parallel^2}{v_{\mathrm{th}}^2}\right)I_0\left(\frac{2v_\perp V_{\mathrm{w}}}{v_{\mathrm{th}}^2}\right), \tag{19}$$

and thus we see that the intrinsically non-gyrotropic distribution function appears to become gyrotropic again after this kind of averaging process. A wider spectrum of waves could lead to a deformation of the distribution function still in the coordinate φ, but as stated above the higher frequencies on shorter time scales than the sampling time T are not expected to change the result much.

We assume next an Alfvén-cyclotron wave. This wave has to fulfill a dispersion relation, which can be taken from the cold plasma limit, yielding the dispersion relation as

$$\left(\frac{\omega}{\Omega_{\mathrm{p}}}\right)^2=(k\ell_{\mathrm{p}})^2+\frac{1}{2}(k\ell_{\mathrm{p}})^4-\frac{1}{2}(k\ell_{\mathrm{p}})^3\sqrt{(k\ell_{\mathrm{p}})^2+4} \tag{20}$$

(Stix, 1992; Chandran et al., 2010). For high values of k, the dispersion shows the asymptotical behavior $\omega\to\Omega_{\mathrm{p}}$, which can be seen by expanding the function $\sqrt{1+x}$ with $x=4/(k\ell_{\mathrm{p}})^2$ to second order. Typical solar wind parameters are used for a distance between spacecraft and sun of about 0.5 AU, which is where strongly non-Maxwellian distributions and high wave activity were usually observed in fast solar wind by the Helios spacecraft. The plasma beta is set to 0.1 and the sampling time to 10 s, which is the real sampling time of the Helios spacecraft. The constant background magnetic field B_0 is assumed to be 5×10^{-4} G, and the proton density to be $n=10\,\mathrm{cm}^{-3}$. The relative wave amplitude is set to $b/B_0=0.25$. The distribution function at $\varphi=\pi$ is plotted at negative values for $v_\perp$, in order to make plots that can more easily be compared with the observations. The calculated distribution function is shown in Fig. 1.

Heavy ions, which are also present in the solar wind (von Steiger, 2008), react on the wave field in a slightly different way. The dependence of V_{w} on the charge-to-mass

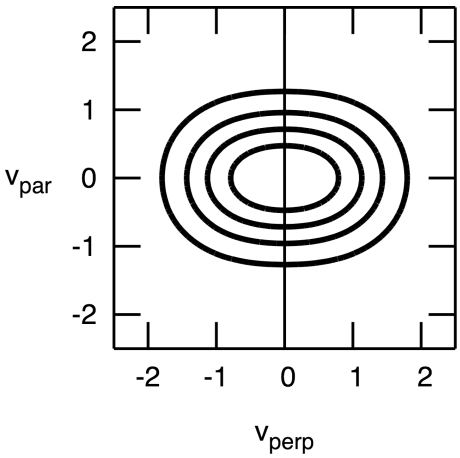

Fig. 1. Distribution function in the presence of a large-amplitude wave. The solid line represents the magnetic field direction. The velocities are given in units of the thermal speed. The broadening in the perpendicular direction is clearly visible.

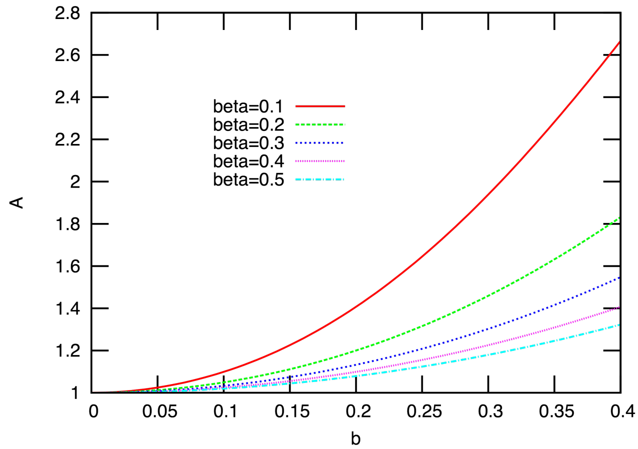

Fig. 2. Apparent temperature anisotropy in dependence on the normalized amplitude b of a wave with $\omega = 2\pi/T$. The evaluation of the anisotropy according to Eq. (21) is shown for different values of the plasma beta.

