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Systematic measurements of ion-proton differential streaming in the solar wind

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The solar wind is a highly rarefied plasma exhibiting many plasma-physics processes usually not accessible in the laboratory. It contains small amounts of heavy ions which can serve as sensitive tracers for these processes. Heavy ions, especially He^{2+} are known to exhibit a systematic flow relative to the background (bulk) solar wind which is determined by solar wind protons. Conflicting results for heavy ion measurements in the past as well as instrumental restrictions have made a systematical study of their flow and detailed micro-physics impossible in the past. For instance, it was not clear whether all ions have the same flow relative to protons or whether there are systematic dependencies on mass, m or m/q (where q is the ions charge). We have analysed the ion-proton differential streaming at 1 AU using combined data from the Solar Wind Ion Composition Spectrometer (SWICS), the Solar Wind Electron Proton Alpha Monitor (SWEPAM) and the Magnetometer (MAG) on the Advanced Composition Explorer (ACE). Heavy ion velocities were determined using a sophisticated maximum-likelihood analysis technique based on Poissonian statistics that allowed us to determine velocities at the highest possible temporal resolution of 12 minutes. 3D vector measurements from SWEPAM and MAG were applied to reconstruct the ion-proton difference vector $\mathbf{v}_{ip} = \mathbf{v}_i - \mathbf{v}_p$ from the 1D SWICS observations. We find that all 44 analysed heavy ions flow along the interplanetary magnetic field at velocities which are smaller than, but comparable to, half 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+}. Our findings for the first time provide observational constraints for theoretical models of solar wind formation and evolution for such a large number of ions.

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 in respect to protons. Recent observations by [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+} in respect to protons with decreasing values of differential streaming, which they interpret as evidence for local absorption of dissipated outward-propagating kinetic Alfén 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 modelling 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 by [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 the Solar Wind Ion Composition Spectrometer (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 (SWEPAM) [16] provides accurate measurements of the proton velocity vector, $\mathbf{v}_p$, in high-speed streams. The

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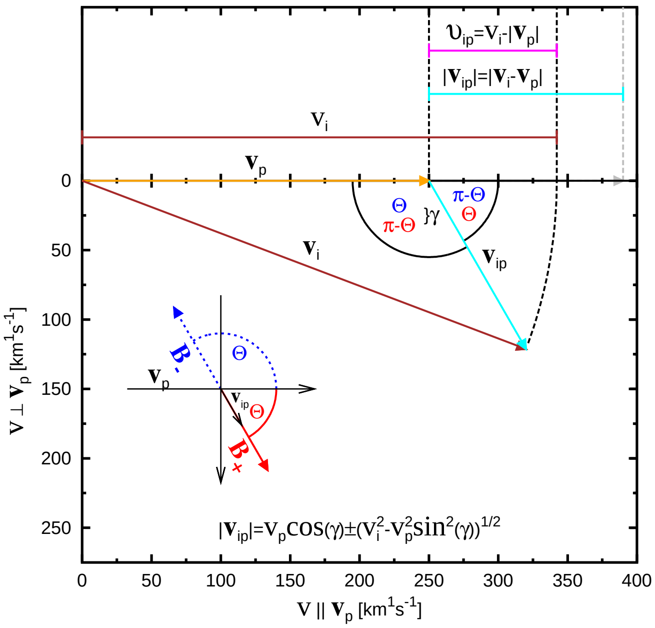

FIG. 1. Reconstruction of differential streaming speed by using measured proton and magnetic-field vectors and ion speed. The flow of heavy ions is assumed to be along the magnetic field, following the analysis of [7] for He^{2+}. The orientation of the magnetic field vector $\mathbf{B}$ for inward $-$ (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.

