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Petr Hellinger, Pavel M. Trávníček, André Mangeney, Roland Grappin. Hybrid simulations of the expanding solar wind: Temperatures and drift velocities. *Geophysical Research Letters*, 2003, 30, pp.15-1. 10.1029/2002GL016409 . hal-03801630

**HAL Id: hal-03801630**

**<https://hal.science/hal-03801630>**

Submitted on 9 Oct 2022

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# Hybrid simulations of the expanding solar wind: Temperatures and drift velocities

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Received 8 October 2002; revised 4 December 2002; accepted 20 January 2003; published 6 March 2003.

[1] We study the evolution of the expanding solar wind using a one-dimensional and a two-dimensional expanding box model [Grappin *et al.*, 1993] implemented here within a hybrid code [Liewer *et al.*, 2001]. We first consider a plasma with protons and 5% of alpha particles, without drift between the protons and alphas, considering successively the low-beta and high-beta cases. Then we consider a strong drift between protons and alphas, again separately the low-beta and high-beta case. Without drift, the evolution of the low-beta plasma is adiabatic. In the high-beta plasma without drift, the fire hose instabilities (both parallel and oblique) disrupt the adiabatic evolution. Finally, with a drift, the adiabatic evolution is stopped by the oblique Alfvén instability and the parallel magnetosonic instability for low-beta plasma and for high-beta plasma, respectively. The two instabilities slow down the alphas and heat alphas and protons. **INDEX TERMS:** 2164 Interplanetary Physics: Solar wind plasma; 2159 Interplanetary Physics: Plasma waves and turbulence; 7843 Space Plasma Physics: Numerical simulation studies; 7871 Space Plasma Physics: Waves and instabilities; 7868 Space Plasma Physics: Wave/wave interactions. **Citation:** Hellinger, P., P. Trávníček, A. Mangeney, and R. Grappin, Hybrid simulations of the expanding solar wind: Temperatures and drift velocities, *Geophys. Res. Lett.*, 30(5), 1211, doi:10.1029/2002GL016409, 2003.

## 1. Introduction

[2] The fast solar wind shows three distinct features: it expands in the transverse directions as it moves in the radial direction; it contains an important wave turbulence; finally, the particle distribution function is far from being Maxwellian. Temperature anisotropies and particle beams are commonly observed in the solar wind. Moreover heavy ions, as alpha particles, are usually hotter and move faster than the solar wind protons [Marsch *et al.*, 1982a, 1982b; Reisenfeld *et al.*, 2001].

[3] The ion evolution in the fast solar wind is largely nonadiabatic: the adiabatic invariant  $T_{\perp}/B$  is not conserved,  $T_{\perp}$  being the perpendicular temperature. The departure from adiabatic behavior could be caused by several effects: the interaction of ions with the solar wind turbulence [Hu and Habbal, 1999; Gary *et al.*, 2001], the appearance of local instabilities driven by drift velocities between protons and heavy ions [Li and Habbal, 2000; Gary *et al.*, 2000, and references therein] and/or by temperature anisotropies [Gary *et al.*, 1998; Hellinger and Matsumoto, 2000].

[4] In this paper we study the evolution of the expanding plasma using a one-dimensional (1-D) and a two-dimensional (2-D) expanding box model [Grappin *et al.*, 1993] implemented here within a hybrid code [Liewer *et al.*, 2001]. We first consider a plasma with protons and 5% of alpha particles, without drift between the protons and alphas, considering successively the low-beta and high-beta cases. Then we consider a strong drift between protons and alphas, again separately the low-beta and high-beta case. We discuss the results and compare them with *in situ* observations.

## 2. Hybrid Expanding Box Model

[5] In this paper we use a modified version of a 1-D and 2-D hybrid code [Matthews, 1994]: a Hybrid Expanding Box (HEB) code. The HEB code is an implementation of the expanding box model used in magnetohydrodynamic context by Grappin *et al.* [1993] to study the effects of plasma expansion on the wave evolution. The 1-D and 2-D HEB codes are similar to the 1-D HEB code by Liewer *et al.* [2001] and was developed independently. The HEB code models the expansion as a linearly driven evolution. One assumes a solar wind with a constant velocity  $U$ . The physical lengths  $x_r$  varies as  $x_r = \mathcal{L}x$  where  $\mathcal{L}$  is a diagonal matrix with  $\mathcal{L}_{11} = 1$ ,  $\mathcal{L}_{22,33} = 1 + t/t_e$  and  $t_e$  is a characteristic time of the expansion,  $t_e = R_0/U$  where  $R_0$  is the initial distance from the sun. The code solves the evolution of the system in the coordinates  $x$  and  $v$  co-moving with the expansion. The physical velocities  $v_r$  are  $v_r = \mathcal{L}v$ . The equation of the movement for an ion with charge  $q$  and mass  $m$  reads:

