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Proton and He^{2+} Temperature Anisotropies in the Solar Wind Driven by Ion Cyclotron Waves *

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Abstract We carried out one-dimensional hybrid simulations of resonant scattering of protons and He^{2+} ions by ion cyclotron waves in an initially homogeneous, collisionless and magnetized plasma. The initial ion cyclotron waves have a power spectrum and propagate both outward and inward. Due to the resonant interaction with the protons and He^{2+} ions, the wave power will be depleted in the resonance region. Both the protons and He^{2+} ions can be resonantly heated in the direction perpendicular to the ambient magnetic field and leading to anisotropic velocity distributions, with the anisotropy higher for the He^{2+} ions than for the protons. At the same time, the anisotropies of the protons and He^{2+} ions are inversely correlated with the plasma $\beta_{||p} = 8\pi n_p k_B T_{||p}/B_0^2$, consistent with the prediction of the quasilinear theory (QLT).

Key words: solar wind – plasmas – waves

1 INTRODUCTION

Temperature anisotropy of protons in the solar wind was first discovered by Feldman et al. (1974). Later, observations by the Helios spacecraft showed that the proton core temperature ratio $T_{p\perp}/T_{p||}$ is about 3–4 in the solar wind near 0.3 AU (Marsch et al. 1982a). Similar core temperature anisotropies have been observed by the spacecraft Ulysses (Gary et al. 2002), ACE (Gary et al. 2001a) and Wind (Kasper et al. 2003). Moreover, the recent observations have found that minor ions such as O^{5+} have even higher thermal anisotropies than protons in the solar corona hole. Observations by the SOHO spacecraft showed that the O^{5+} temperature anisotropy $T_{O\perp}/T_{O||}$ can be as high as 20–80 (Kohl et al. 1998). So, how the anisotropic velocity distributions of protons and minor ions are formed in the solar corona is now an important topic in coronal physics, which has not yet been fully understood.

Collisionless wave particle scattering by ion cyclotron fluctuations has been considered as the source of energy for heating the protons and minor ions. Recently Marsch & Tu (2001)

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and Tu & Marsch (2002) found the existence of a cyclotron-wave resonance "plateau", which provides direct evidence for cyclotron resonance process operating in the high-speed solar wind. However, to date no direct observation has been made of ion cyclotron waves in the solar wind, and the source of the ion cyclotron waves is still unknown. Many authors have addressed this issue (Marsch et al. 1982b; Isenberg & Hollweg 1983; Hollweg & Johnson 1988; McKenzie 1994; Tam & Chang 1999; Li et al. 1999; Hollweg 1999a, 1999b, 2000; Cranmer 2000; Cranmer 2001; Tu & Marsch 2001; Isenberg et al. 2001; Isenberg 2003; Vocks & Marsch 2002; Gary et al. 2001b). One scenario is that large-amplitude, low-frequency ($\omega_r \ll \Omega_p$ where Ω_p is the proton cyclotron frequency) nonresonant Alfvén waves are generated at the base of the corona and perhaps throughout the corona (Cranmer et al. 1999), but as they propagate away from the Sun, the decreasing magnetic field leads wave-particle interactions at the cyclotron resonance of ions of successively larger charge-to-mass ratios. This view predicts stronger heating of the heavier ions, and the heating driven by resonant pitch angle scattering predominating in the direction perpendicular to the ambient magnetic field, which leads to the thermal anisotropies of the protons and heavier ions. However, almost in all of the models ion cyclotron waves are assumed to obey a fixed power law with a fixed slope, so such models have the limitation of not being self-consistent. If the power spectrum is allowed to evolve self-consistently, the thermal anisotropies for the ions would decrease. For example, Isenberg (1984) obtained $T_{p\perp}/T_{p||} = 2.5$ near 0.3 AU and 1.7 near 1AU by assuming a fixed –2 spectral index. Marsch et al. (1982b) considered the self-consistent evolution of the wave spectrum and found that $T_{p\perp}/T_{p||}$ approaches only 1.6 (for $\beta_{||p} \approx 0.1$). In addition, these models may be classified as either linear or quasilinear, and the velocity distribution of the ions is assumed to follow the bi-Maxwellian function.

