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Observed Constraint on Proton-Proton Relative Velocities in the Solar Wind

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Abstract. From June 1994 to December 1995 the Ulysses spacecraft was within 3 AU of the Sun and traveled from high southern to high northern heliospheric latitudes. For this period, SWOOPS instrument data obtained when the magnetic field was approximately aligned with the radial direction from the Sun have been analyzed. In the fast wind at high latitudes, two resolvable proton components are typically present. Statistical studies of the relative densities and the field- aligned velocity difference, v_o, of the two components are carried out, considering the dependence on distance from the Sun, the local Alfvén speed, and the type of solar wind flow. The observed values of v_o/v_A, where v_A is the local Alfvén speed, are less than the upper bound determined from the linear theory for electromagnetic proton-proton instabilities. This result is good evidence that these microinstabilities constrain the relative streaming of the two components in the solar wind.

Introduction

A long-standing hypothesis in the theory of collisionless plasmas is that wave-particle scattering by enhanced fluctuations from a kinetic instability should constrain the anisotropy that drives the unstable mode [*Kennel and Petschek,* 1966]. A corollary [*Manheimer and Boris,* 1977] is that an instability threshold derived from linear theory should correspond to an observable bound on the anisotropy driving the growing mode. This hypothesis and its corollary have been substantiated in the terrestrial magnetosheath and outer magnetosphere where the proton temperature anisotropy drives an electromagnetic proton cyclotron instability which imposes an observable upper bound on that anisotropy [*Anderson et al.*, 1996; *Gary et al.*, 1997; and references therein]. But similar efforts to relate instability threshold and solar wind proton observations have been less conclusive [*Marsch and Livi*, 1987].

Especially during periods of relatively fast flow speeds, $v_{sw} > 600$ km/s, the proton velocity distribution of the solar wind often can be represented as two bi-Maxwellian components with an average relative drift velocity parallel to the background magnetic field of order of v_A, the Alfvén speed [*Marsch and Livi*, 1987, and references therein]. For this source of free energy, the hypothesis may be stated such that enhanced fluctuations from proton-proton instabilities should impose a constraint on the relative drift between the two components, v_o. The corollary is that linear theory instability thresholds should correspond to upper bounds on observed values of the dimensionless parameter v_o/v_A.

Gary [1991; 1993] has reviewed early theoretical and computational studies of electromagnetic proton-proton instabilities. The most recent research on such growing modes under solar wind conditions is the linear theory of *Daughton and Gary* [1998] and the hybrid simulations of *Daughton et al.* [1999]. The former paper shows that, under the representative conditions of $v_o/v_A = 2$, isotropic temperatures for both the beam and the core proton components, and $T_b = T_c$, two modes are likely to arise. One is the magnetosonic instability with maximum growth rate at propagation parallel to the background field; the second is the Alfvén instability with maximum growth rate at propagation oblique to the magnetic field. The former mode has the lower threshold value of v_o/v_A at relatively large β_p (proton pressure/magnetic pressure) and relatively small n_b/n_e where n_b is the density of the beam and n_e is the electron density; the latter mode has the lower threshold in the opposite senses of these parameters. *Daughton et al.* [1999] showed that the enhanced field fluctuations generated by these instabilities yield a reduction in the proton-proton relative drift speed and a characteristic heating of the more tenuous beam component temperature perpendicular to $\vec{B}_o$.

Observations

The Ulysses SWOOPS instrument [*Bame et al.*, 1992] provides much better velocity-space resolution in the radial direction, that is, along the Sun-spacecraft line, than in directions perpendicular to that line. Therefore, proton temperature observations in the radial direction are much more accurate than those in the perpendicular directions, and it is not possible to examine the *Daughton et al.* [1999] prediction that proton-proton instability growth should produce enhanced perpendicular temperatures of the proton beams. However, when the interplanetary magnetic field is approximately in the radial direction, SWOOPS can accurately measure the relative difference between the average field-aligned velocities of the two proton components; we report

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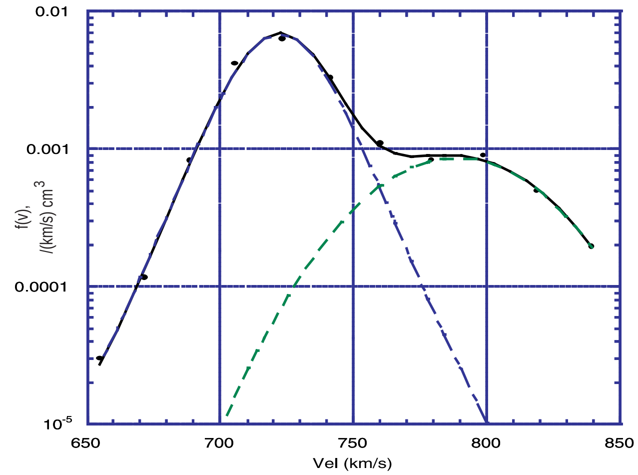