ratio in Eq. (10) is small for lower frequencies. The thermal speed, however, is significantly lower than the proton thermal speed by a factor of $\sqrt{m_{\mathrm{p}}/m_{\mathrm{i}}}$. Therefore, the distribution function of heavy ions is more narrow than the proton distribution function but shifted by the same amount due to the wave motion as can be seen in Eq. (13). This can lead to a more severe deformation of the distribution function after the averaging process, which might also lead to ring-like apparent VDFs for heavy ions in strong wave fields.

The apparent temperature anisotropy can now be calculated by taking the second moment of the distribution function according to the formula:

$$A = \frac{T_\perp}{T_\parallel} = \frac{\int\limits_{-\infty}^{+\infty}\int\limits_{0}^{+\infty} \bar{f}_1 v_\perp^3 \,\mathrm{d}v_\perp \mathrm{d}v_\parallel}{2\int\limits_{-\infty}^{+\infty}\int\limits_{0}^{+\infty} \bar{f}_1 v_\parallel^2 v_\perp \,\mathrm{d}v_\perp \mathrm{d}v_\parallel}. \tag{21}$$

The integration over φ leads to the factor 2 in the denominator. The above distribution function of Fig. 1 has an apparent temperature anisotropy of $A = 1.64$.

By varying the wave parameters and the particle thermal speed, corresondingly varying forms of the distribution function can be created. The dependence of the resulting apparent temperature anisotropy on the plasma beta and the wave amplitude b is shown in Fig. 2.

The obtained distribution function looks from the first point of view very similar to a classical bi-Maxwellian distribution function of the form

$$f_{\mathrm{bm}} \sim \exp\left(-\frac{v_\perp^2}{v_{\mathrm{th}\perp}^2} - \frac{v_\parallel^2}{v_{\mathrm{th}\parallel}^2}\right). \tag{22}$$

In Fig. 3, we show a bi-Maxwellian VDF for an (intrinsic) anisotropy of $v_{\mathrm{th}\perp}^2/v_{\mathrm{th}\parallel}^2 = 2$. The general form of the VDF in Fig. 1 can also be approximated by this mathematical representation, which underlines the difficulties arising from the correct definition of the observed temperature. Interpreting the wave-broadened distribution function $\bar{f}$ as a bi-Maxwellian leads to an apparent difference in the two thermal velocities of the bi-Maxwellian VDF. Therefore, the wave-broadening can also be expressed in terms of a corresponding apparent thermal velocity anisotropy. Applying the second moment relation from Eq. (21) to a bi-Maxwellian distribution function yields the ratio $A = v_{\mathrm{th}\perp}^2/v_{\mathrm{th}\parallel}^2$. This means that the anisotropy in the apparent thermal speeds is given directly by $\sqrt{A}$.

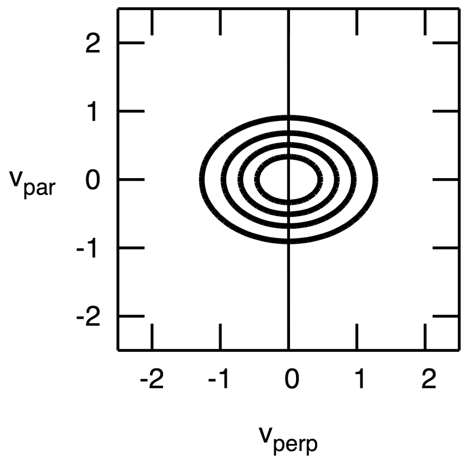

Fig. 3. Bi-Maxwellian velocity distribution function for a temperature anisotropy of 2.