Recently, Liewer et al. (2001) investigated the heating of the protons and He^{2+} ions in the solar wind using a hybrid simulation, in which an initial magnetic power spectrum is imposed on a spatially homogeneous distribution. Then Ofman et al. (2002) drove a magnetic power spectrum in a small computational domain throughout the duration of their hybrid simulation. The hybrid modeling treats the ions kinetically and the electrons as a fluid, and allows the relaxing of many approximations used in the fluid, or in the linear or quasilinear kinetic theory. For example, there are no restrictions on the form of the ion distribution, and self-consistent, fully nonlinear numerical experiments are allowed. The simulation results of Liewer et al. (2001) and Ofman et al. (2002) showed that the minor ions are easily heated in the direction perpendicular to the ambient magnetic field and form an anisotropic velocity distribution. However, in their simulations due to the elimination of high frequency part in ion cyclotron wave power, the protons cannot resonantly interact with the waves, so the protons remain nearly isotropic and are weakly heated.

In this paper, using a one-dimensional hybrid simulation we investigate self-consistent heating of the protons and He^{2+} ions by resonant scattering of ion cyclotron waves in the solar wind, for initial ion cyclotron waves having a power-law spectrum. The relation of the anisotropies of the protons and He^{2+} ions with the plasma $\beta_{||p}$ is also studied. Gary et al. (2001) have calculated an upper limit of anisotropy from the maximum growth rate, $\gamma_m = 0.01\Omega_p$ (where Ω_p is the proton cyclotron frequency), and the threshold for the protons has the form

$$A = \frac{T_{\perp p}}{T_{||p}} - 1 = \frac{S_p}{\beta_{||p}^{\alpha_p}} \quad , \tag{1}$$

where S_p and α_p are fitting parameters, S_p is of order unity but varies as a function of the threshold growth rate, whereas $\alpha_p \approx 0.4$ is independent of the growth rate. Tu & Marsch (2003) also studied the correlation between the anisotropies and the plasma $\beta_{||p}$ by wave-induced plateau formation according to the quasilinear theory. Marsch et al. (2004) analyzed the dependence of the temperature anisotropy of the proton velocity distribution on the plasma $\beta_{||p}$ measured by the Helios spacecraft in fast wind, and their results show that the proton anisotropy satisfies the following empirical relation

$$A = \frac{T_{\perp p}}{T_{||p}} - 1 = 1.16\beta_{||p}^{-0.55} - 1 \quad . \tag{2}$$

This paper is organized as follows. The one-dimensional hybrid simulation model is described in Sect. 2. Section 3 presents the simulated anisotropies of the protons and He^{2+} ions, for an initial magnetic power spectrum of power index –1. A brief summary as well as a comparison of our simulation results with the quasilinear theory and the observations is presented in Sect. 4.

2 HYBRID SIMULATIONS

A one-dimensional hybrid code (Winske & Omidi 1993; Lu & Wang 1998; Guo et al. 2003) is used to model a homogeneous, collisionless and magnetized plasma. Actually such a treatment assumes that the time scale of resonant scattering of the protons and He^{2+} ions by ion cyclotron waves is much shorter than the solar wind expansion time, which has been shown to be true by Isenberg et al. (2000, 2001) if the wave energy is large enough. The plasma consists of two ion components (the protons and He^{2+} ions) and the electron component. The ions are treated kinetically, the electrons are treated as a fluid, and the He^{2+} ions account for 5% of the total ion number density. The abundance of He^{2+} ions are sufficiently large so that their influence on our results must be included self-consistently. Initially, both ion components follow isotropic Maxwellian velocity distributions of the same temperature without a drift. The particles are advanced according to the well-known Boris algorithm. The electromagnetic fields are calculated with an implicit algorithm.