$$d_x/dt = v, \quad dv/dt = q/m \cdot (\mathcal{L}^{-1}E + \mathcal{L}^{-2}v \times \tilde{B}) - 2\mathcal{L}\dot{\mathcal{L}}^{-1}v. \quad (1)$$

The effective magnetic field  $\tilde{B}$  in these coordinates evolves with the physical electric field  $E$  as  $\partial\tilde{B}/\partial t = -\text{rot}(\mathcal{L}E)$  and is related to the physical magnetic field by  $B = \mathcal{L}\tilde{B}/\det \mathcal{L}$ . The electric field  $E$  is given as  $E = (\text{rot } B \times B/\mu_0 - J_i \times B - \text{grad } p_e)/en$ , where  $\mu_0$  is the magnetic permeability of vacuum,  $n$  is the physical electron number density, a sum over different ion species,  $en = \sum q/\det \mathcal{L} \int fd^3v$ ,  $J_i$  is the ion current, a sum over different ion species,  $J_i = \sum q/\det \mathcal{L} \int fd^3v$ , and  $p_e$  is the electron pressure  $p_e = nk_B T_e$  ( $k_B$  is Boltzmann constant and  $T_e$  is the electron temperature; electrons are assumed to be isothermal).

[6] Units of space and time are  $c/\omega_{pi0} = v_{A0}/\Omega_{i0}$  and  $\Omega_{i0}$ , respectively, where  $c$  is the speed of light,  $\omega_{pi0} = \sqrt{n_0 e^2/m_p \epsilon_0}$  is the initial proton plasma frequency,  $v_{A0} = B_0/\sqrt{\mu_0 n_0 m_p}$  is the initial Alfvén speed, and  $\Omega_{i0} = eB_0/m_p$  is the initial proton

gyrofrequency ( $B_0$  is the initial magnitude of  $B$ ,  $n_0$  is the initial density,  $e$  and  $m_p$  are the proton electric charge and mass, respectively; finally,  $\epsilon_0$  is the dielectric permittivity of vacuum). The codes use a spatial resolution  $dx$ ,  $dy$  and there are  $N_p$  particles per cell. Fields and moments are defined on a 1-D and 2-D grid with dimensions  $n_x$  and  $n_x \times n_y$ , respectively. The exact values of  $dx$ ,  $dy$ ,  $N_p$ ,  $n_x$ , and  $n_y$  will be given in the text. The time step for the particle advance is  $dt = 0.05\Omega_{p0}^{-1}$ , while the magnetic field  $B$  is advanced with a smaller time step  $dt_B = dt/4$  for all the simulations.

### 3. Plasma Without Alpha-Proton Drift

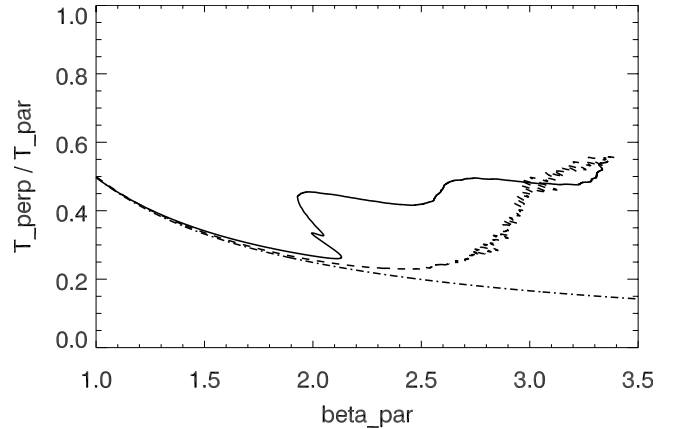
[7] A homogeneous slowly expanding plasma (without any fluctuating wave energy) evolves adiabatically. The ion parallel and perpendicular temperatures  $T_{\parallel}$  and  $T_{\perp}$  satisfy the CGL equations  $T_{\perp} \propto B$  and  $T_{\parallel} \propto n^2/B^2$ , respectively. In the case of a strictly radial expansion,  $B(0) = (1, 0, 0)$ , the temperature anisotropy evolves as  $T_{p\perp}/T_{p\parallel} \propto (1 + t/t_e)^{-2}$ .