Figure 1. Two beam model fit to the logarithm of phase space density for the spectrum obtained at 1994 252 15:10; $FitGoodness = 0.913$.

here on a statistical study of this speed difference. From Day 151 of 1994 through Day 356 of 1995, Ulysses was in the high speed polar wind (defined as v_{sw} >700 km/s) within 3 AU of the Sun. During that time, 842 SWOOPS spectra were obtained for which $\vec{B}_o$, the magnetic field, was aligned within 10°of the radial direction. This was a bit less than 1% of the total data set. One-dimensional energy spectra of SWOOPS data were obtained by summing over all angles for a given energy step of the instrument. These 1D spectra were then least squares fit (logarithm of phase space density) to a two-beam model, with the model for the slower beam being a Kappa distribution and the model for the faster beam being a Maxwellian distribution. A typical example of such a fit is shown in Figure 1. A Maxwellian was used for the faster beam rather than a Kappa to avoid possible complications from the tail of the Kappa distribution being influenced by alpha particle observations. A Kappa distribution [*Kivelson*, 1995] is defined as: $f(v) = A_k[1 + \frac{(v-v_1)^2}{\kappa v_c^2}]^{-\kappa-1}$, where κ and v_c are fitting parameters. Spectra were rejected of they did not have a goodness of fit parameter, $Fit\ Goodness = 1 - \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\frac{y_i^{Fit}-y_i^{Data}}{y_i^{Data}})^2}$, better than 0.9 or had the secondary peak lying outside the boundary of the energy range used for fitting. There are 747 spectra that survive the cut, 89% of the total. If the goodness of fit criterion is relaxed to be > 0.8, then 840 spectra (99.8%) survive the cut. In essentially all cases for which fits were made the velocity difference between the two peaks was greater than 20 km/sec; i.e., there really were two beams present rather than a single beam with its density divided arbitrarily into two model beams. We conclude that for the periods examined, i.e., radial orientation of $\vec{B}_o$ in the fast solar wind, double streaming is present almost all the time.

Analysis

Figure 2 displays the observations (shown as dots) of v_o/v_A and linear theory threshold conditions from Fig. 9 of *Daughton and Gary* [1998]; v_A is computed including alpha particle density. The theory provides statistical constraints on the observations; that is, many of the points lie near but below the predicted threshold, with only a small percentage appearing above threshold (1.1% for the $\beta_{\parallel c} = 1$ curves, where $\beta_{\parallel c}$ is defined [*Daughton and Gary*, 1998] from the parallel temperature of the proton core component, the total plasma density, and the magnetic pressure).

Figure 2 shows that the upper limit of proton beam velocity differences is in excellent agreement with theory, but that the bulk of the velocity differences are considerably below the instability threshold with both the mean and median values being approximately 1.1. There are a number of possible explanations for this: cooling by Coulomb collisions (calculations show this to be unimportant), adiabatic (or double adiabatic) cooling, or nonresonant interaction with low frequency Alfvén waves in the presence of a spatial gradient. A further possibility is that, since the Alfvén speed in the solar wind fluctuates, at some time previous to the observation the local Alfvén speed was lower than at the time of observation, and the velocity difference between the beams was set by this lower value. To test this hypothesis we have computed for 12 hour intervals the average value, the variance, and the minimum value of the Alfvén speed. This time interval was chosen because˜12 hours is the convected spatial extent sampled by beams travelling with relative velocity of the Alfvén speed during the time the solar wind as a whole is convected one solar wind scale height (about an AU). The results of this calculation are shown in Figure 3. The solid line gives $(mean - standarddeviation)/mean$, which gives an idea of the average amount the Alfvén speed is fluctuates below its mean. However, the actual minima (shown as open diamonds for the entire period of time) are much less than this average value. Since it could be argued that fluctuations might be due to filamentary structure across field lines being convected past the spacecraft, we have singled out the 12-hour periods when $\vec{B}_o$ was within 10°of radial; these are shown as solid squares. There is no readily discernible

