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Proton temperature anisotropy constraint in the solar wind: ACE observations

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Abstract. The electromagnetic proton cyclotron anisotropy instability may arise in collisionless plasmas in which the proton velocity distribution is approximately bi-Maxwellian with $T_{\perp p}/T_{\parallel p} > 1$, where $\perp$ and $\parallel$ denote directions relative to the background magnetic field $\mathbf{B}_o$. Theory and simulations predict that enhanced field fluctuations from this instability impose a constraint on proton temperature anisotropies of the form $T_{\perp p}/T_{\parallel p} - 1 = S_p/\beta_{\parallel p}^{\alpha_p}$ where $\beta_{\parallel p} \equiv 8\pi n_p k_B T_{\parallel p}/B_o^2$, and the fitting parameters $S_p \lesssim 1$ and $\alpha_p \simeq 0.4$. Plasma and magnetic field observations from the ACE spacecraft reported here show for the first time that this constraint is statistically satisfied in the high speed solar wind near 1 AU, and magnetic power spectra provide evidence that this instability is the source of the constraint.

Introduction

In this paper we use measurements from the Advanced Composition Explorer (ACE) spacecraft to show for the first time in the solar wind that the proton cyclotron instability threshold constitutes a statistical upper bound on $T_{\perp p}/T_{\parallel p} > 1$ anisotropies. Here p represents protons and the directional subscripts indicate directions relative to the background magnetic field $\mathbf{B}_o$.

Linear Vlasov theory predicts that, for a constant γ_m/Ω_p (where γ_m is the maximum growth rate and Ω_p is the proton cyclotron frequency), the threshold condition for onset of the electromagnetic proton cyclotron anisotropy instability (hereafter the "proton cyclotron instability") in an electron-proton plasma at $\beta_{\parallel p} \lesssim 10$ can be written as

$$\frac{T_{\perp p}}{T_{\parallel p}} - 1 = \frac{S_p}{\beta_{\parallel p}{}^{\alpha_p}} \quad . \tag{1}$$

Here $\beta_{\parallel p} \equiv 8\pi n_p k_B T_{\parallel p}/B_o^2$, and the S_p and α_p are fitting parameters; the former is a function of the choice of γ_m/Ω_p but $\alpha_p \simeq 0.40$ for a broad range of parameters [*Gary et al.*, 1994a; *Gary and Lee*, 1994]. Hybrid simulations have demonstrated that this instability imposes a constraint on $T_{\perp p}/T_{\parallel p}$ at the threshold condition of Equation (1) [*Gary et al.*, 1994a, 1997]. [*Nakamura*, 2000] used the maximum entropy principle to confirm that Equation (1) represents an upper bound on the proton temperature anisotropy in a collisionless plasma.

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Experimental support for this conclusion has come from observations of this constraint as a statistical upper bound in the low-latitude magnetosheath [*Phan et al.*, 1994; *Anderson et al.*, 1994; *Fuselier et al.*, 1994; *Phan et al.*, 1996], in the high-latitude magnetosheath [*Tan et al.*, 1998], and in the outer magnetosphere [*Anderson et al.*, 1996; *Ober et al.*, 1999]. Further support for the validity of this constraint has been provided by its measurement in a laboratory plasma experiment [*Scime et al.*, 2000].

Yet, until now this proton anisotropy constraint has not been observed in the solar wind. The simple picture of the solar wind expanding in a radial magnetic field predicts the development of $T_{\parallel p}/T_{\perp p} > 1$ which may excite the firehose, rather than the proton cyclotron instability, and [*Eviatar and Schulz*, 1970] have shown that the threshold condition of the former mode is essentially a limit on that anisotropy. Nevertheless, observations in high speed streams [*Feldman et al.*, 1974; *Marsch et al.*, 1982a] often have shown a more dense proton core component with $T_\perp > T_\parallel$ and an additional, more tenuous, beam-like proton component with modest velocity displacement along $\mathbf{B}_o$. [*Richardson et al.*, 1996] used Voyager 2 observations to show that $T_{\perp p}/T_{\parallel p}$ increases as $\beta_{\parallel p}$ decreases. Furthermore, recent studies of magnetic field depressions in the fast solar wind [*Fränz et al.*, 2000; *Neugebauer, et al.*, 2001] have shown that these "magnetic holes" typically exhibit $T_{\perp p}/T_{\parallel p} > 1$.

A $T_{\perp p}/T_{\parallel p} > 1$ may be generated by several different processes in the solar wind, including short wavelength fluctuations which have cascaded from longer wavelengths [*Marsch et al.*, 1982b; *Verma et al.*, 1995], and instabilities driven by interplanetary pickup ions [*Gray et al.*, 1996]. But our concern here is not the source of this anisotropy. Rather, our point is that, whatever processes drive $T_{\perp p} > T_{\parallel p}$, wave-particle scattering will in all circumstances constrain this anisotropy.

