Systematic Measurements of Ion-Proton Differential Streaming in the Solar Wind

L. Berger* and R. F. Wimmer-Schweingruber
Extraterrestrial Physics, Institute for Experimental and Applied Physics, Christian-Albrechts-University Kiel, Leibnizstrasse 11-19, 24118 Kiel, Germany

G. Gloeckler
Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, Michigan 48109-2143, USA
(Received 20 December 2010; published 14 April 2011)

The small amount of heavy ions in the highly rarefied solar wind are sensitive tracers for plasma-physics processes, which are usually not accessible in the laboratory. We have analyzed differential streaming between heavy ions and protons in the solar wind at 1 AU. 3D velocity vector and magnetic field measurements from the Solar Wind Electron Proton Alpha Monitor and the Magnetometer aboard the Advanced Composition Explorer were used to reconstruct the ion-proton difference vector $\mathbf{v}_{ip} = \mathbf{v}_i - \mathbf{v}_p$ from the 12 min 1D Solar Wind Ion Composition Spectrometer observations. We find that all 44 analyzed heavy ions flow along the interplanetary magnetic field at velocities which are smaller than, but comparable to, the local Alfvén speed C_A. The flow speeds of 35 of the 44 ion species lie within the range of $\pm 0.15 C_A$ around $0.55 C_A$, the flow speed of He^{2+}.

DOI: 10.1103/PhysRevLett.106.151103 PACS numbers: 96.50.Ci, 52.35.Bj

Introduction.—He^{2+} is often observed to flow faster in the solar wind than its bulk, which is determined by protons [1,2]. Although between 0.3 and 1 AU the absolute value of differential flow speed decreases with increasing distance, it stays comparable to, but generally lower than, the local Alfvén speed. The mechanisms that regulate this differential flow are not well understood. One possible interpretation is that wave-particle interaction driven by electromagnetic and magnetosonic He^{2+}-proton instabilities [3,4] reduce large values of differential streaming produced in the solar corona [5,6] down to, or even below, the local Alfvén speed and simultaneously preferentially heat He^{2+} perpendicular to the magnetic field with respect to protons. Recent observations in Ref. [7] have confirmed that the flowing or differential streaming for He^{2+} is aligned with the Interplanetary Magnetic Field (IMF) and is efficiently decreased by Coulomb collisions. They also found increasing preferential perpendicular heating of He^{2+} with respect to protons with decreasing values of differential streaming, which they interpret as evidence for local absorption of dissipated outward-propagating kinetic Alfvén waves. To understand the complex interaction of competing processes in the solar wind, observational constraints are crucial to extend and refine existing theoretical models [8].

So far, most constraints on solar wind modeling are based on proton and He^{2+} observations. Here we focus on measurements of heavy-ion differential streaming in the solar wind. In contrast to He^{2+}, these measurements are rare and the results are sometimes contradictory [9–11]. Most heavy-ion observations were made in the Earth's vicinity, at 1 AU where Fe and Si were found to flow slower than He^{2+}. The only measurements beyond 1 AU are those performed in Refs. [12,13] with the Solar Wind Ion Composition Spectrometer (SWICS) [14] on Ulysses, whose orbit extended out to 5.4 AU. Those authors observed no differential streaming among heavy ions and did not measure differences between proton and heavy-ion speeds. Using SWICS [15] on the Advanced Composition Explorer (ACE) at the first Lagrangian point (L1), we have performed the first systematic study of heavy-ion differential streaming for a total of 44 ions. We compare the bulk speeds of heavy ions with the measured proton velocity and IMF vectors to derive the first accurate measurements of differential streaming between heavy ions and protons. We present the method in the following section.

