LIMITS ON ALPHA PARTICLE TEMPERATURE ANISOTROPY AND DIFFERENTIAL FLOW FROM KINETIC INSTABILITIES: SOLAR WIND OBSERVATIONS

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1. INTRODUCTION

In situ spacecraft measurements indicate that solar wind plasma deviates significantly from local thermodynamic equilibrium. Ions exhibit distinct non-thermal kinetic features, such as proton core temperature anisotropy, proton beams, and the preferential heating and acceleration (with respect to the protons) of alpha particles and minor ions (Marsch 2006). All these non-thermal features can be a source of kinetic instabilities, such as the Alfvén/ion-cyclotron (A/IC) and fast-magnetosonic/whistler (FM/W) instabilities. In this Letter, we use a long period of in situ measurements provided by the Wind spacecraft’s Faraday cups to investigate the combined constraint on the alpha proton differential flow velocity and the alpha particle temperature anisotropy due to A/IC and FM/W instabilities. We show that the majority of the data are constrained to lie within the region of parameter space in which A/IC and FM/W waves are either stable or have extremely low growth rates. In the minority of observed cases in which the growth rate of the A/IC (FM/W) instability is comparatively large, we find relatively higher values of \( T_{\alpha} / T_{\parallel} \) (\( T_{\ perpendicular} / T_{\parallel} \)) when the alpha proton differential flow velocity is small, where \( T_{\alpha} \) and \( T_{\parallel} \) (\( T_{\ perpendicular} \)) are the perpendicular (parallel) temperatures of alpha particles and protons. We conjecture that this observed feature might arise from preferential alpha particle heating which can drive the alpha particles beyond the instability thresholds.

Key words: instabilities – solar wind – turbulence – waves

Online-only material: color figures

2. OBSERVATIONS AND RESULTS

The measurements of ion parameters used in this study were derived from in situ data from the Wind spacecraft’s Faraday cups (Ogilvie et al. 1995). This instrument produces an ion spectrum (i.e., a distribution of ion speeds projected along various axes) about once every ninety seconds. The bulk
parameters (e.g., density, flow velocity, and temperature) of the protons and alpha particles can be deduced from each spectrum by fitting a model velocity distribution function for each species (Kasper 2002; Kasper et al. 2006). Perpendicular and parallel temperature components can be separated using measurements of the local magnetic field, which are available from Wind's Magnetic Field Investigation (Lepping et al. 1995).

For this study, we use the dataset of ion parameters produced by Maruca (2012, Chapter 4), who processed nearly 4.8 million Wind ion spectra (i.e., all spectra from the spacecraft’s launch in late 1994 through mid-2010) with a fully-revised fitting code. These revisions dramatically improved the code’s analysis of temperature anisotropy and differential flow (especially during periods of significant fluctuations in the background magnetic field) (Maruca & Kasper 2013). Nevertheless, only about 2.1 million of the spectra processed were included in the final dataset due to two sets of selection requirements. First, a spectrum needed to have been measured at a time when Wind was well outside the Earth’s bow shock (i.e., actually in the solar wind). The spacecraft, especially during the early part of its mission, spent significant amounts of time exploring the Earth’s magnetosphere. Second, the fit results had to be of high quality as gauged by reduced-$\chi^2$, uncertainty in the fit parameters, and other metrics. The most frequent cause for this second criterion not being met was low alpha particle signal (from, e.g., low densities or high temperatures).

To study the instabilities resulting from a combination of relative drift and temperature anisotropy of alpha particles, we restrict our data analysis to solar wind intervals in which $3 \leq \frac{T_a}{T_p} \leq 5$. The selected interval of $T_a/T_p$ represents the typical range of variation of the ratio alpha-to-proton temperature in weakly collisional solar wind streams (Kasper et al. 2008). Also, our selection is consistent with the theoretical value of $3 \lesssim \frac{T_a}{T_p} \lesssim 5$ used below to determine the threshold values for the drift–anisotropy instabilities.