ACE Observations

Instrumentation on the ACE spacecraft includes the Solar Wind Electron Proton Alpha Monitor (SWEPAM) [*McComas et al.*, 1998a] and the Magnetic Field Experiment (MAG) [*Smith et al.*, 1998]. SWEPAM consists of two fully independent sensors: one for electrons and one for ions. Both instruments are based on spherical section electrostatic analyzers followed by sets of channel electron multiplier detectors. Each can make full three-dimensional measurements of the electron and ion velocity distributions with 64 second time resolution. Here we use proton and alpha densities as well as $T_{\parallel p}$ and $T_{\perp p}$ moments derived from the observed distributions.

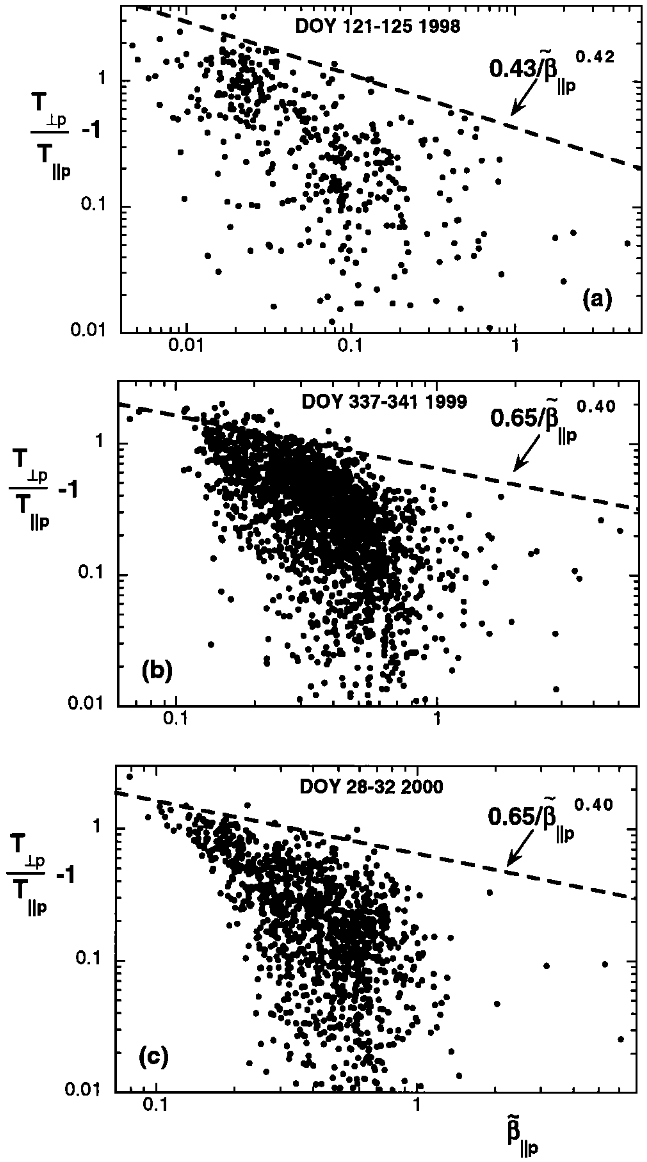

Figure 1. Proton temperature anisotropies as functions of $\tilde{\beta}_{\parallel p}$ for ACE observations corresponding to $v_{sw} \geq 600$ km/s. The three panels represent data from three intervals: (a) 30 April through 4 May (DOY 121-125) 1998, (b) 3 through 7 December (DOY 337-341) 1999, and (c) 28 January through 1 February (DOY 28-32) 2000. The dashed lines represent Equation (1) with (a) $S_p = 0.43$ and $\alpha_p = 0.42$ ($\gamma_m/\Omega_p = 0.001$); (b) and (c) $S_p = 0.65$ and $\alpha_p = 0.40$ ($\gamma_m/\Omega_p = 0.010$).

Parallel and perpendicular temperatures are useful parameters only if the thermal part of the proton velocity distribution is approximately bi-Maxwellian. We have examined proton distributions observed by the SWEPAM instrument using the analysis tool which produced Plate 3 of [*Tokar et al.*, 2000]. Our analysis of anisotropic distributions sampled from several high speed intervals shows that the beam-like component is typically much more tenuous than the core component. We therefore assume that its presence does not strongly violate the bi-Maxwellian condition, and proceed under the assumption that the $T_{\perp p}$ and $T_{\parallel p}$ derived by integration over the measured distributions are appropriate indicators of proton temperatures.