Periodic boundary conditions for the particles and fields are used in the x direction with the background magnetic field $\boldsymbol{B}_0 = B_0\hat{\boldsymbol{x}}$. We use 1024 grid cells in the simulation with 200 particles per cell for each ion component, and the grid size is $\Delta x = 0.2c/\omega_{pp}$, where c/ω_{pp} is the ion inertial length (c and ω_{pp} being light speed and ion plasma frequency, respectively). Here we choose a very small grid size, because we expect to retain high frequency part of the ion cyclotron wave power. The time step is taken to be $\Omega_p t = 0.002$.

Initially, the input wave spectrum is generated in the computational domain in the form:

$$B_y(x) = B_0 F(x), \tag{3}$$

$$B_z(x) = B_0 F(x + \pi/2), \tag{4}$$

$$F(x) = b_0 \sum_{i=1}^{N} a_i \cos(k_i x + \Gamma_i), \tag{5}$$

where Γ_i is the random phase, and N is the number of modes. The wave number k_i satisfies the following ion cyclotron dispersion relation

$$k_i V_A = \frac{\omega_i}{\sqrt{1 - (\frac{\omega_i}{\Omega_p})^2}} \quad , \tag{6}$$

where $\omega_i = \omega_1 + (i-1)\Delta\omega$, $\Delta\omega = (\omega_N - \omega_1)/(N-1)$. The mode amplitude $a_i = i^{-p/2}$, and the value of p is 1.0. The range of ω_i is $0.3\Omega_p - 0.9\Omega_p$, and $N = 1000$. The value of b_0 is chosen to be 0.02. In order to determine the evolution of the wave power spectrum due to its resonant interaction with the protons and He^{2+} ions, there are no waves injected from the boundary during the simulations.

3 SIMULATION RESULTS

In the simulations, the initial magnetic fluctuation may excite left-hand polarized waves which propagate parallel and anti-parallel to the ambient magnetic field $\boldsymbol{B}_0$. Here we choose the parameters $\beta_{||p} = 0.09$. Figure 1 shows the time history of the fluctuating magnetic field energy density $\delta B^2/B_0^2\,(\delta B^2 = B_y^2 + B_z^2)$: first there is a relatively rapid damping of the magnetic fluctuations, which are transferred into the kinetic energy of the protons and He^{2+} ions. At about $\Omega_p t = 10.0$ the magnetic fluctuations reach an almost constant value, which is a quasi-equilibrium stage. At the same time, the protons and He^{2+} ions are heated in the direction perpendicular to the ambient magnetic field. Figure 2a describes the time history of the parallel temperature $T_{||p}/T_{||p0}$ (where $T_{||p0}$ is the initial parallel temperature for the protons) and $T_{\perp p}/T_{||p} - 1$, the anisotropy of the protons. Figure 2b shows the corresponding quantities for the He^{2+} ions, $T_{||\alpha}/T_{||\alpha 0}$ (where $T_{||\alpha 0}$ is the initial parallel temperature for the He^{2+} ions) and $T_{\perp\alpha}/T_{||\alpha} - 1$. The anisotropies for the protons and He^{2+} ions first pass through a stage of rapid growth, then attain their maximum values, about 0.6 for the protons and and 4.2 for the He^{2+} ions. After this stage, the anisotropies begin to decrease slowly, and reach their constant values of about 0.3 at about $\Omega_p t = 10.0$ for the protons, and of about 2.5 at $\Omega_p t = 25.0$ for the He^{2+} ions. However, the parallel temperatures for the protons and He^{2+} ions are almost kept constant, which means that the heating only occurred in the direction perpendicular to the ambient magnetic field.

