Kinetic temperatures of iron ions in the solar wind observed with STEREO/PLASTIC


*Space Science Center, University of New Hampshire, Durham, NH 03824, USA
†Permanent address: Bahnhofstrasse 54, CH-3127 Mühlethurnen, Switzerland
**Physikalisches Institut, University of Bern, CH-3012 Bern, Switzerland
‡Max-Planck-Institut für extraterrestrische Physik, D-85471 Garching, Germany
§Institute for Experimental and Applied Physics, Christian-Albrechts-University Kiel, Leibnizstrasse 11, D-24098 Kiel, Germany
¶National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, MD 20771, USA
∥Space Science Laboratory, University of California, Berkeley, CA 94720, USA
††Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, CA 90024, USA
‡‡Centre d’Etude Spatiale des Rayonnements (CNRS-UPS), F-31028 Toulouse, France

Abstract. STEREO/PLASTIC provides detailed information on the three-dimensional velocity distributions of solar wind iron ions with a time resolution of 5 minutes. In general the distributions at 1 AU contain complicated structures showing persistence over several records, i.e., over intervals of up to 30 minutes, but no clear correlation of the properties of these distributions with the direction of the ambient magnetic field is evident. We have performed a statistical analysis using nearly 9000 observations. Iron ions follow the same trends as protons, alpha particles, and electrons: The ratio $T_\perp/T_\parallel$ seems to be limited by the ion cyclotron instability, whereas $T_\parallel/T_\perp$ is bounded by the firehose instability.

Keywords: Solar wind plasma, minor ions, velocity distributions
PACS: 52.35.Qz, 96.50.Ci

INTRODUCTION

A topic of permanent interest is how minor ions adapt their distributions to conditions in the expanding solar wind with gradually decreasing Alfvén speed. Schmid et al. [1] and later Hefti et al. [2] found that iron ions travel on average slower than oxygen ions in fast speed wind. Hefti et al. [2] explained this in terms of less efficient wave acceleration for wave power spectra with spectral indices $\gamma \leq 2$. On the other hand, Ipavich et al. [3] have not observed this speed difference among minor ions. As the Alfvén speed decreases with the outward moving wind, a species, traveling typically at the bulk speed plus the Alfvén speed will create a streaming instability, and its excess kinetic energy will be converted into thermal energy [4] [5]. Due to their higher mass density, oxygen ions streaming ahead of the bulk plasma contain more free energy than iron ions. Whether oxygen ions will therefore become unstable first and readapt faster to the decreasing Alfvén speed, remains to be demonstrated in a self-consistent theory.

The PLASTIC (Plasma and Suprathermal Ion Composition) instruments [6] onboard the STEREO spacecraft have an unprecedented capability of mapping three-dimensional velocity distributions of iron ions with a high cadence. Typically, 300 to 1000 iron counts are registered each 5 minutes. Thus this instrument provides a unique opportunity to study the behavior of iron ions under changing solar wind conditions. The PLASTIC Solar Wind Sector provides a 45° field of view in the ecliptic plane, centered on the Sun-spacecraft line, and ±20° in the direction perpendicular to the ecliptic through the use of electrostatic deflectors. The angular resolution within the ecliptic is 3 degrees (FWHM), perpendicular to the ecliptic it is 1.9 degrees; this corresponds to typical velocity resolutions of 5% within the ecliptic (i.e., ± 20 km/s) and 3 % (± 10 km/s) out of the ecliptic, respectively. For the analysis we assume that the dominant charge states are Fe9+ and Fe10+. A contour map of a distribution of iron counts

DATA ANALYSIS
For an extensive, particularly quiet period observed by STEREO/A is shown in Fig. 1. It is well known that in a collision-free expanding solar wind, in which the adiabatic moments ($T_\parallel B^2/n^2$ and $T_\perp/B$) are conserved, $T_\perp$ decreases much more rapidly than $T_\parallel$. If the solar wind were to expand without heating and without collisions, one would expect to find values $T_\perp/T_\parallel$ at 1 AU, which are far below the result found for the distribution of Fig. 1, which is already an atypically low $T_\perp/F_{\perp}[Fe]$ $\approx 0.2$. Undoubtedly, thermal energy is re-distributed during solar wind expansion also among rare ions, such as iron, even in very quietly flowing plasma.

Another example of a stable velocity distribution is shown in Fig. 2. In this case lower kinetic temperatures are observed in the axis of symmetry of the distribution, whereas higher temperatures are found perpendicular to it, i.e., the distribution appears oblate (pancake-shaped). For the data analysis we routinely use a Maximum-Likelihood routine. Four parameters are used to determine the zeroth and the first moment, i.e., iron density and three components of the velocity vector. Four parameters describe the second moment of the distribution, which is assumed to be gyrotropic; these parameters are the lengths of the principal axes, corresponding to $T_\parallel$ and $T_\perp$, and their orientation with respect to $T_\parallel$.

In order to accelerate the convergence of the procedure, only the magnitude of the flow vector is determined with the Maximum-Likelihood approach. The flow direction, mostly close to the radial direction, is determined with a moment method. The full-fledged, eight-parameter approach and the reduced six-parameter method usually yielded an agreement within a few percent.