We used a merged SWEPAM/MAG high resolution data set to carry out a statistical analysis of proton temperature anisotropies measured during several intervals, each of which was several days in length. We extracted from the data two fundamental parameters: $\tilde{\beta}_{\parallel p} \equiv 8\pi(n_p+2n_\alpha)k_B T_{\parallel p}/B_o^2$, and $T_{\perp p}/T_{\parallel p}$. The alphas are of course observed by ACE [*McComas et al.*, 1998b; *Skoug et al.*, 1999] but we include only their contribution to the total density because the details of their velocity distributions cause only weak changes in the thresholds of the proton cyclotron instability for most solar wind conditions [*Gary et al.*, 1994b]. To obtain $T_{\perp p}/T_{\parallel p}$, the second velocity moments of the proton distribution were computed, diagonalized, and then rotated into a frame with one axis parallel to $\mathbf{B}_o$. After this operation, most observations yielded two perpendicular proton temperatures which are similar; in Figure 1 we include only those points such that the ratio of these two temperatures is not larger than 1.3.

As the solar wind expands, conservation of the first adiabatic invariant predicts that the proton velocity distribution should develop, on average, $T_{\perp p}/T_{\parallel p} < 1$. ACE measurements show that the protons indeed show such an anisotropy much of the time; sample intervals show percentages of this anisotropy ranging from 40% to 80% of the observations. But we have not considered data with this anisotropy.

We examined proton temperature anisotropies from a number of intervals, including several which included high speed flows ($v_{sw} > 600$ km/s). On each of these intervals we plotted $T_{\perp p}/T_{\parallel p}-1$ versus $\tilde{\beta}_{\parallel p}$. In all intervals, as illustrated in Figure 1 we found the same general result as has been observed in the papers cited in the Introduction; that is, the maximum values of proton temperature anisotropies show a statistical decrease with increasing $\tilde{\beta}_{\parallel p}$. For the low speed wind, unless we chose relatively short intervals, these maximum values were typically not well fit with a single power law like Equation (1). However, most high speed intervals showed similar results: $T_{\perp p}/T_{\parallel p}$ is bounded by Equation (1) with $0.43 \leq S_p \leq 0.65$ and $\alpha_p \simeq 0.40$, and the constraint is a statistical one, with only a small number of observations lying above the threshold condition.

Figure 1 shows this with plots of proton anisotropies at $T_{\perp p}/T_{\parallel p} > 1$ observed during three high speed intervals as functions of $\tilde{\beta}_{\parallel p}$. Here also are plotted Equation (1) with $\tilde{\beta}_{\parallel p}$ substituted for $\beta_{\parallel p}$ and with α_p and S_p chosen as linear theory thresholds which provide tight constraints on the measured anisotropies. Thus Equation (1) with $\alpha_p \simeq 0.40$ represents a statistical upper bound on the observed proton temperature anisotropies. The statistical nature of the constraint is probably due in part to measurement errors, and in part to different strengths of the sources driving the anisotropy.

Figure 2 illustrates the critical anisotropy parameter $(T_{\perp p}/T_{\parallel p} - 1)\tilde{\beta}_{\parallel p}^{0.40}/0.65$ and three corresponding magnetic power spectra measured during an interval which includes a large proton temperature anisotropy on 28 January 2000. In fractions of the day, the three spectra correspond to the intervals [028.270, 028.320], [028.320, 028.370] and [028.375, 028.425]. (We do not calculate power spectra over the interval [028.370, 028.375] because there is a very rapid 2 nT decrease in B_o at 028.372.) The mean values of the critical anisotropy parameter for these three intervals are 0.42, 0.64, and 0.097, respectively, confirming the indication of the figure that the middle interval (which includes two points at