#### 3.1. Low-Beta Protons

[8] We perform 1-D and 2-D HEB simulations starting with an initially low proton beta  $\beta_p = 0.1$  and a characteristic expansion time  $t_e = 2000$  for a time interval  $\Delta t = 4000$ . The 1-D simulation had  $dx = 0.5$ ,  $N_p = 1024$ ,  $n_x = 512$ , while the 2-D simulation had  $dx = dy = 1$ ,  $N_p = 256$ ,  $n_x = n_y = 256$ . During the time period  $\Delta t = 4000$  the evolution of the two 1-D and 2-D systems was adiabatic and at the end of the simulation we observe a strong proton temperature anisotropy  $T_{p\perp}/T_{p\parallel} = 1/9$ . In the low-beta case, the plasma is stable. Indeed, electromagnetic instabilities, driven by the proton temperature anisotropy, needs a substantial proton beta [Gary *et al.*, 1998; Hellinger and Matsumoto, 2000]. Adding 5% of alpha particles ( $\beta_{\parallel\alpha} = 0.01$ ) does not change much the results.

#### 3.2. High-Beta Protons

[9] We now perform 1-D and 2-D HEB simulations starting with high-beta protons ( $\beta_{p\parallel} = 1$ ) that are already anisotropic:  $T_{p\perp}/T_{p\parallel} = 0.5$ ; the anisotropic proton plasma is at the beginning stable. Other parameters are identical to those used in section 3.1 cold protons. During the expansion the plasma evolves adiabatically and the ratio  $T_{p\perp}/T_{p\parallel}$  decreases. In the 1-D simulation, the parallel fire hose instability Gary *et al.* [1998] appears later on, and stops this decrease. The system then evolves around marginal stability. In the 2-D simulation, the parallel fire hose instability appears as well, but soon after its appearance the oblique fire hose instability appears [Hellinger and Matsumoto, 2000]. The essentially non-quasilinear evolution of oblique fire hose [Hellinger and Matsumoto, 2001] leads to an important increase of  $T_{p\perp}/T_{p\parallel}$  and a decay of wave activity. The system returns to a nearly adiabatic evolution and the parallel and oblique fire hose reappear. The system oscillates between stability and marginal stability. Figure 1 shows the evolution of the two simulations in the 2-D space ( $\beta_{p\parallel}$ ,  $T_{p\perp}/T_{p\parallel}$ ). The solid and dashed curves show the evolution of the 2-D and 1-D simulations, respectively. The dashed-dotted curve shows the adiabatic prediction. Figure 1 clearly shows the initial adiabatic evolution for the two simulations and the appearance of instabilities later on. The anisotropy  $T_{p\perp}/T_{p\parallel}$  stops around 0.25 for the 1-D simulation and slowly increases with  $\beta_{p\parallel}$  [Gary *et al.*, 1998]. The 2-D evolution is different, the  $T_{p\perp}/T_{p\parallel}$  rapidly increases from 0.3



**Figure 1.** High-beta, pure protons plasma: Evolution in the space ( $\beta_{p\parallel}$ ,  $T_{p\perp}/T_{p\parallel}$ ) for (dashed) 1-D simulation and for (solid) 2-D simulation. The adiabatic prediction is denoted by the dash-dotted curve.

to about 0.5 and then again decreases, nearly adiabatically. The instabilities then set up again and all the evolution repeats twice, however with smaller excursions in the ( $\beta_{p\parallel}$ ,  $T_{p\perp}/T_{p\parallel}$ ) space. Adding 5% of alpha particles ( $\beta_{\parallel\alpha} = 0.05$ ) does not change much the results, but the increase of  $T_{p\perp}/T_{p\parallel}$  due to the fire hose instabilities is lower, at the expense of heating the alpha particles.