Data selection and methods.—The Solar Wind Electron Proton and Alpha Monitor [16] provides accurate measurements of the proton velocity vector $\mathbf{v}_p$ in high-speed streams. The data are provided at the ACE Science Center [17] at 64 s time resolution. The ACE Magnetometer [18] provides measurements of the IMF vector $\mathbf{B}$ at the ACE Science Center at 1 s resolution. For heavy ions, the high time resolution and the separation of ion species required for the studies reported here necessitate a sophisticated maximum-likelihood analysis based on Poissonian statistics of SWICS pulse-height analysis data [19]. We determine the bulk speed $|\mathbf{v}_i|$ of 44 solar wind ions (ranging from He^{2+} to Fe^{7+}) which cover a large range in mass m and mass per charge m/q. We analyzed these data for two high-speed streams in early 2008 by using the scheme depicted in Fig. 1 and described below. With SWICS, no directional information is available; thus, we derive the absolute value of the heavy-ion speed: $\mathrm{v}_i = |\mathbf{v}_i|$. Following Ref. [7], we assume that the heavy ions flow along $\mathbf{B}$ in the solar wind reference frame defined by the bulk proton velocity $\mathbf{v}_p$. In a first step, we determine the angle Θ spanned by the proton velocity $\mathbf{v}_p$ and IMF $\mathbf{B}$. Figure 1 shows the situation just explained. Obviously, the difference $v_i - |\mathbf{v}_p|$ always underestimates the magnitude of differential streaming, $|\mathbf{v}_i - \mathbf{v}_p|$. If differential streaming is generated in the corona pointing away from the Sun, the polarity of the magnetic field needs to be accounted for. Defining the angle γ as $\pi - \Theta$ for the case in which the IMF points outward, and as Θ when the IMF points inward, one can easily derive

$$|\mathbf{v}_{ip}| = v_p \cos(\gamma) \pm \sqrt{v_i^2 - v_p^2 \sin^2(\gamma)}. \quad (1)$$

Sometimes, the IMF exhibits large kinks, which make a field of globally outward polarity appear to have inward-pointing polarity for the duration of such a kink (and vice versa). During such periods, $\mathbf{B}_+$ would point into the lower-left quadrant and $\mathbf{B}_-$ into the upper right. In this case we would expect to measure a negative $v_{ip} = v_i - v_p$; i.e., the heavy ions would appear to be lagging behind the protons.

Figure 2 shows the results of this analysis. The top panel shows bulk proton, He^{2+}, and O^{6+} speeds observed during two successive high-speed streams in early 2008. The second panel shows the proton number density (blue) and IMF magnitude (red), while the third shows the local Alfvén speed C_A. The two streams have opposite magnetic polarity as can be inferred from the fourth panel, which shows the angle Θ defined above. The overall behavior of Θ is a good indicator for the polarity of the stream, because the protons flow radially away from the Sun to a good approximation. The two panels below show the magnitude of differential streaming, $v_{ip} = v_i - v_p$, for He^{2+} and O^{6+} divided by the local Alfvén speed C_A. Much of the apparent scatter in v_{ip} is correlated with the scatter in Θ, as we will show below. The gray shaded regions correspond to kinks in the magnetic field in which the inferred v_{ip} turns negative as discussed above. The lowest panel shows differential streaming of Fe. It was derived by averaging the v_i of Fe^{8+} to Fe^{12+} and then determining v_{ip} with this averaged Fe ion speed. This average shows the same behavior as the two most abundant ions He^{2+} and O^{6+}. The light blue shaded region separating the two streams contains a crossing of the heliospheric current sheet and the stream interface of the corresponding corotating interaction region and has been excluded from this study.