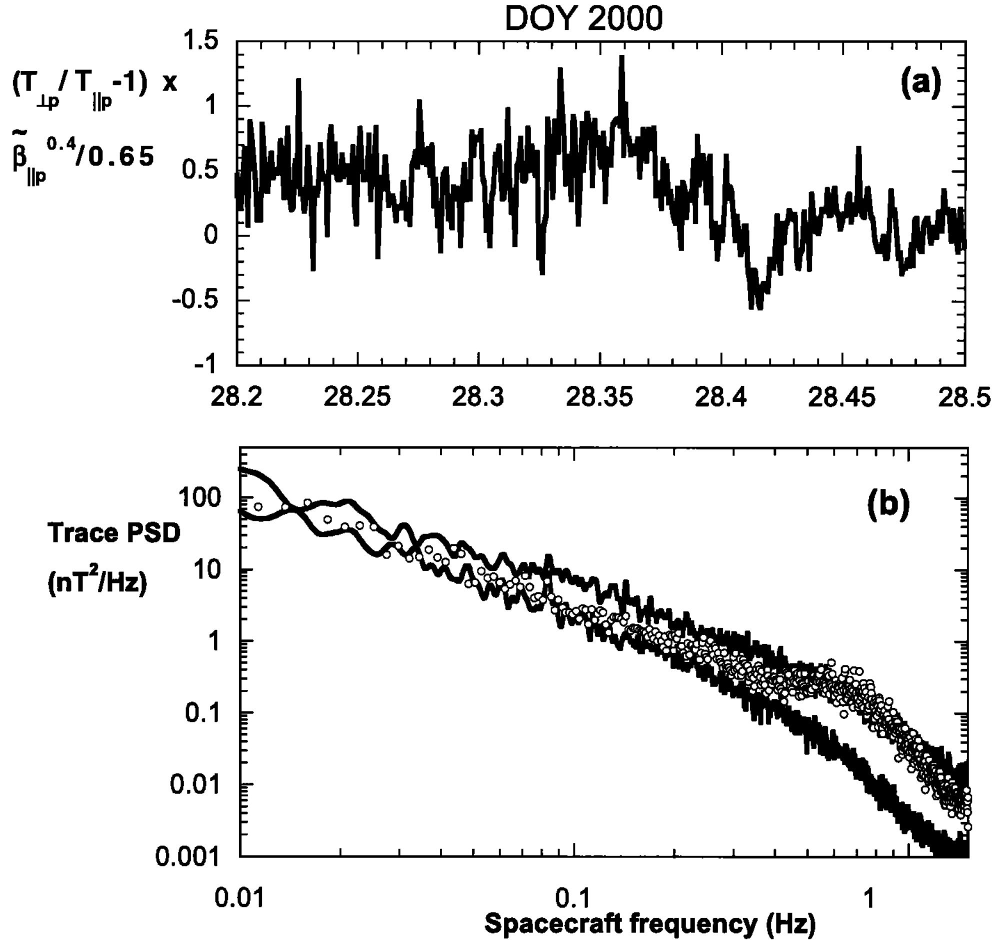

Figure 2. ACE observations during part of a high speed interval ($v_{sw} \simeq 700$ km/s) on 28 January 2000. (a) The critical anisotropy parameter as a function of time. (b) Three traces of the magnetic power spectral density matrix as functions of the frequency measured in the spacecraft frame corresponding to the intervals [028.270, 028.320] (upper solid line), [028.320,028.370] (open circles), and [028.375,028.425] (lower solid line).

which the critical parameter exceeds unity) is the one most likely to yield evidence of instability activity. Indeed, the power spectrum corresponding to this middle interval shows a clear enhancement near 0.7 Hz which, for the solar wind speed of about 700 km/s, corresponds to $kc/\omega_p \sim 1$. This is approximately the wavenumber at which linear theory predicts the proton cyclotron instability should have maximum growth rate for the observed average value of $\tilde{\beta}_{\parallel p} \simeq 0.2$. Earlier solar wind measurements have shown clear enhancements of both density [*Neugebauer*, 1975] and magnetic [*Unti and Russell*, 1976; *Tsurutani et al.*, 1994] power spectra near 1 Hz, but we believe this is the first report of such a power enhancement in association with a measured proton anisotropy.

Conclusions

We have used plasma and magnetic field measurements from ACE to show for the first time that the theoretical threshold of the proton cyclotron instability provides a statistical upper bound on observed values of $T_{\perp p}/T_{\parallel p}$ in the high speed solar wind. We have also demonstrated that, during one high-speed interval, enhanced short-wavelength magnetic fluctuations are observed exactly when the proton temperature anisotropy is on average closest to instability threshold and most likely to yield growth of electromagnetic waves.

[*Richardson et al.*, 1996] observed from Voyager 2 that the average $T_{\perp p}/T_{\parallel p}$ increases with decreasing $\tilde{\beta}_{\parallel p}$ and hypothesized that this increase is due, in part, to an ion cyclotron instability driven by pickup ions which they claimed operates most effectively where the plasma β is low. We hold the opposite position: the average increase in anisotropy with decreasing $\tilde{\beta}_{\parallel p}$ is a property of the growing mode which constrains, not enhances, that anisotropy. Whatever the source of this nonthermal property, as long as the velocity distribution is approximately bi-Maxwellian, we predict that Equation (1) with $\alpha_p \simeq 0.40$ will provide a statistical upper bound on $T_{\perp p}/T_{\parallel p}$. We recommend simulation studies to predict the fitting parameters of Equation (1) for various driving processes, and further observational studies to test these predictions, as well as to improve the statistics of the results presented here.

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