Using Kennel & Wong’s (1967) expression for the growth rate $\gamma$ of weakly growing waves, Verscharen et al. (2013) derived approximate analytic expressions for the instability thresholds of A/IC and FM/W waves taking into account both the alpha proton drift and alpha particle temperature anisotropy. For this calculation, they assumed that the wavevector $\mathbf{k}$ is parallel to the background magnetic field $\mathbf{B}_0$ and took the alpha particles (protons) to have a bi-Maxwellian (Maxwellian) distribution. We note at this point that some authors refer to the parallel FM/W instability as the parallel FH instability. Verscharen et al. (2013) validated their analytic results by comparing them to numerical solutions of the hot plasma dispersion relation. For the parameters we consider in this Letter the minimum value of $U_{a}$ needed to excite the A/IC instability is given by (see Verscharen et al. (2013) for further details)

$$U_{A/IC} = v_A - \sigma \left( R_a - 1 \right) w_{[a]} - \frac{v_A^2}{4 \omega w_{[a]} R_a},$$

(1)

where $w_{[j]} = (2 k_B T_{[j]}/m_j)^{1/2}$ is the parallel thermal speed and $m_j$ the mass per particle of species $j$. The minimum value of $U_{a}$ needed to excite the parallel FM/W instability is

$$U_{FM/W} = v_A - \sigma \left( 1 - R_a \right) w_{[a]} + \frac{v_A^2}{4 \sigma w_{[a]} R_a}.$$  

(2)

The value of the dimensionless quantity $\sigma$ in these equations depends very weakly upon the alpha-to-proton density ratio $n_a/n_p$ and the exact definition of the instability threshold. In this Letter, we use the values of $\sigma$ for which Equations (1) and (2) correspond to growth rates of $10^{-4} \Omega_p$ (where $\Omega_p$ is the proton cyclotron frequency) in a plasma with $n_a/n_p = 0.05$. These values are $\sigma = 2.4$ in Equation (1) and $\sigma = 2.1$ in Equation (2) (Versharen et al. 2013). In addition to these approximate analytic instability thresholds, we use numerical solutions of the hot plasma dispersion relation to find contours in different parameter planes (e.g., the $U_{a} - w_{[a]}$ plane) corresponding to various values of the maximum A/IC or FM/W growth rate. To solve the linear dispersion relation we used the following parameters: $n_a/n_p = 0.05$, $T_e = T_p$, $R_p = 1$, $T_{[a]} = 4T_p$, and $v_A/c = 10^{-4}$, where $c$ is the speed of light. We plot some of these contours in the figures below. As shown by Verscharen et al. (2013), Equations (1) and (2) correspond closely to the numerical contours with $\gamma = 10^{-4} \Omega_p$, except for the portion of the analytic curve for $U_{A/IC}$ at small $w_{[a]}/v_{A}$ in Figure 1 where $U_{A/IC}$ decreases as $w_{[a]}/v_{A}$ decreases, which is not reproduced in the numerical solutions.

In Figure 1, we compare the theoretical instability threshold of the A/IC wave with the subsets of the Wind measurements in
fraction of the data satisfies $U_\parallel > U_{\text{FM/W}}$, but the majority of the data is constrained to lie below the curve corresponding to $\gamma = 10^{-3}\Omega_p$. In addition, the curves of constant maximum growth rates and the contours of the PDF at $w_{1\alpha} \gtrsim v_A$ have similar slopes.

We note that the constant-$\gamma$ contours for the parallel A/IC and FM/W instability thresholds do not coincide with the contours of the data distribution at small $w_{1\alpha}/v_A$ in Figures 1 and 2, where the upper bound on $U_\parallel$ is approximately proportional to $w_{1\alpha}$. The reason for this upper bound on $U_\parallel$ at small $w_{1\alpha}/v_A$ is not clear from our analysis.