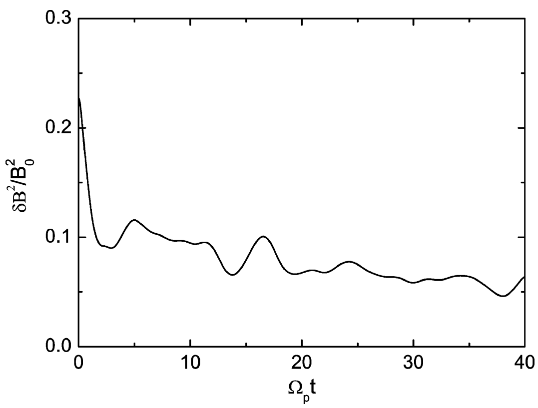

Fig. 1 Time history of the fluctuating magnetic field energy density $\delta B^2/B_0^2(\delta B^2 = B_y^2 + B_z^2)$.

Figure 3 shows the contour plot of the two dimensional velocity distributions for the protons at different times $\Omega_p t = 0.0, 4.0, 10.0$ and 30.0. Initially, the protons follow an isotropic velocity distribution, then due to resonant pitch angle scattering by the ion cyclotron waves the protons are heated in the direction perpendicular to the ambient magnetic field until an almost constant value. The velocity distribution of the protons is approximately a bi-Maxwellian function. The resonance condition can be expressed as

$$\frac{v_{||}}{V_{\mathrm{A}}} = \frac{\omega}{k_{||}V_{\mathrm{A}}} - \frac{\Omega_j}{k_{||}V_{\mathrm{A}}} \quad , \tag{7}$$

where ω is the frequency in the plasma frame of reference, $k_{||}$ the wave number parallel to the ambient magnetic field, V_{A} the Alfvén speed, and Ω_j the ion cyclotron frequency, for protons

$\Omega_j = \Omega_p$. If $k_{||} > 0$, then $v_{||} < 0$, while if $k_{||} < 0$, then $v_{||} > 0$. This means the waves propagating in $+x$ direction are in resonance with the protons for $v_{||} < 0$, and the waves propagating in $-x$ direction are in resonance with the protons for $v_{||} > 0$. Figure 4 shows contour plots of the two dimensional velocity distribution of the He^{2+} ions at different times $\Omega_p t = 0.0, 4.0, 10.0$ and 30.0. The He^{2+} ions also can be heated in the direction perpendicular to the ambient magnetic field, and with more effectiveness.

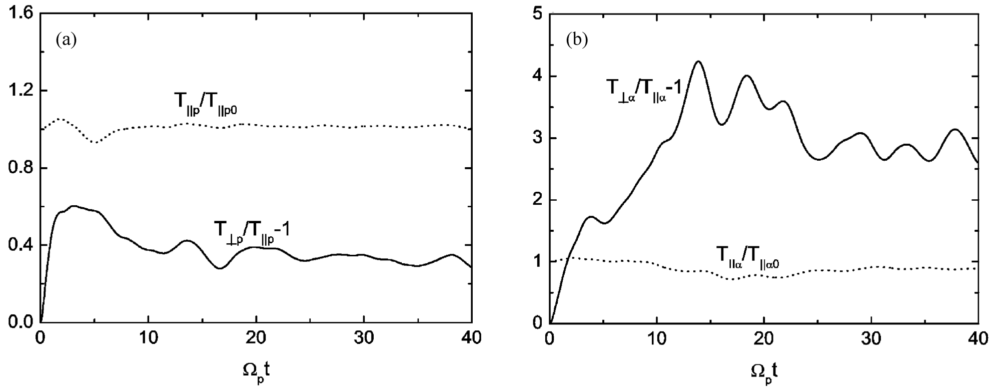

Fig. 2 Time history of the anisotropy $A = T_\perp/T_{||} - 1$ and parallel temperature $T_{||}/T_{||0}$ for (a) the protons and (b) He^{2+} ions, here $T_{||0}$ is the initial parallel temperature for the protons.