### 4. Plasma With a Strong Alpha-Proton Drift

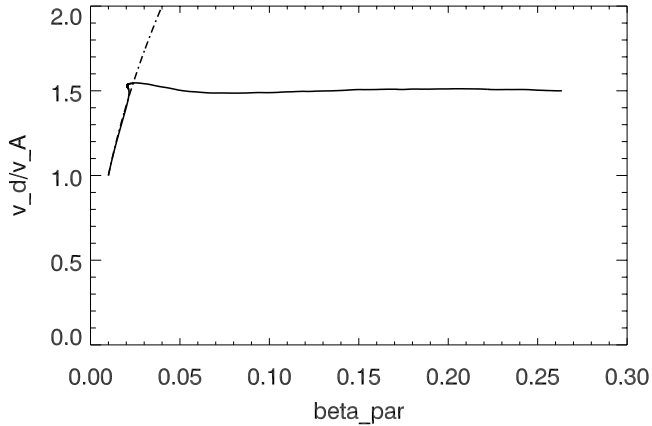
[10] In situ observations in the solar wind shows that the alpha particles travel faster than protons and the drift velocity between the two populations is about the local Alfvén velocity. Let us now look at the consequences of this drift. We investigate low-beta and high-beta plasmas with the number density of alpha particles 5% of the number density of electrons and with a strong alpha-proton drift.

#### 4.1. Low-Beta Plasma

[11] In this section we study the evolution of the expanding plasma for low-beta protons and alpha particles with  $\beta_{\parallel p} = 0.1$  and  $\beta_{\parallel\alpha} = 0.03$ . The 2-D simulation has  $dx = dy = 2$ ,  $n_x = 256$ ,  $n_y = 128$ , and number of particles per cell:  $N_{pp} = 128$  for protons and  $N_{\alpha p} = 64$  for alpha. In the expanding plasma, the radial velocities are constant. Therefore, during an adiabatic evolution, the radial drift velocity  $v_d$  is constant while the local Alfvén velocity  $v_A$  decreases. The ratio  $v_d/v_A$  thus increases and one expects ion-beam instabilities to appear [Gary *et al.*, 2000].

[12] We start the simulation with the drift velocity  $v_d = v_{A0}$  and the characteristic time for the expansion  $t_e = 1000$ , corresponding to a wind speed twice that of Section 3. In this simulation, the dominant instability is left-handed, oblique Alfvén, resonant via cyclotron resonance [Gary *et al.*, 2000]. Figure 2 shows the evolution of the ratio between the drift velocity  $v_d$  and the local Alfvén velocity in the simulation (solid curve). The predicted adiabatic evolution is denoted by the dash-dotted curve.

[13] The oblique Alfvén instability strongly modifies the ion temperatures. This effect is illustrated in Figure 3 for protons (left panel) and for alpha particles (right panel). Figure 3 shows the evolution (solid curve) in the 2-D space



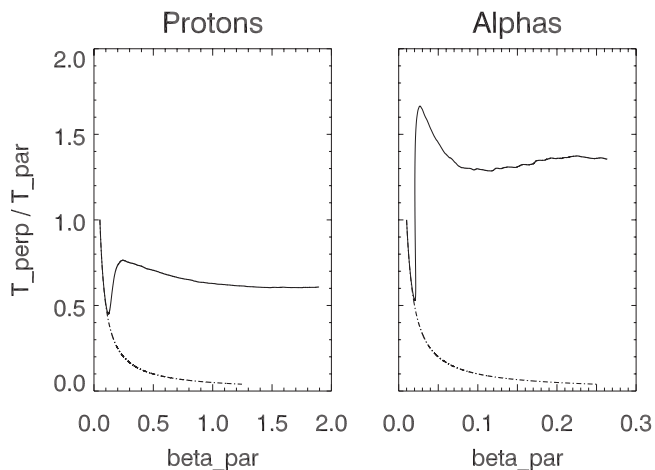
**Figure 2.** Low-beta plasma: alpha-proton drift velocity in units of the local Alfvén velocity (solid curve) as a function of  $\beta_{\alpha\parallel}$ . The adiabatic prediction is denoted by the dash-dotted curve.

of  $(\beta_{p\parallel}, T_{p\perp}/T_{p\parallel})$  (left panel), and  $(\beta_{\alpha\parallel}, T_{\alpha\perp}/T_{\alpha\parallel})$  (right panel). The dash-dotted curve shows the adiabatic prediction. Figure 3 clearly shows that the instability is able to stop the adiabatic cooling in the case of low-beta protons. The free energy from the drift velocity of alphas is transferred to perpendicular temperature of protons and alpha particles.