Considering waves with higher frequencies, we must admit that the approximation $kv_\parallel \ll \Omega$ is not valid anymore. Then we have to accept further modifications of the VDF in the wave field, and we find a non-Maxwellian dependence

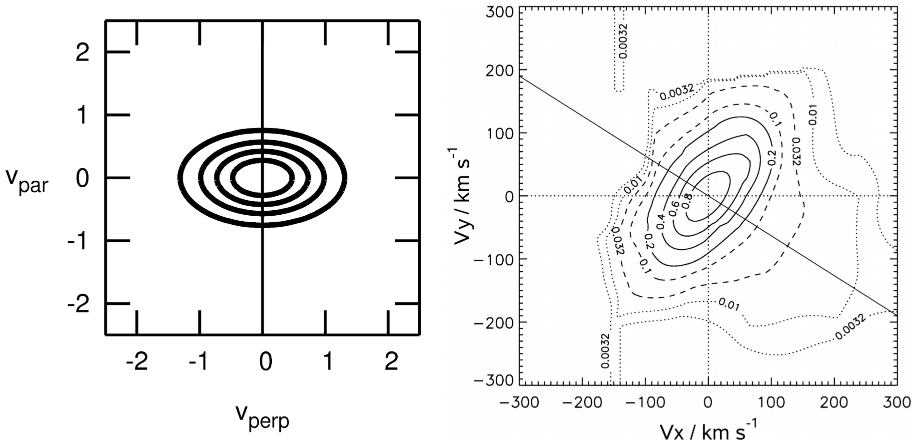

Fig. 4. Left: like in Fig. 1 but including higher-order corrections. Right: typical proton distribution function measured by the Helios 2 spacecraft in 1976. The black line indicates the direction of the background magnetic field.

also on the parallel speed coordinate $v_\parallel$. Accordingly, the distribution is

$$f_\mathrm{h} = f_\mathrm{w} \exp\left(\frac{2v_\parallel}{v_\mathrm{th}^2}\left[\frac{\omega}{k} + \frac{B_0}{b} V_\mathrm{w}\left(1 - \frac{\omega}{\Omega} + \frac{k v_\parallel}{2\Omega}\right)\right]\right). \qquad (23)$$

If we apply the time-averaging process to this distribution function, the results change significantly. The additional term makes the distribution function more prolate, already at lower wave amplitude and for higher beta values. Thus, it becomes even more similar to a bi-Maxwellian distribution function as it is shown in Fig. 3. An example for this situation is shown in Fig. 4, where we assumed the parameters $\omega = 10\pi/T$, $b = 0.1$, and $\beta = 0.5$.

For comparison, also a typical measurement by the Helios 2 spacecraft from 1976 is shown. The anisotropy of the observed distribution function is comparable to the calculated apparent anisotropy, whereas other effects such as the formed beam along the background field is not reproduced by the above calculations. We find that the model distribution function fits the observed distribution function well. This shows that the broadening effect and the detailed shaping mainly depend on the frequency of the waves and the plasma beta. The measured distribution function is better represented by the corrected distribution function for higher frequencies. This distribution is not simply a shifted Maxwellian but has a further non-Maxwellian dependence on $v_\parallel$, which can represent the observations better.

3 Conclusions

In this study, we have shown how the VDF is shaped by the presence of a large-amplitude wave. In the case of transversal wave activity, the distribution function obtains a shift in the direction perpendicular to the background magnetic field. If the distribution function is averaged over time, this shift will lead to a smearing in the perpendicular velocity component, which in turn would be interpreted as a temperature anisotropy in favour of the perpendicular direction. Every real measured distribution function can only be determined by sampling within a certain time period, and this implies averaging. Thus the resulting temperature as the second moment of the VDF reflects this procedure.

We could demonstrate, using a simplified model, how this effect can lead to a significant change in the observed distribution functions, as plasma measurements are always done by counting particles over a certain sampling time T. This sampling period corresponds again to time averaging. The broadening of particle distributions due to microturbulence is a well-known fact, which is exploited in spectroscopy to determine remotely, for example, the turbulence level in the solar corona (e.g. Kohl et al., 2006) from ultraviolet emission line broadenings. In the context of measurements of plasma VDFs in the solar wind, however, this was not taken into account before to the authors' knowledge.