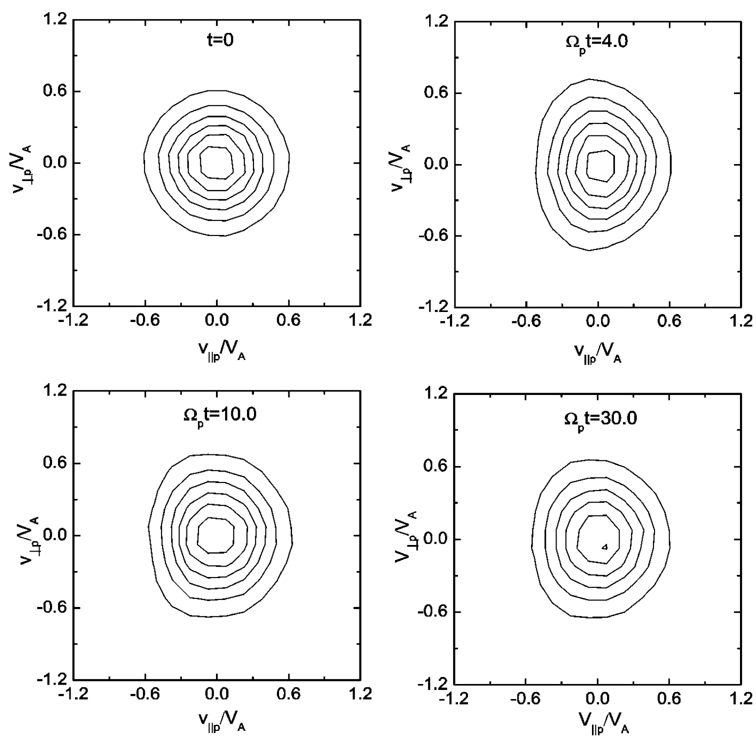

Fig. 3 Contour plot of the two dimensional velocity distributions for the protons at different times $\Omega_p t = 0$, $\Omega_p t = 4.0$, $\Omega_p t = 10.0$ and $\Omega_p t = 30.0$. In this figure the upper half part corresponds to $v_z > 0$, while the other half corresponds to $v_z < 0$.

Figure 5 compares the B_y power spectrum at the quasi-equilibrium stage to the initial spectrum. At the low frequency part, there was no damping of the wave; however, at the high frequency part where $\frac{k_{||}\omega_{pp}}{c} \geq 0.5$, the ion cyclotron waves are damped due to their resonant interactions with the protons and He^{2+} ions. Figure 6 shows the wave numbers for the ion cyclotron waves propagating in the parallel direction that are in resonance with the protons and He^{2+} ions. If we choose $v_{||}$ equals to the corresponding thermal speed for the protons and He^{2+} ions, we shall find that the ions can be in resonance with the waves with wave numbers $\frac{k_{||}\omega_{pp}}{c} \geq 0.5$, in agreement with our simulation results.