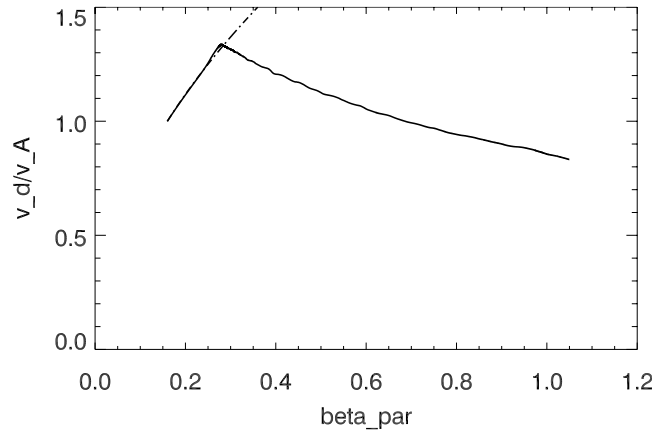
[14] The growth rate of instabilities driven by the ion-beams strongly depends on plasma properties (temperatures and drift velocities), therefore, let us now finish this study with a case of relatively high-beta protons and alpha particles with a drift velocity.

#### 4.2. High-Beta Plasma

[15] In this section we study the evolution of the expanding plasma for high-beta protons and alpha particles  $\beta_{\parallel p} = 0.5$  and  $\beta_{\parallel \alpha} = 0.16$ . Other parameters are identical to those used in the section 4.1. In this simulation the dominant instability is right-handed, magnetosonic, with maximum growth rate at parallel propagation, resonant via cyclotron



**Figure 3.** Low-beta plasma with drift: Evolution of protons (left panel) and alphas (right panel) in the space  $(\beta_{p\parallel}, T_{p\perp}/T_{p\parallel})$  and  $(\beta_{\alpha\parallel}, T_{\alpha\perp}/T_{\alpha\parallel})$ , respectively. The adiabatic prediction is denoted by the dash-dotted curves.

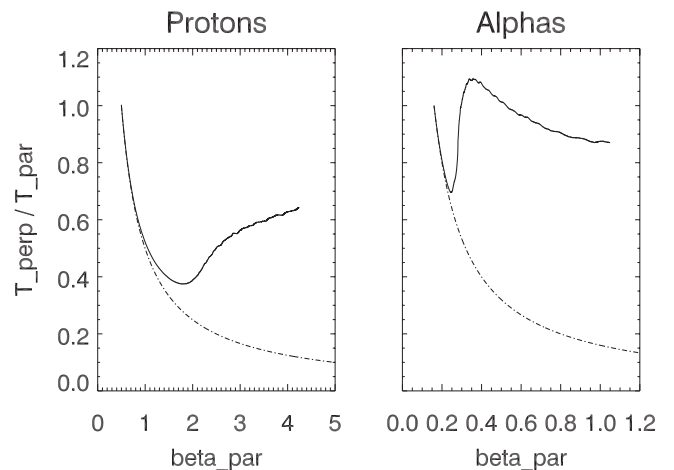


**Figure 4.** High-beta plasma: alpha-proton drift velocity in units of the local Alfvén velocity (solid curve) as a function of  $\beta_{\alpha\parallel}$ . The adiabatic prediction is denoted by the dash-dotted curve.

resonance [Gary *et al.*, 2000]. Figure 4 shows the evolution of the ratio between the drift velocity  $v_d$  and the local Alfvén velocity in the simulation (solid curve). The predicted adiabatic evolution is denoted by the dash-dotted curve. The magnetosonic instability strongly modifies the ion temperatures. This effect is illustrated in Figure 5 for protons (left panel) and for alpha particles (right panel). Figure 5 shows the evolution (solid curve) in the  $(\beta_{p\parallel}, T_{p\perp}/T_{p\parallel})$  space (left panel) and the  $(\beta_{\alpha\parallel}, T_{\alpha\perp}/T_{\alpha\parallel})$  space (right panel). The dash-dotted curve shows the adiabatic prediction.