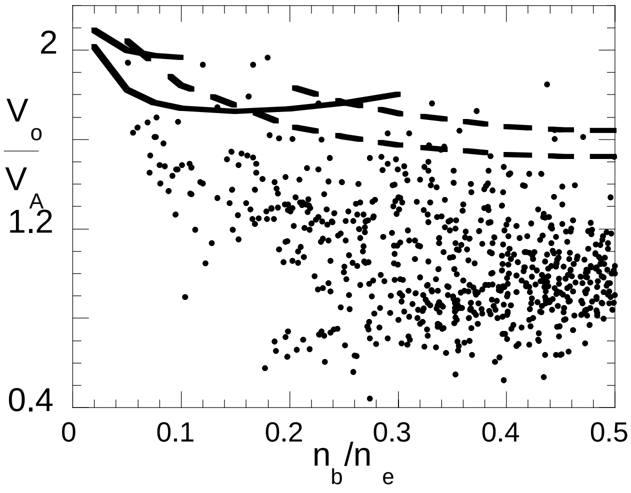

Figure 2. Dimensionless proton-proton relative drift speeds as measured by Ulysses/SWOOPS are represented as individual dots. The four lines represent threshold conditions for two proton-proton instabilities as shown in Fig. 9 of *Daughton and Gary* [1998]. The linear theory assumes that each proton component is isotropic in its own frame, and that the instability growth rate at threshold is $\gamma_m/\Omega_{cp} = 0.01$. The upper and lower solid lines represent the thresholds of the magnetosonic instability at $\beta_{\parallel c} =$ 0.2 and 1.0, respectively, whereas the upper and lower dashed lines display the thresholds of the Alfvén instability at $\beta_{\parallel c} = 1.0$ and 0.2, respectively.

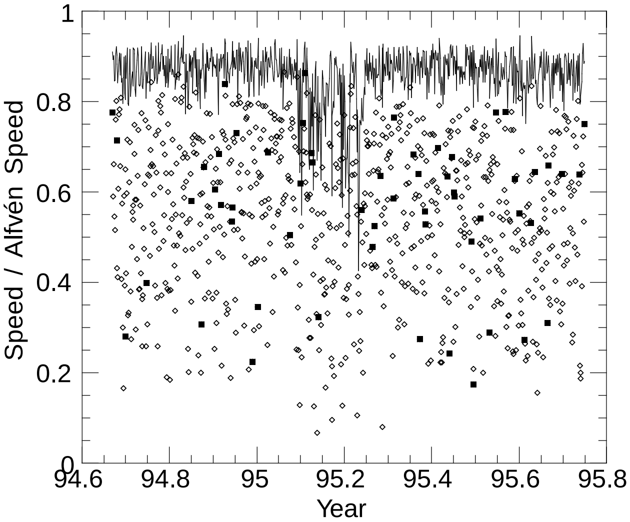

Figure 3. The (mean - σ)/mean of the Alfvén speed for 12 hour periods shown as a solid line, the minimum/mean shown as open diamonds, and the minimum/mean for radially aligned fields shown as solid squares.

difference between the aligned and unaligned minima. Comparison of the minima shown in Figure 3 to the scatter of beam velocity differences below threshold shown in Figure 2 indicates it is quite plausible that the large spread of velocity beam differences below threshold might simply reflect operation of the linear instability at some prior time when the local Alfvén speed was lower. This is not to say that other processes such as adiabatic cooling are not important; in fact it seems likely that several mechanisms are operating simultaneously to slow the beams.

Discussion and Conclusions

The fundamental idea that instability thresholds correspond to observable constraints on plasma species anisotropies presents a means by which collisionless transport expressions may be developed, tested against observations, and applied to large-scale fluid models of the solar wind. Substantial recent progress has been made in this direction with respect to the solar wind electron heat flux, the instabilities driven by this anisotropy, and the imposition of constraints on the former by wave-particle scattering due to the latter [*Scime et al.*, 1994; *Gary et al.*, 1999]. There has, however, been no clear correlation between the solar wind observations by Ulysses and theoretical/computational predictions for ion-driven instabilities.