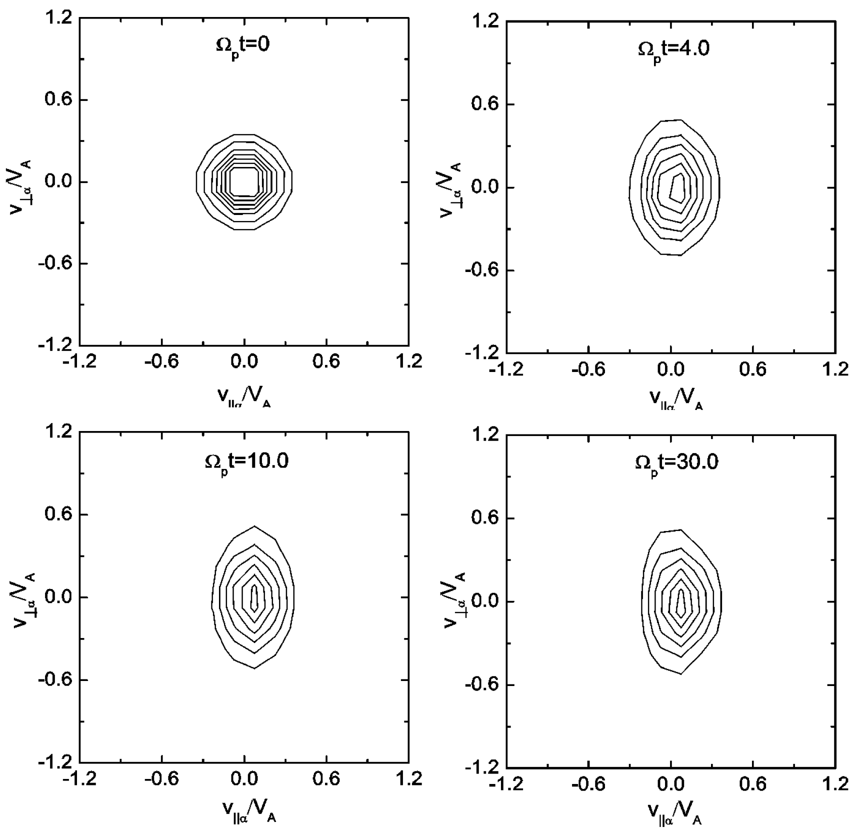

Fig. 4 Contour plot of the two dimensional velocity distributions for the He^{2+} ions at different times $\Omega_p t = 0$, $\Omega_p t = 4.0$, $\Omega_p t = 10.0$ and $\Omega_p t = 30.0$. In this figure the upper half part corresponds to $v_z > 0$, while the other half corresponds to $v_z < 0$.

Figure 7 shows the temperature anisotropies at the quasi-equilibrium stage for the protons and He^{2+} ions as functions of the plasma $\beta_{||p}$. Obviously, the anisotropies vary inversely to the plasma $\beta_{||p}$, approximately as $A \sim \beta^{-0.98}$. The relation between anisotropy and the plasma beta can be easily deduced from the quasilinear theory supposing the ion cyclotron waves to be non-dispersive (Tu & Marsch 2002), that is,

$$A_j = 2\Big/\sqrt{\beta_j}\ , \tag{8}$$

where the anisotropies are defined as $A_j = (V_{\perp j}/V_{||j})^2 - 1$ and $\beta_j = (V_{||j}/V_A)^2$. It gives an upper limit for the anisotropies, and a relation similar to Eq. (8) was derived by Gary & Lee (1994) for a thin shell in the velocity space, which is qualitatively consistent with our simulation results.

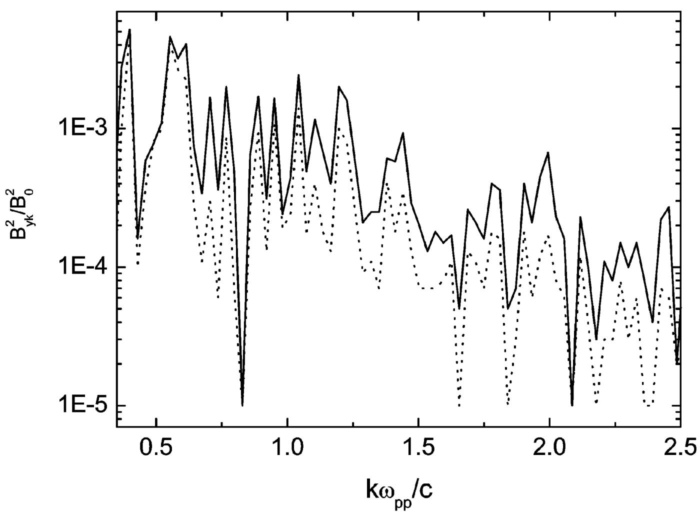

Fig. 5 Comparison of B_y power spectrum at $\Omega_p t = 26.0$ (solid line) to the initial spectrum (dotted line).