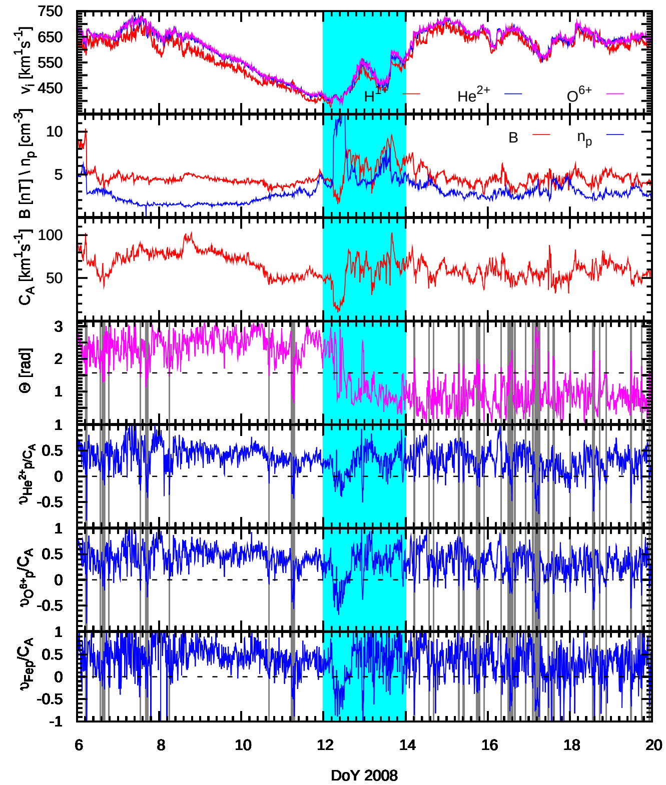

FIG. 2. Time series of (from top to bottom) proton, He, and O bulk speeds, proton density, Alfvén speed, IMF orientation, and scaled differential streaming of He^{2+}, O^{6+}, and elemental mean for Fe (charge states 8-12). The data are shown in the highest time resolution possible (12 minutes). Two 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 $\sim 0.5 C_A$.

data are provided at the ACE Science Center `http://www.srl.caltech.edu/ACE/ASC/` at 64s time resolution. The ACE magnetometer MAG [17] provides measurements of the IMF vector, $\mathbf{B}$, at the ACE Science Center at 1s 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 of SWICS pulse-height analysis data [18]. 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 m and m/q. We analysed these data for two high-speed streams in early 2008 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, $v_i = |\mathbf{v}_i|$. Following [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, $\mathbf{B}$. Fig. 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

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

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 stream in early 2008. The second panel shows 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 behaviour of Θ is a good indicator for the polarity of the stream because the protons flow radially away

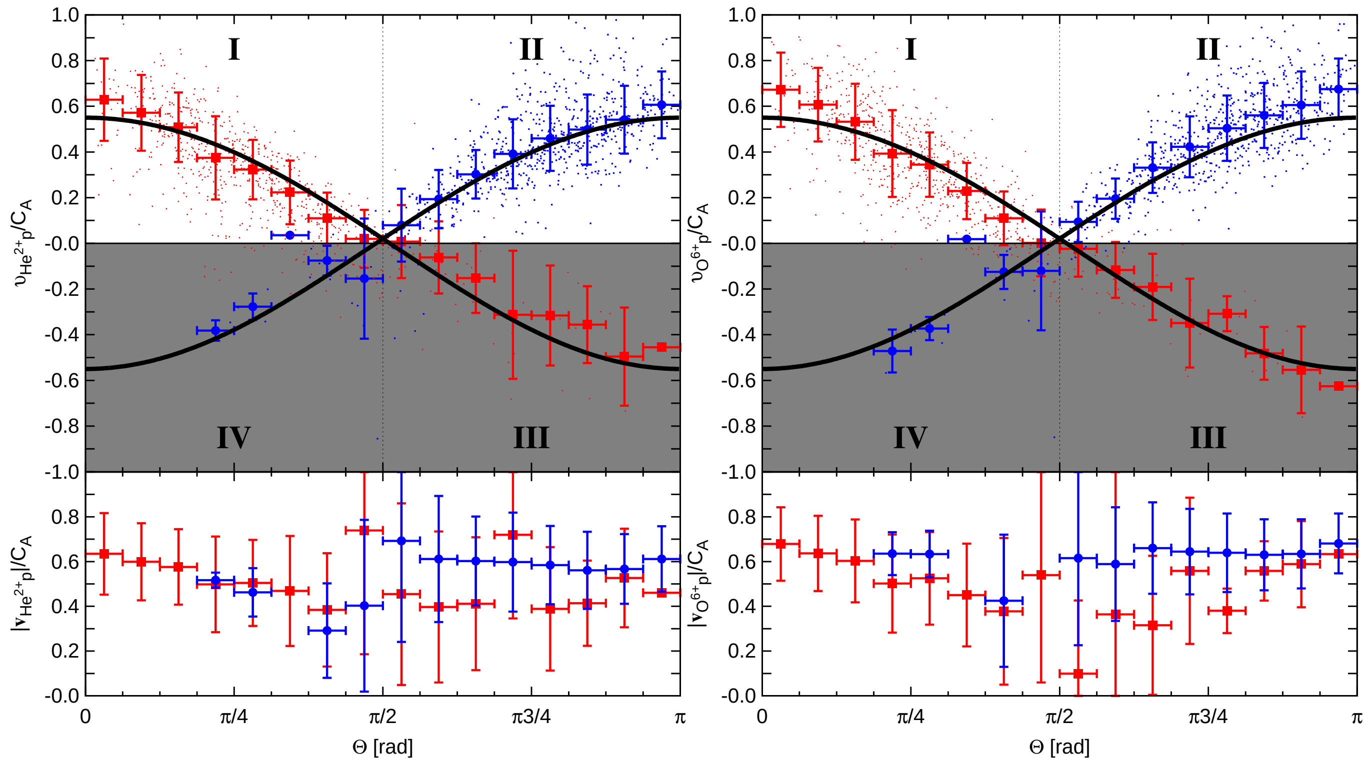

FIG. 3. 12-minute measurements of $v_{\mathrm{He}^{2+}\mathrm{p}}/C_A$ (left-hand panel) and $v_{\mathrm{O}^{6+}\mathrm{p}}/C_A$ (right-hand panel) plotted versus measured angle Θ (the angle between $\mathbf{v}_p$ and $\mathbf{B}$) for the two cases shown in Fig. 1. Red dots are measurements made in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

