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 $T_{\perp p}/T_{\| p} > 1$, where $\perp$ and $\|$ denote directions relative to the background magnetic field. Theory and simulations predict that enhanced field fluctuations from this instability impose a constraint on proton temperature anisotropies of the form $T_{\perp p}/T_{\| p} - 1 = S_p/\beta_{\| p}^{\alpha_p}$ where $\beta_{\| p} \equiv 8\pi n_p k_B T_{\| p}/B_o^2$, and the fitting parameters $S_p \lesssim 1$ and $\alpha_p \simeq 0.4$. Observations in both the terrestrial magnetosheath and the magnetosphere have shown that this expression represents a statistical upper bound for this anisotropy. 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 as well.

1. Introduction

The hot, tenuous collisionless plasmas of space are diverse; solar wind, solar corona, and each planetary magnetospheric plasma have distinct, specific properties which must be addressed by distinct, specific models. But at the fundamental level, all of these plasmas (indeed, all collisionless plasmas of the universe) are described by the Vlasov equation coupled to Maxwell's equations. So if we step back from the phenomenology of these diverse regimes, we may discover basic, underlying principles which apply to many different space, astrophysical and laboratory plasmas.

It is a long-standing general hypothesis that wave-particle scattering by enhanced fluctuations from a kinetic instability in collisionless plasmas should constrain the anisotropy or anisotropies which drive that unstable mode. Consider the specific case of plasmas with bi-Maxwellian proton velocity distributions and anisotropies such that $T_{\perp p}/T_{\| p} > 1$ (The p represents protons and the other subscripts represent directions relative to the background magnetic field $\mathbf{B}_o$.). Under such conditions research has shown that an anisotropy constraint exists, that it may be written as a concise function of local parameters, and that it should be applicable to all such plasmas which are relatively homogeneous, magnetized, and collisionless.

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 maximum growth rate but $\alpha_p \simeq 0.40$ for a broad range of parameters [*Gary et al.*, 1994a; *Gary and Lee*, 1994]. For example, at $\gamma_m/\Omega_p \simeq 0.010$, a least-squares fit to Equation (1) of the linear theory thresholds over $0.01 \leq \beta_{\parallel p} \leq 10$ yields $S_p = 0.65$ and $\alpha_p = 0.40$. Hybrid simulations have demonstrated that this instability imposes a constraint on the proton temperature anisotropy with the form of Equation (1) [*Gary et al.*, 1994a; 1997; 2000]. *Nakamura* [2000] has used the maximum entropy principle to confirm that Equation (1) represents an upper bound on the proton temperature anisotropy in a collisionless plasma.

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] where the proton distributions are clearly bi-Maxwellian [*Sckopke et al.*, 1990], in the high-latitude magnetosheath [*Tan et al.*, 1998], and in the outer magnetosphere [*Gary et al.*, 1995; *Anderson et al.*, 1996; *Ober et al.*, 1999]. This conclusion has been further substantiated through the observation of enhanced proton cyclotron fluctuations in association with this constraint [*Anderson et al.*, 1994; *Fuselier et al.*, 1994; *Anderson et al.*, 1996]. Still further support for the validity of this constraint has been provided by its measurement in a carefully controlled laboratory experiment [*Keiter et al.*, 2000; *Scime et al.*, 2000].

However, until now this proton anisotropy constraint has not been observed in the solar wind. Of course, the simple picture of the solar wind expanding in a radial magnetic field predicts the development of $T_{\parallel p} > T_{\perp p}$ which does not lead to the development of the proton cyclotron instability, and indeed it is that condition which is more often observed [*Marsch*, 1991]. Nevertheless, the opposite anisotropy is sometimes measured in the solar wind. Observations in high speed streams [*Feldman et al.*, 1974; *Bame et al.*, 1975; *Marsch et al.*, 1982a] often have shown a more dense proton core component with $T_{\perp} > T_{\parallel}$ with an additional, more tenuous, beam-like proton component with a 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.*, 2000] 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. These include strong magnetic compressions, double adiabatic expansion in the spiralling interplanetary magnetic field [*Richardson et al.*, 1996], heating by short wavelength fluctuations which have cascaded from longer wavelenths [*Marsch et al.*, 1982b; *Verma et al.*, 1995], heating by quasi-perpendicular interplanetary shocks [see the low-Mach bow shock observations of *Thomsen et al.*, 1985], and heating by instabilities driven by interplanetary pickup ions [*Gray et al.*, 1996]. However, 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 act to maintain the constraint described by Equation (1).