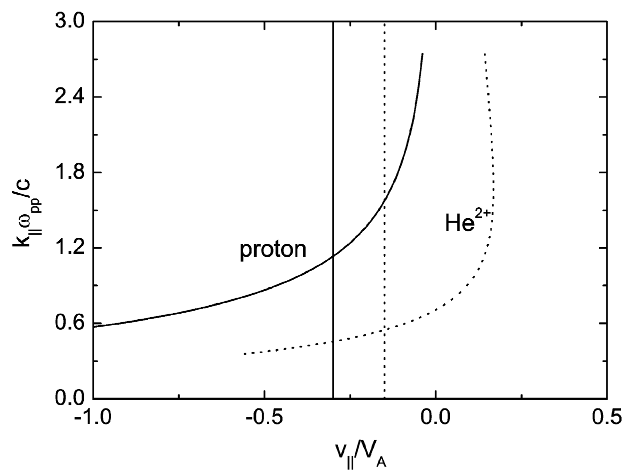

Fig. 6 Resonance relation for the protons (solid line) and He^{2+} ions (dotted line): the horizontal axis shows the resonance speed and the vertical axis shows the resonance wave number, the vertical lines in the figure denote the initial thermal speed for the protons (solid line) and He^{2+} ions (dotted line). Here we only show the branch of the ion cyclotron waves which propagates parallel to the ambient magnetic field, while the resonance relation for the other branch which propagates anti-parallel to the ambient magnetic field is symmetric.

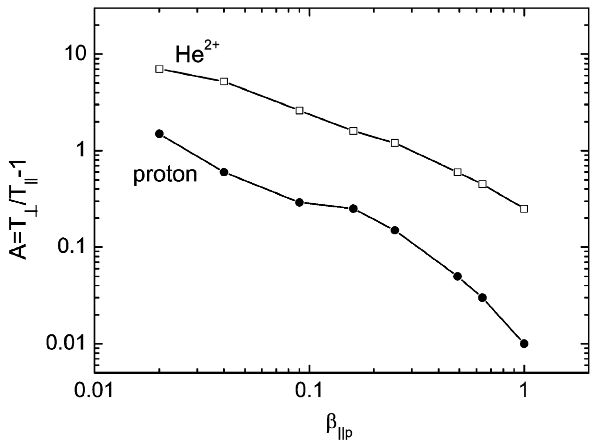

Fig. 7 Temperature anisotropies for the protons and He^{2+} ions as a function of the plasma $\beta_{||p}$, where the temperature anisotropies are obtained at the quasi-equilibrium stage.

4 DISCUSSION AND CONCLUSIONS

With a hybrid simulation code we have investigated the heating of the protons and He^{2+} ions due to resonant pitch angle scattering by ion cyclotron waves in the solar wind. Initially, the solar wind is regarded as a homogeneous, collisionless and magnetized plasma, and the ion cyclotron waves are excited by a magnetic fluctuation with a power spectrum of the form f^{-1}. The excited ion cyclotron waves, which can interact with the protons and He^{2+} ions self-consistently, propagate both parallel and anti-parallel to the ambient magnetic field.

Due to the resonant interactions with ion cyclotron waves, protons as well as He^{2+} ions in the solar wind can be heated in the direction perpendicular to the ambient magnetic field and form an anisotropic velocity distributions. He^{2+} ions can be heated more effectively because of their resonant interactions with lower frequency cyclotron wave modes. Another characteristic of the solar wind is that the anisotropies of the ions vary inversely with the plasma $\beta_{||p}$, which has recently been observed by Gary et al. (2002) and Marsch et al. (2004). The similar relation can also be deduced by wave-induced plateau formation according to a quasilinear theory with a zero pitch angle gradient (Tu et al. 2002). Our simulations show that the anisotropies of the protons and He^{2+} ions have the form $A \sim \beta^{-0.98}$.

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