Two other instabilities driven by pressure anisotropies are the mirror mode and the oblique FH instabilities (Hellinger & Matsumoto 2002; Pokhotelov et al. 2004; Stix 1992). If the temperature anisotropy crosses the instability threshold of the mirror mode or the oblique FH instability, the unstable mode shows maximum growth rate at a non-vanishing angle between the wavevector $k$ and the background magnetic field $B_0$. The frequencies of these oblique instabilities in the proton frame are purely imaginary if $U_\parallel = 0$, and the real parts of the frequencies slowly increase with increasing $U_\parallel$. In Figure 3 we plot numerically determined isocontours of constant maximum growth rates $\gamma$ for both the mirror mode instability and the oblique FH instability in the $w_{1\alpha}/v_A-U_\parallel/v_A$ plane for two different values of $R_A$. The points represent parameter combinations for which the particular mode has $\gamma = 10^{-3}\Omega_p$ at one wavevector only and has lower $\gamma$ at all other wavevectors. Both the analytical thresholds and the isocontours with $\gamma = 10^{-3}\Omega_p$ for the A/IC and FM/W instabilities are much closer to the data distribution in parameter space than the isocontours for the oblique instabilities (compare Figure 3 to Figures 1 and 2). Furthermore, the threshold of the mirror mode instability hardly depends on the value of $U_\parallel$, and the slopes of the lines in Figure 3 are very different from the slopes of the outer contours of the data distribution plotted in Figures 1 and 2. Therefore, we conclude that the oblique instabilities seem not to limit the alpha temperature anisotropy in the presence of alpha drift in our cases.

We now turn to a consideration of the preferential heating of alpha particles near the thresholds of the A/IC and FM/W
assuming isotropic proton temperature, using the analytical fitting formula (8) of Maruca et al. (2012) (where $U_A < v_A$ for which $\text{Wind}$ instabilities. For this part of our analysis, we select all data.

In Figure 4 we order the data as a function of $\beta_{\parallel} \alpha/T_\alpha$ and $T_{\parallel}/T_\parallel$ (where $\beta_{\parallel} \alpha = 2n_\alpha k_B T_{\parallel} \mu_0 / B_0^2$). The curves in Figure 4 are contours of constant maximum growth rate $\gamma = 10^{-2} \Omega_p$ using the analytical fitting formula (8) of Maruca et al. (2012) assuming isotropic proton temperature, $n_\alpha = 0.05 n_\parallel$ and equal parallel thermal speeds of alpha particles and protons. The curves we plot thus serve primarily to indicate the vicinity of the many different growth rate contours that would apply to this data set. In the top panel of Figure 4, we plot the data distribution as a function of $\beta_{\parallel} \alpha$ and $R_\alpha$. In the panels (b) and (c) of Figure 4, we plot the average value of $T_{\parallel}/T_\parallel$ and $T_{\parallel}/T_\parallel$, respectively. These plots show that the ratio $T_{\parallel}/T_\parallel$ is relatively higher near the threshold of the A/IC (FM/W) instability than elsewhere in the $(\beta_{\parallel} \alpha, T_{\parallel}/T_\parallel)$ plane. This observational finding for alpha particles, to the best of our knowledge, has not been reported before. However, Maruca et al. (2011) reported a similar finding for protons. Although we do not focus on the origin of the enhanced alpha particle temperatures in this study, we note that cyclotron resonant heating and stochastic heating models can explain the preferential heating of alpha particles to temperatures exceeding the proton temperature (Isenberg & Vasquez 2007; Kasper et al. 2013; Chandran et al. 2013).

3. CONCLUSIONS

By analyzing Wind measurements of solar wind streams, we find that the alpha particle differential flow is limited to values comparable to the instability thresholds of A/IC and FM/W waves. Importantly, these thresholds depend upon the temperature anisotropy of the alpha particles. In contrast to the $U_A$ thresholds of beam instabilities in isotropic-temperature plasmas, which are $\geq v_A$, the thresholds of the A/IC and FM/W instabilities can be significantly smaller than $v_A$ when $T_{\parallel}/T_\parallel \neq T_{\parallel}/T_\parallel$ and when $w_{\parallel} > v_A$. Our findings support previous suggestions that A/IC and FM/W instabilities limit the alpha particle differential flow in the solar wind. Our results also emphasize the importance of treating differential flow and temperature anisotropy on an equal footing when $w_{\parallel} > v_A$, since these properties are of comparable importance for these instabilities.

Within the subset of the data in which $U_A < 0.1 v_A$, we find strong preferential heating of alpha particles relative to protons for conditions under which the A/IC and FM/W instabilities occur. When the plasma is near the threshold of the A/IC instability, $T_{\parallel}/T_\parallel$ is unusually large. On the other hand, when the plasma is near the threshold of the FM/W instability, $T_{\parallel}/T_\parallel$ is unusually large. This suggests that exceptionally strong perpendicular (parallel) heating is the reason why, in a small fraction of the small-$U_A$ data, alpha particles are in the A/IC-unstable (FM/W-unstable) region of parameter space.

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