Analysis.—It is evident from Fig. 2 that the inferred value of v_{ip} depends strongly on Θ. This dependence can be made more visible by plotting v_{ip} versus Θ for the two possible IMF polarities, as done in Fig. 3. The left side shows v_{ip}/C_A

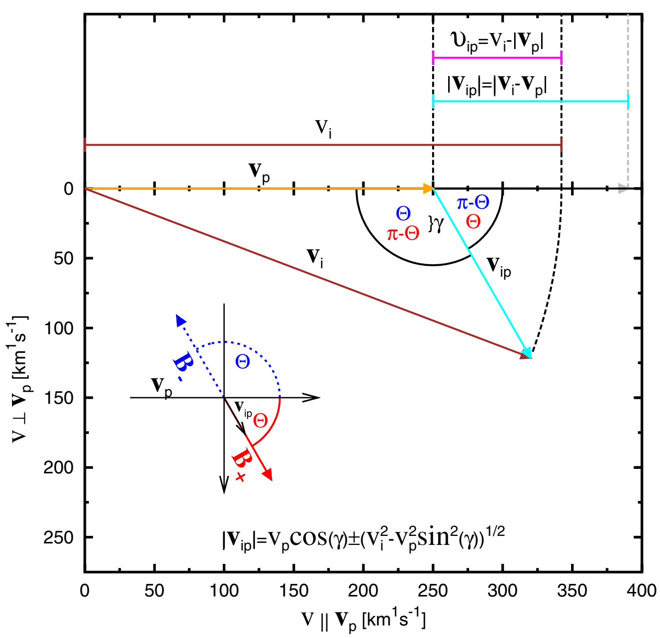

FIG. 1 (color online). Reconstruction of differential streaming speed by using measured proton and magnetic-field vectors and ion speed. The flow of heavy ions is assumed to be along the magnetic field, following the analysis of Ref. [7] for He^{2+}. The orientation of the magnetic-field vector $\mathbf{B}$ for inward − (blue) and outward + (red) polarity and the expected direction of differential streaming is illustrated in the lower left. If the magnetic-field vector $\mathbf{B}_+$ ($\mathbf{B}_-$) points into the lower-left (upper right) quadrant, a negative v_{ip} is expected to be measured.

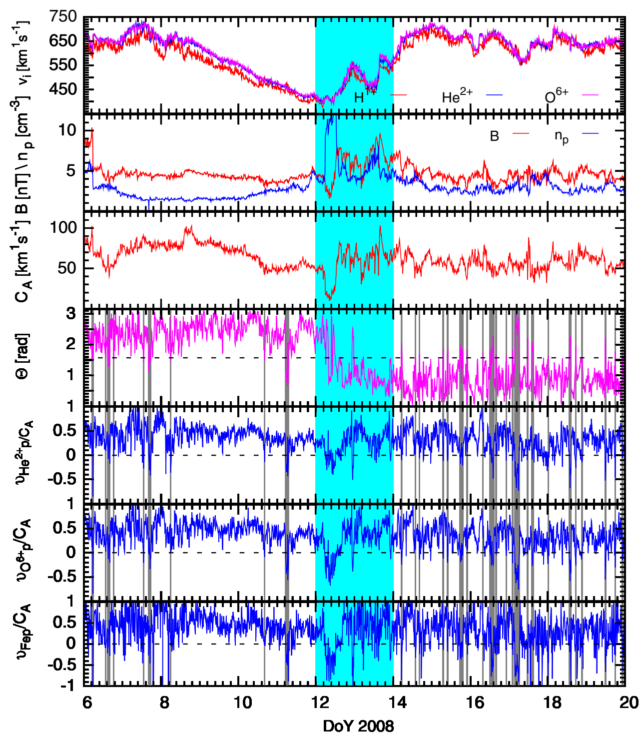

FIG. 2 (color online). Time series of (from top to bottom) proton, He^{2+}, and O^{6+} bulk speeds, proton density, Alfvén speed, IMF orientation, and scaled differential streaming of He^{2+}, O^{6+}, and the elemental mean for Fe (charge states 8–12). The data are shown in the highest time resolution possible (12 min). Two high-speed streams of opposite magnetic polarity and with v_p around 600–650 km/s are separated by a slow and dense interstream region and a corotating interaction region (light blue shaded period). He^{2+}, O^{6+}, and Fe appear to outrun the protons by $\sim 0.5 C_A$.