Here we use measurements from the Advanced Composition Explorer (ACE) spacecraft to show for the first time that the proton cyclotron instability threshold constitutes a statistical upper bound on $T_{\perp p}/T_{\parallel p} > 1$ anisotropies observed in the high speed solar wind near 1 AU and that these anisotropies are tightly constrained by Equation (1). Among the approximations we make here are the neglect of the proton beam-like component and alpha particle contributions to the threshold conditions. The alphas are of course are observed by ACE [*McComas et al.*, 1998b; *Skoug et al.*, 1999] but they are often tenuous enough that they do not make qualitative changes in the thresholds [*Gary et al.*, 1994b].

2. 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 the proton and alpha densities as well as $T_{\parallel p}$ and $T_{\perp p}$ moments derived from the observed ion distributions.

The 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. A detailed analysis of this tenuous component is beyond the purview of this manuscript, so 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 observed 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 the proton temperature anisotropy. To obtain the latter, 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 data points yielded two perpendicular proton temperatures which are similar; here 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. Such proton anisotropies may correspond not only to a bi-Maxwellian distribution, but also to two-component proton/proton type distributions, so that an analysis of the $T_{\perp p}/T_{\parallel p} < 1$ condition may involve consideration of both the proton resonant firehose [*Gary et al.*, 1998] as well as the various proton/proton instabilities [e.g., *Daughton et al.*, 1999]. To avoid this complication, 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). Figure 1 presents the solar wind parameters measured from ACE during the representative high speed interval of 3 through 7 December 1999. The solar wind proton speed shows the classic high speed stream profile, with a relatively rapid rise to approximately 700 km/s, followed by a more gradual decrease of v_{sw}. The proton density shows a gradual decrease during the period of increasing solar wind speed, but remains approximately constant at a few particles/cm^{-3} during the declining phase of the high speed interval. The magnetic field magnitude shows, on average, an increase through most of the increasing speed phase, but then drops suddenly and remains near 5 nT during that portion of the declining phase illustrated here.

On each of these intervals we plotted $T_{\perp p}/T_{\parallel p}-1$ versus $\tilde{\beta}_{\parallel p}$. In all intervals, 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 $\tilde{\beta}_{\parallel p}$. 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 of high speed wind intervals showed similar results: the proton temperature anisotropy 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 2 illustrates this result with plots of proton anisotropies at $T_{\perp p}/T_{\parallel p} > 1$ observed from ACE 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 observed anisotropies.

Different values of S_p correspond to different values of the instability growth rate and suggest that the proton anisotropy is driven more or less strongly under different solar wind conditions. Nevertheless, the clear result here is that the threshold condition of Equation (1) with $\alpha_p \simeq 0.40$ represents a statistical upper bound on the observed proton temperature anisotropies. This confirms the specific conclusion that the proton cyclotron instability grows and bounds the proton temperature anisotropy in the solar wind. It also once again substantiates the general hypothesis that wave-particle scattering in collisionless plasmas should constrain the anisotropy which drives the associated kinetic instability.

We now return to Figure 1 and in particular consider the bottom panel which illustrates the parameter $(T_{\perp p}/T_{\parallel p} - 1)\tilde{\beta}_{\parallel p}{}^{0.40}/0.65$. If this parameter is greater than unity, the corresponding observation lies above the dashed line of Figure 2b and indicates that the proton anisotropy is above the instability threshold at that time. Thus relatively large values of this parameter indicate times of strong anisotropy and possible instability activity. Comparison of the various panels of Figure 1 shows, surprisingly, that the strongest anisotropies arise not during times of increasing magnetic field, but rather as B_o decreases or has fallen to a relatively low value later in the interval. There is no clear correlation of strong anisotropy with either density or proton temperature, and strong anisotropy intervals occur during both the increasing and decreasing phases of solar wind flow speed. We have carried out similar analyses of this parameter for other high speed intervals, and have reached similarly inconclusive results. It may be that our observed correlation between enhanced proton anisotropies and reduced magnetic field magnitudes bears some relationship to the observations of $T_{\perp p}/T_{\parallel p} > 1$ in solar wind magnetic depressions by *Fränz et al.* [2000] and *Neugebauer et al.* [2000]. But we must relegate a deeper understanding of how the solar wind drives the $T_{\perp p}/T_{\parallel p} > 1$ anisotropy to future studies.