Also compressive fluctuations can be treated in a similar way. However, then broadening would be observed mostly in the parallel direction. Consistently with the present emphasis on perpendicular broadening, most recent observations show a higher transversal wave activity in almost all cases in the fast solar wind (Horbury et al., 2005; Alexandrova et al., 2008).

The meaning of intrinsic temperature anisotropies should be further discussed in the future. As mentioned before, a severe limitation to $T_\perp/T_\parallel$ is observed in the solar wind (Marsch et al., 2006, 2009; Bale et al., 2009) in relation with plasma micro-instabilities which reveal a sensitive beta dependence. This finding gives a clear indication that the observed temperature anisotropies are largely intrinsic. This finding even more underlines the importance of an adequate definition and treatment of the measured plasma temperatures. The apparent higher temperature that we find in our model VDFs is not the result of resonant heating processes, such as Landau damping or cyclotron resonant wave–particle interactions. Hence, this wave-related mechanism is reversible, and for a vanishing wave field also the apparent anisotropy would disappear.

Nonresonant wave–particle interactions have been studied in the framework of quasi-linear theory by Bourouaine et al. (2008). They demonstrate that the nonresonant heating is more effective for lower plasma betas since the efficiency of the quasi-linear diffusion is mainly proportional to $v_{\mathrm{A}} - v_{\parallel}$. We can confirm the beta dependence and find the dependence of the parallel particle velocity in the wave frame also in our considerations as in Eq. (8) for example. However, we could show that the dispersion of Alfvén/ion-cyclotron waves can compensate for the reference frame shift in the Vlasov picture. Furthermore, Bourouaine et al. (2008) found a stronger effect of the nonresonant heating on heavy ion species which is also consistent with our model.

In the context of our measurement effect according to Eq. (16), the determination of temperature is not an ergodic measurement anymore if wave fields lead to a coherent particle motion as it is the case in the solar wind. This leads to the problem that the assumption of Markovian statistics is violated since the particle motion is additionally affected by the deterministically time-dependent wave motion during the averaging. Non-ergodicity in our case means that the temperature based on time averaging is different from the temperature based on ensemble averaging. But all real temperature measurements in dilute plasmas have to be done by averaging over time leading to the apparent deformations in the distribution function that we showed above. An appropriate ensemble average, however, is not accessible on the required scales in the solar wind due to the low particle number density. Recently, Hizanidis et al. (2010) found that the applicability of classical quasi-linear diffusion is not guaranteed in a coherent electromagnetic wave field. They developed a new kinetic theory for wave–particle interactions and find time-dependent diffusion tensors describing the velocity evolution of the VDF. This is a manifestation of the non-ergodicity of the measurement process. Maybe a completely different description of the microphysical behavior should be applied to these coherent cases as it is proposed and discussed in the textbook by Elskens and Escande (2003). The wave broadening effect could be excluded locally if, at the position and time where the measurement is taken, enough particles are present with the local coherent speed additional to their thermal speed. In all accessible solar wind plasma cases however, the number of particles that can be counted under constant conditions compared to $\phi = kz - \omega t$ is practically always too small.

A shorter sampling time would bring the observation closer to a "snapshot" of the real distribution function. A faster measurement would help avoiding heavy smearing in velocity space due to wave activity. The comparatively small number density of particles in the solar wind, however, requires long sampling times or larger geometry factors which are not affordable. The Solar Orbiter mission should provide new insights, because the improved instruments to be flown on board this spacecraft and the higher particle densities expected closer to the sun will permit much shorter sampling times down to 100 ms.

In this work, we assumed a monochromatic wave that leads to smearing out of the VDF by the time-averaging process. A more realistic assumption would be a broad spectrum of waves, which the particles have to follow and the VDF to respond to. Furthermore, the particle flux will not be steady in all directions during the sampling time T. Also, a realistic spacecraft model should be applied, including the detailed time dependence of the sampling method as well as the relative velocity of the spacecraft with respect to the solar wind. If such appropriate models were available, the analysis of the distribution function could in turn provide new information about the waves, such as their polarization or propagation direction. Up to now, in our model only waves propagating parallel to the background magnetic field have been dealt with. To complete our analysis also oblique wave propagation should be taken into account.

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