from the Sun to a good approximation. The two panels below show the magnitude of differential streaming, $v_{ip} = \mathrm{v}_i - \mathrm{v}_p$, for He^{2+} and O^{2+} 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 grey shaded regions correspond to kinks in the magnetic field in which the inferred v_{ip} turns negative as discussed above. The lowest panels show 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 behaviour 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 CIR 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 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-minutes, the filled circles and squares show the mean values in the Θ-intervals (10 degrees) spanned by the error bars in x-direction. The error bars in y-direction are standard deviations. Both single-point measurements and their mean values are well organised 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 behaviour for v_{ip} if its value was $0.55C_A$ and the proton velocity $|\mathbf{v}_p|$ was 600 km/s. Quadrants I (B_+) and II (B_-) show the regions where v_{ip} is expected to be positive. The shaded quadrants III (B_+) and IV (B_-) correspond to kinks in $\mathbf{B}$ resulting in negative v_{ip}. The same overall behaviour is seen for both He^{2+} and O^{6+}. Because the errors of $\mathrm{v}_{\mathrm{He}^{2+}}$ and $\mathrm{v}_{\mathrm{O}^{6+}}$ 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_{ip}, $\mathbf{v}_p$, and $\mathbf{B}$ 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. [7] used higher time resolution (92 s) and, as we show below, obtained similar value for $|\mathbf{v}_{He^{2+}p}|/C_A$, indicating that our resolution of 12 minutes is sufficient. Redoing our analysis at 1-hour 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 analysed, we can now determine whether there is any overall m/q or m dependence of ion-proton differential streaming. The following charge states were analysed: 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), 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 $70^\circ < \Theta < 110^\circ$. 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 comparable but significantly less than the local Alfvén speed, C_A. Evidently the results are not well organised 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 [7]. Comparing the results of all ions to He^{2+}, we find that the 35 of 44 ions lie within $|\mathbf{v}_{\mathrm{He}^{2+}\mathrm{p}}|/C_A \pm 0.15$ corresponding to differences in $|\mathbf{v}_{ip} - \mathbf{v}_{He^{2+}p}| < 10$ km/s. Although the influence of statistical uncertainties in v_i on $|\mathbf{v}_{ip}|/C_A$ should be negligible due to the good statistic for most ions, small systematical uncertainties in v_i can not be ruled out. Possible sources of error are discretisation of v_i due to small countrates, mis-assignment of counts between neighbouring species, and small deviations from the nominal slope of SWICS's electrostatic analyser. Thus we can not 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.

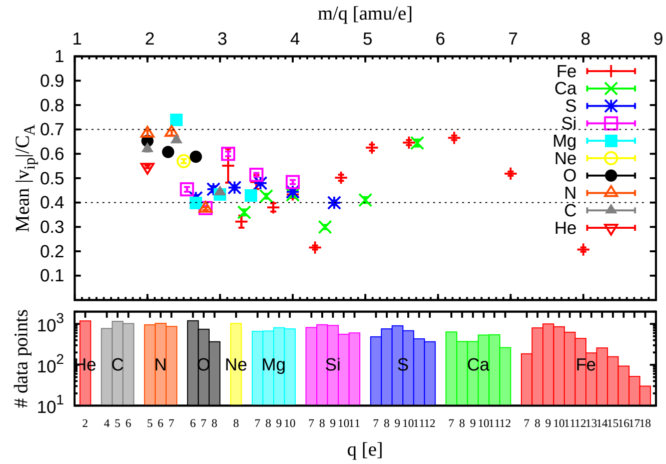

FIG. 4. Upper panel: Summary of the m/q-dependence of differential streaming of all 44 ions investigated here. Error bars show the 1-σ uncertainty of the mean. The standard deviations of the measurements are considerably larger and would extend throughout the plot. All ions show pronounced differential streaming. The deviation from $|\mathbf{v}_{\mathrm{He}^{2+}\mathrm{p}}|/C_a$ 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.

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 [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 analysed ions lie within $|\mathbf{v}_{\mathrm{He}^{2+}\mathrm{p}}|/C_A \pm 0.15$, a range that corresponds to $|\mathbf{v}_{ip} - \mathbf{v}_{He^{2+}p}| < 10$ km/s there are significant deviations from a constant value independent on m/q and m. This and the absence of a clear trend with m/q or m indicates that the differential streaming can not 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.

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