for He^{2+} versus Θ; the right side shows the same but for O^{6+}. The dots show measurements at the highest possible time resolution of 12 min; the filled circles and squares show the mean values in the Θ intervals (10°) spanned by the error bars in the x direction. The error bars in the y direction are standard deviations. Both single-point measurements and their mean values are well organized by Θ. The statistics in the Θ bins varies strongly and is highest around the nominal Parker angle. The symbols without error bars in the y direction are single measurements and should be treated with caution. The black curves show the expected behavior for v_{ip} if its value was $0.55C_A$ and the proton velocity $|\mathbf{v}_p|$ was 600 km/s. Quadrants I ($\mathbf{B}_+$) and II ($\mathbf{B}_-$) show the regions where v_{ip} is expected to be positive. The shaded quadrants III ($\mathbf{B}_+$) and IV ($\mathbf{B}_-$) correspond to kinks in $\mathbf{B}$ resulting in negative v_{ip}. The same overall behavior is seen for both He^{2+} and O^{6+}. Because the errors of $v_{He^{2+}}$ and $v_{O^{6+}}$ are small compared to C_A, the variations around the means of the measurements in the individual Θ bins are probably due to natural fluctuations in the true value of $|\mathbf{v}_{ip}|$. These natural fluctuations are not expected to depend on Θ, and, thus, we expect the means to qualitatively follow the theoretical black curves. The true differential streaming $|\mathbf{v}_{ip}|$ can be reconstructed from v_i, $\mathbf{v}_p$, and $\mathbf{B}$ by using Eq. (1) and is shown in the bottom panel of Fig. 3. Apart from deviations that are probably caused by the natural variability, as discussed above, its value is approximately constant. Because the IMF vector varies on very short time scales, it is important to use the highest time resolution possible with SWICS. Reference [7] used higher time resolution (92 s) and, as we show below, obtained a similar value for $|\mathbf{v}_{He^{2+}p}|/C_A$, indicating that our resolution of 12 min is sufficient. Redoing our analysis at 1-h cadence resulted in a significant decrease of $|\mathbf{v}_{ip}|$ as expected if ions flow along the IMF in the solar wind frame of reference. Taking the average of $|\mathbf{v}_{ip}|$ for every ion analyzed, we can now determine whether there is any overall m/q or m dependence of ion-proton differential streaming. The following charge states were analyzed: He (2), C (4–6), N (5–7), O (6–8), Ne (8), Mg (7–10), Si (7–11), S (7–12), Ca (7–12), and Fe (7–18), spanning a $2 \leq m/q \leq 8$ range. For each ion we get a distribution of derived $|\mathbf{v}_{ip}|$ from which the mean value is calculated. Because the impact of uncertainties in v_i on derived $|\mathbf{v}_{ip}|$ is strongest for Θ around $\pi/2$, we neglected data from $70° < \Theta < 110°$. The upper panel of Fig. 4 shows the mean $|\mathbf{v}_{ip}|/C_A$ for all 44 ions plotted versus m/q; the lower panel shows the number of measurements for each ion. The barely visible error bars are the uncertainties of the mean. All ions appear to show pronounced differential flow relative to protons which is