#### 5. Discussion and Conclusion

[16] We have presented results of a recently developed simulation technique: a HEB code. We have applied this tool to study the evolution of ion temperature anisotropies and a drift speed in a slowly (strictly radially) expanding plasma. In the low-beta plasma case without drift between alphas and protons, the evolution of the system is double



**Figure 5.** High-beta plasma with drift: Evolution of protons (left panel) and alphas (right panel) in the space  $(\beta_{p\parallel}, T_{p\perp}/T_{p\parallel})$  and  $(\beta_{\alpha\parallel}, T_{\alpha\perp}/T_{\alpha\parallel})$ , respectively. The adiabatic prediction is denoted by the dash-dotted curves.

adiabatic (CGL) and important ion temperature anisotropies appear, with parallel temperatures much greater than the perpendicular ones. In the high-beta plasma case without drift between alphas and protons, the plasma evolves at the beginning adiabatically, and later on, the parallel fire hose appears. In 1-D simulations, the waves generated by the instability keep the system around marginal stability with an anticorrelation between the proton anisotropy  $T_{p\parallel}/T_{p\perp}$  and the proton parallel beta  $\beta_{p\parallel}$  [Gary *et al.*, 1998]. In 2-D simulations, the oblique fire hose becomes dominant and the evolution departs from marginal stability [Hellinger and Matsumoto, 2001]. The results of the simulation of pure proton plasmas are in a good agreement with linear theory and with previous simulation studies that used standard hybrid codes [Gary *et al.*, 1998; Hellinger and Matsumoto, 2000, 2001].

[17] However, these results are not applicable to the physics of fast solar wind, where an important drift velocity between protons and alphas exists. The inclusion of a drift between protons and alphas strongly changes the plasma behavior. In a low-beta plasma, the dominant mode is an oblique left-handed mode [Gary *et al.*, 2000 and references therein]. In this case, when the instability develops, the drift velocity is continuously slowed down so that it remains 1.5 times local Alfvén velocity. The generated waves heat protons and alphas preferably in the perpendicular directions. This heating compensates the adiabatic cooling of protons and alphas. The proton temperature anisotropy is  $T_{p\parallel}/T_{p\perp} \sim 0.6$  while the alpha temperature anisotropy is  $T_{\alpha\parallel}/T_{\alpha\perp} \sim 1.3$  in later stages of the evolution. Our simulation with a strictly radial magnetic field a low-beta plasma with drift corresponds to the fast solar wind around poles with the radial distance  $< 1AU$  from the Sun (for typical fast solar wind parameters). For these distances there are only observations by Helios [Marsch *et al.*, 1982a, 1982b], however, in the ecliptic plane. The results of the HEB code are only in a partial agreement with these observations. The drift velocity is comparable to the local Alfvén velocity, however observations show that the drift velocity is usually smaller than the local Alfvén velocity.

[18] In the high-beta plasma case, we observe a slightly different behavior. In this case the dominant instability is the magnetosonic one and this instability is able to importantly decelerate alphas and heat protons and alphas. The ratio between drift velocity and the local Alfvén velocity decreases with  $\beta_{\alpha\parallel}$ , and, at the later stages of the simulations, the drift velocity is smaller than the local Alfvén velocity. The proton temperature anisotropy is  $T_{p\parallel}/T_{p\perp} \sim 0.6$  and has a tendency to increase while the alpha temperature anisotropy is  $T_{\alpha\parallel}/T_{\alpha\perp} \sim 0.9$  and decreases with  $\beta_{\alpha\parallel}$ . These results are in good qualitative agreement with high latitude Ulysses observations of Reisenfeld *et al.* [2001] of higher beta plasma at 2–5 AU that show an anticorrelation between the proton temperature and the ratio between the drift velocity and the local Alfvén speed, with the drift velocity being below the local Alfvén speed. Also the observed anisotropy  $T_{\alpha\parallel}/T_{\alpha\perp} \sim 0.7$  is not far from what

the HEB simulation shows. However, the observed proton anisotropy is  $T_{p\parallel}/T_{p\perp} > 1$ .

[19] In conclusion, a HEB simulation shows a trajectory in parameter space (along the marginal stability path and departures from it) induced by the expansion, which could be approximatively traced by many standard hybrid simulations [Gary *et al.*, 2000, and reference therein]. This trajectory represents self-consistently the effect of a slow expansion on the plasma properties. The results are in a good agreement with linear theory and standard hybrid simulations [Li and Habbal, 2000; Gary *et al.*, 2000]. The comparison with observations shows many points of agreement, both on the pressure anisotropies and the proton-alpha drift. Future work will be devoted to study the influence of the initial plasma parameters, the impact of the transverse components of the mean magnetic field and also to a detailed comparisons between observations and HEB simulations.

[20] **Acknowledgments.** The authors thank the CIAS at Meudon Observatory for hospitality during summer 2001 and 2002 (MHD workshop) and acknowledge the grants PICS 1175 and GA AV B3042106.

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