The results presented here are the first use of the Ulysses data to show that solar wind protons are subject to a constraint predicted by collisionless plasma theory and simulations. The average and median v_o/v_A are 1.1; the agreement between theory and the upper limit of the observations shown in Figure 2 is good but not compelling, so that our work provides the basis for further refinements of the theory as well as more careful analysis of the data. For example, the theoretical thresholds of Figure 1 are based on the assumptions that the electrons, proton core and proton beam all have the same temperature and are isotropic in their own frames [Table 1 of *Daughton and Gary*, 1998]. Variations in each of the associated dimensionless parameters can provide major changes in the threshold conditions. In order to provide more stringent tests of the theoretical constraint, it will be necessary to bin the observations with respect to various parameters including $\beta_{\parallel c}$ and to compare these restricted data sets against more specific threshold criteria. Theory predicts that the beam temperature anisotropy is a particularly important parameter for determining threshold conditions; observational studies of this quantity are especially important for further tests of the predictions. An additional issue is the actual propagation speed of Alfvén waves in the solar wind: is it significantly modified by processes not in our theoretical model? *Goldstein et al.* [1995] estimated that known sources (crosses in their Fig. 4) would reduce the Alfvén speed by from 5 to 15% at high latitudes from 1.5 to 3 AU; the contribution of the two parallel proton beams is implicitly included in our theoretical calculation. They also presented evidence from the fact that transverse velocities of alpha particles were reversed in sign from those of protons that the actual wave propagation speed is lower than the estimates. However, there is no other supporting evidence for the lower wave speeds, and effects other than Alfvén waves in the solar wind that could produce a high V-B correlation similar in sign to that seen for outward going Alfvén waves would invalidate the analysis of *Goldstein et al.* [1995]. But, candidates we have considered for mimicking outward-going Alfvén waves seem problematic as explanations. If the reduced Alfvén speeds as indicated by *Goldstein et al.* [1995] are correct, then many of the points in Figure 2 would lie above the calculated instability limit. *Marsch and Livi* [1987] also found points above the instability limit in Helios data obtained in the inner heliosphere. Another issue which could be addressed as future research is the relative importance of the two proton-proton instabilities. Linear theory (*Daughton and Gary* [1998]) predicts that the Alfvén mode is more likely to arise if T_b/T_c and$\beta_{\parallel c}$ are relatively small, and that the magnetosonic instability has the lower threshold in the opposite cases. By examining observed values of v_o/v_A as functions of these parameters as well as n_b/n_e, it may be possible to obtain information about the relative importance of these two modes as a function of distance from the Sun.

Finally, we note that there is an important difference between the present results and the results of *Marsch and Livi* [1987]. We find from Ulysses that v_o/v_A is almost always observed to be less than 2, and thus to statistically well satisfy the constraint corresponding to the instability threshold conditions. In contrast, a large number of the Helios observations reported by *Marsch and Livi* [1987] are at $v_o/v_A > 2$, and more than 20% of the total observations were strongly unstable to the proton- proton magnetosonic instability. Although the two data sets were gathered at different distances from the Sun, there must be some basic property or properties of the proton (or perhaps alpha particle) velocity distribution that causes higher instability thresholds of v_o/v_A closer to the Sun. Once again, the proton beam temperature anisotropy is a critical parameter. The discrepancy between Helios and Ulysses results may be mitigated if it turns out that $T_{\perp b}/T_{\parallel b}$ is relatively large close to the Sun and decreases with increasing distance from the source of the solar wind.

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References

Anderson, B. J., R. E. Denton, G. Ho, D. C. Hamilton, S. A. Fuselier, and R. J. Strangeway, Observational test of local proton cyclotron instability in the Earth's magnetosphere, *J. Geophys. Res., 101,* 21,527, 1996.

Bame, S. J., D. J. McComas, et al., The Ulysses solar wind plasma experiment, *Astron. and Astrophys. Suppl. 92(2):* 237, 1992.

Daughton, W., and S. P. Gary, Electromagnetic proton/proton instabilities in the solar wind, *J. Geophys. Res., 103,* 20,613, 1998.

Daughton, W., S. P. Gary, and D. Winske, Electromagnetic proton/proton instabilities in the solar wind: Simulations, *J. Geophys. Res.,* it104, 4657, 1999.

Gary, S. P., Electromagnetic ion/ion instabilities and their consequences in space plasmas: A review, *Space Sci. Rev., 56,* 373, 1991.

Gary, S. P., *Theory of Space Plasma Microinstabilities,* Cambridge University Press, New York, 1993.

Gary, S. P., J. Wang, D. Winske, and S. A. Fuselier, Proton temperature anisotropy upper bound, *J. Geophys. Res., 102,* 27,159, 1997.

Gary, S. P., R. M. Skoug, and W. Daughton, Electron heat flux constraints in the solar wind, *Phys. Plasmas, 6,* in press, 1999.

Goldstein, B. E., M. Neugebauer, and E. J. Smith, Alfvén waves, alpha particles, and pickup ions in the solar wind, *Geophys. Res. Lett., 22,* 3389, 1995.

Kennel, C. F., and H. E. Petschek, Limit on stably trapped particle fluxes, *J. Geophys. Res., 71,* 1, 1996.

Kivelson, M. G., Physics of Space Plasmas, in *Introduction to Space Physics,* ed. by M. G. Kivelson and C. T. Russell, p. 38, Cambridge University Press, New York, 1995.

Manheimer, W., and J. P. Boris, *Comments Plasma Phys. Controlled Fusion, 3,* 15, 1977.

Marsch, E., and S. Livi, Observational evidence for marginal stability of solar wind ion beams, *J. Geophys. Res., 92,* 7263, 1987.

Scime, E. E., S. J. Bame, W. C. Feldman, S. P. Gary, J. L. Phillips, and A. Balogh, Regulation of the solar wind electron heat flux from 1 to 5 AU: Ulysses observations, *J. Geophys. Res., 99,* 23,401, 1994.

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