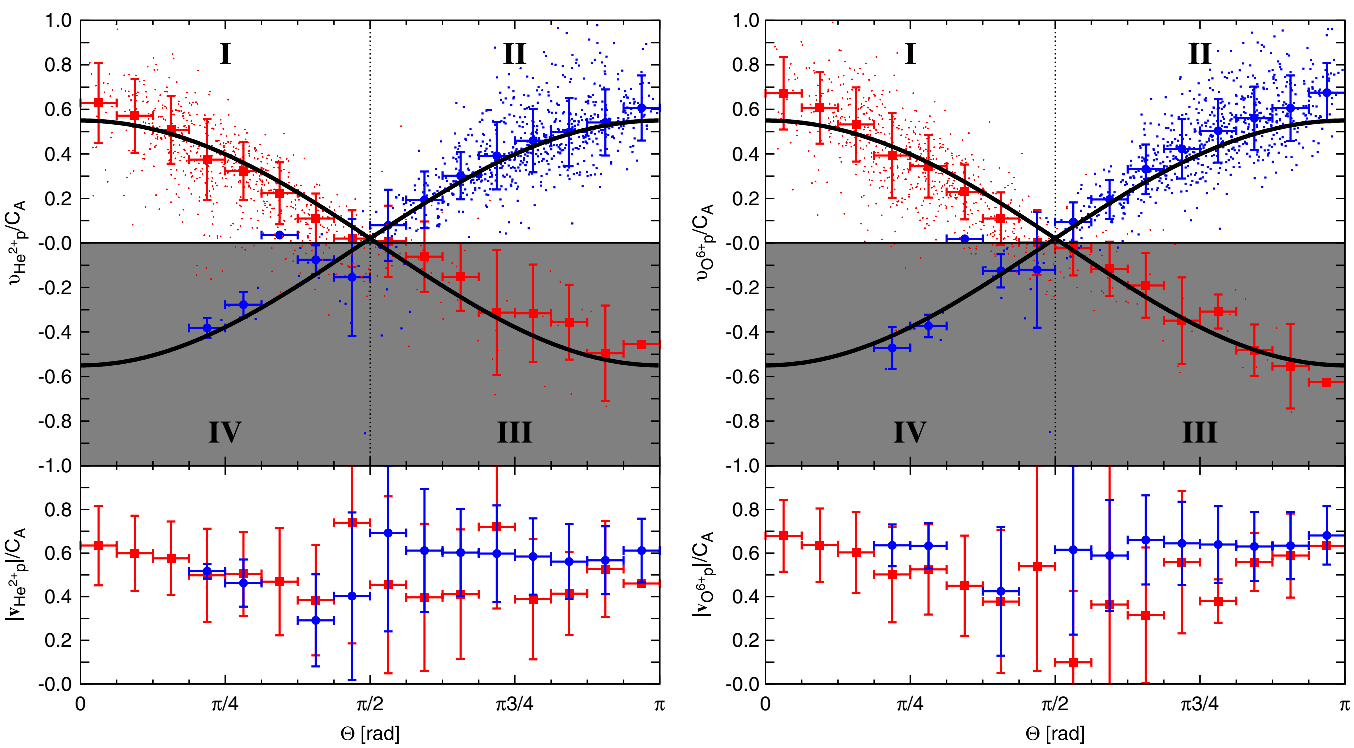

FIG. 3 (color online). 12-min measurements of $v_{He^{2+}p}/C_A$ (left-hand panel) and $v_{O^{6+}p}/C_A$ (right-hand panel) plotted versus measured angle Θ (the angle between $\mathbf{v}_p$ and $\mathbf{B}$) for the two cases shown in Fig. 1. Red dots are measurements made in the second fast stream of Fig. 2, blue dots from the first stream. Measurements were made only for DoY 6–12 (first stream) and DoY 14–20 (second stream). Quadrants I ($\mathbf{B}_+$) and II ($\mathbf{B}_-$) show the regions where v_{ip} is expected to be positive (see Figure 1), and the gray shaded quadrants III ($\mathbf{B}_+$) and IV ($\mathbf{B}_-$) correspond to kinks in $\mathbf{B}$ (see gray shaded area in Fig. 2) where v_{ip} is expected to be negative.