3. Conclusions

We have used plasma and magnetic field measurements from the ACE spacecraft 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. This demonstration is a confirmation of the *Gary et al.* [1997] prediction that "the anisotropy bound should satisfy Equation (1) with $0.4 \lesssim \alpha_p \lesssim 0.5$ in statistical data sets from any space plasma...that satisfies our basic assumptions."

Richardson et al. [1996] observe from Voyager 2 data that the average $T_{\perp p}/T_{\parallel p}$

increases with decreasing $\tilde{\beta}_{\parallel p}$ and hypothesize that this increase is due, in part, to an ion cyclotron instability driven by pickup ions which they claim 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 $T_{\perp p}/T_{\parallel p}$.

Linear theory predictions for instability thresholds correspond to monotonically increasing values of S_p as γ_m/Ω_p is increased, suggesting a possibly broad range of observed values for this fitting parameter. However, both observations and computer simulations yield a relatively limited range of $0.4 \lesssim S_p \lesssim 1.0$. Our interpretation of these results is that the larger the initial anisotropy, the faster the instability grows, the more rapidly the ions are scattered, and the greater the reduction in S_p. Thus the constraint in general and the S_p values in particular represent a balance between a force or forces driving an increased anisotropy and wave-particle scattering acting to reduce that anisotropy. The net result is the relatively narrow range of observed values of S_p. The condition of $\alpha_p \simeq 0.4$ is predicated on the assumption that the anisotropy source corresponds to a uniform maximum growth rate of the instability across the domain of observable β_p. For sources which drive proton anisotropies at different rates for different $\beta_{\parallel p}$, as may well be the case for proton heating by turbulent cascade and pickup ion instabilities, the observed values of α_p may vary. We recommend simulation studies to predict the fitting parameters of Equation (1) for these processes, and further observational studies to test these predictions.

Our study has ignored contributions to the anisotropy provided by the proton beam-like component and the heavy ions including the alpha particles. It would be useful to examine the ACE ion observations more carefully, to characterize these contributions, to determine how frequently these contributions significantly change the threshold conditions of the proton cyclotron instability, and to compare the observations against the revised predictions of theory. We further expect that, if the alphas are sufficient dense and sufficiently anisotropic, that the alpha cyclotron anisotropy instability will also be excited and will constrain the alpha anisotropy [*Gary et al.*, 1993, 1994b]. It would be interesting to determine whether this effect could be observed via ACE observations. It also would be useful to study magnetic fluctuation spectra for those intervals during which the proton anisotropy is close to its maximum value for a given $\tilde{\beta}_{\parallel p}$. We expect that, if the electromagnetic proton cyclotron instability is indeed the source of the constraint, then enhanced magnetic fluctuations near and below the Doppler-shifted proton cyclotron frequency should be observed at the same time.

Recent SOHO observations imply that protons bear a strong temperature anisotropy in the solar corona [*Kohl et al.*, 1998] with $T_{\perp p}/T_{\parallel p} \lesssim 4$. This anisotropy, which may be due to proton cyclotron heating induced by magnetic fluctuation energy cascading from lower frequencies, should be subject to the same constraint as reported here. Assuming that Equation (1) with $S_p = 0.65$ and $\alpha_p = 0.40$ is valid in the solar corona, a proton temperature anisotropy of 4 implies a corresponding value of $\tilde{\beta}_{\|p} \simeq 0.02$ in the corona. *Kohl et al.* [1998] report that heavy ions in the solar corona appear to bear even stronger temperature anisotropies than the protons. If this is true, then it is likely that these heavy ions are subject to anisotropy constraints similar to the proton anisotropy bound *Ofman et al.* [2000].

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Figure Captions

Figure 1. ACE observations: Proton density, proton speed, proton temperature, magnetic field magnitude, and the parameter $(T_{\perp p}/T_{\| p} - 1)\tilde{\beta}_{\| p}{}^{0.40}/0.65$ as functions of time through the high speed interval of 3-7 December 1999.

Figure 2. Ace observations: Proton temperature anisotropies as functions of $\tilde{\beta}_{\| p}$ 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 $\alpha_p = 0.40$ ($\gamma_m/\Omega_p = 0.010$).