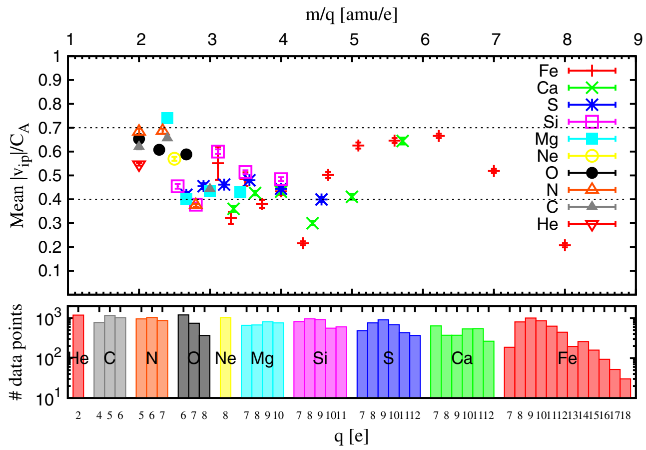

FIG. 4 (color online). Upper panel: Summary of the m/q dependence of differential streaming of all 44 ions investigated here. Error bars show the 1-σ uncertainty of the mean. The standard deviations of the measurements are considerably larger and would extend throughout the plot. All ions show pronounced differential streaming. The deviation from $|\mathbf{v}_{\mathrm{He}^{2+}p}|/C_a$ for 35 of 44 ions is smaller than 0.15. The corresponding area is indicated by the dashed black lines. Lower panel: Number of measurements for each observed ion.

comparable to but significantly less than the local Alfvén speed C_A. Evidently, the results are not well organized by m/q, but also no dependence on m can be seen. The obtained value for He^{2+} of $0.55C_A$ is in very good agreement with Ref. [7]. Comparing the results of all ions to He^{2+}, we find that 35 of 44 ions lie within $|\mathbf{v}_{\mathrm{He}^{2+}p}|/C_A \pm 0.15$ corresponding to differences in $|\mathbf{v}_{ip} - \mathbf{v}_{\mathrm{He}^{2+}p}| < 10$ km/s. Although the influence of statistical uncertainties in v_i on $|\mathbf{v}_{ip}|/C_A$ should be negligible due to the good statistics for most ions, small systematical uncertainties in v_i cannot be ruled out. Possible sources of error are discretization of v_i due to small count rates, misassignment of counts between neighboring species, and small deviations from the nominal slope of SWICS's electrostatic analyzer. Thus we cannot fully exclude the possibility that all ions stream with the same velocity. The two lowest data points correspond to Fe^{7+} and Fe^{13+}, which also display a too small number of data points in the lower panel of Fig. 4; thus, they should be treated with caution.

Discussion and conclusions.—We have for the first time performed a systematic study of the true differential streaming between heavy ions and protons at 1 AU. Using the assumption that it is parallel to the IMF, we found that all 44 ions flow differentially with similar velocities comparable to half the local Alfvén speed. An increase of $|\mathbf{v}_{ip}|$ with increasing time resolution and the value of $|\mathbf{v}_{\mathrm{He}^{2+}p}| = 0.55C_A$ which is consistent with the one reported by Ref. [7] lend further support to the assumption that all heavy ions flow along the IMF in the solar wind frame. Our results are directly deduced from observations; the only assumption made is backed up by previous observations [7]. Although 35 of all 44 analyzed ions lie within $|\mathbf{v}_{\mathrm{He}^{2+}p}|/C_A \pm 0.15$, a range that corresponds to $|\mathbf{v}_{ip} - \mathbf{v}_{\mathrm{He}^{2+}p}| < 10$ km/s, there are significant deviations from a constant value independent of m/q and m. This and the absence of a clear trend with m/q or m indicates that the differential streaming cannot be understood as the result of a single process but rather as the interplay of competing processes, for instance, Coulomb collisions or instability-related wave-particle interactions. These processes are capable of regulating differential flow but do so on widely different time scales. The observations presented here should serve as constraints on further theoretical work by adding measurements of 43 additional ions, thus greatly expanding the parameter space in m and m/q.

This work was supported by the German Science Foundation (DFG) under Grant No. Wi-2139/2 and by NASA under the ACE data analysis Contract No. 44A-1080828.

*berger@physik.uni-kiel.de

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