**RESULTS**

Fig. 3 shows the distribution of observations of temperature anisotropies in a format that has been frequently used before for protons and electrons (e.g. [7], [8], [9]). Since we have not yet determined the two components of the proton temperatures individually with STEREO/PLASTIC, here, we have used $\beta_p$ for the ratio of the total proton pressure to the magnetic pressure as a proxy for $\beta_{\parallel,p}$. In contrast to the observations for protons as in Kasper et al. [7] (their Fig. 4), iron ion observations are not equally distributed in the allowed range of stability, but rather seem to cluster along the lines of marginal stability indicated by the dashed lines. We have
rigorously solved the parallel dispersion relation for mixtures of protons, electrons and alpha particles, for a variety of plasma conditions as given by the ranges of the plot in Fig. 3. The dashed lines delineate the limit where the imaginary part of the frequency, which solves the dispersion relation, becomes positive. For all cases we have assumed that all species travel at the same speed. Although the dashed boundaries in Fig. 3 have been determined by evaluating the plasma dispersion relation for parallel propagation, they may be estimated as follows: The frequency of Alfvén waves propagating parallel to the ambient magnetic field vanishes approximately when $P_\parallel-P_\perp= \frac{B^2}{4\pi}$, where $P_\parallel$ and $P_\perp$ are the plasma pressures parallel and perpendicular to the ambient magnetic field of magnitude $B_\parallel$. This provides the condition for the onset of the firehose instability. In terms of the plasma-$\beta$ parallel to the magnetic field, this marginal stability condition may be expressed as $T_\parallel/T_\perp=1-1/\beta_\parallel$. It should be noted that here $P_\parallel$ and $P_\perp$ refer to the total plasma pressures rather than the iron partial pressures. Nevertheless, if $T_\parallel/T_\perp$ is comparable for iron ions and protons, then the marginal conditions for the two species will be similar.

The marginal stability condition for the ion-cyclotron instability follows from the requirement that contours of the iron distribution function are spherical caps centered on the ion-cyclotron wave phase velocity in the direction opposite that of the resonant ions. Although spherical caps are an approximation appropriate for non-dispersive waves, which is not the case for ion-cyclotron waves, the approximation is sufficient for our purposes. This condition may be written approximately as

$$P_\parallel = \left( P_\perp + \frac{B^2}{\beta^2} \right)^{1/2} - \left( \frac{B^2}{4\pi} \right)^{1/2},$$

which may be written as $T_\parallel/T_\perp=1+2/(\beta_\parallel)^{1/2}$. Since the ion-cyclotron instability is resonant, it should be excited by iron ions as well as by other species. The form of Eq. (1) captures the gross behavior of the upper dashed curves in Fig. 3, although the inclusion of alpha particles complicates the structure of the dispersion relation. The boundary against the ion-cyclotron instability depends sensitively on the amount of alpha particles. Apparently, alpha particles tend to stabilize otherwise unstable distributions. The three dashed lines in the upper part of the figure are for three different concentrations of alpha particles. For the cases of $T_\parallel/T_\perp < 1$, the dashed line against the ion-cyclotron instability depends sensitively on the assumption about the relative speed of alpha particles. As the speed difference relative to the bulk plasma increases, the stability line shifts towards lower values of $\beta_p$. Similar 2D-histograms on temperature anisotropies for protons [7] [8], have shown more or less equally distributed observations within the allowed realm of stability, or even a clustering towards weak temperature anisotropies, far away from the limits of instability. In our case, we find more observations near the boundary of marginal stability, and a weak population of the area of low anisotropy. Because of this surprising difference between our observations and the reported distributions of proton (and electron) measurements, we have carefully investigated the possibility of an instrumental bias in our data. Our most reliable and least ambiguous determinations are those for isotropic distributions, i.e.,
DISCUSSION

A poster presented at this conference [10] could possibly provide the explanation for the apparent difference between the behavior of protons and iron ions. In the case of the ion-cyclotron instability, particles with the largest speeds perpendicular to the magnetic field tend to excite ion-cyclotron waves, which in turn preferentially pitch-angle scatter these particles back onto the axis of the magnetic field to allowed values near limit of marginal stability, thereby reducing the $T_{\parallel}/T_{\perp}$ ratio of the distribution. Once the distribution is stable, it essentially remains unchanged. Bale et al. [10] find evidence that collisional aging of proton distributions has a strong influence on the further fate of these distributions, moving them into areas far away from the ranges of instability. If this interpretation holds, our observation would mean that iron ions are more sluggish than protons. This is surprising because the Coulomb cross section of the highly charged iron ions seems more favorable for a rapid adjustment to the thermal conditions of protons: Taking the expression from Spitzer [11] for the thermal equipartition times of iron ions with charge $Z$ and nuclear mass $A$ in a population of protons as field particles and comparing equipartition times of hot iron ions with hot protons one finds

$$t_{eq,Fe} = \frac{A_{Fe}}{Z_{Fe}^{2}} \left[ \frac{T_{Fe,hot}}{\delta p} + \frac{T_{p}}{\delta p} \right]^{3/2}.$$

Thus, comparing thermal distributions of iron ions (typically charge 10+) with protons with similar thermal widths, one expects a ratio of typically 1/2 for the equipartition times in Eq. (2). However, it seems that iron ions do not equilibrate faster than protons in our case. Perhaps this is related to the fact that iron ion distributions do not exhibit the typical core-halo structure; clearly, a dense core distribution equilibrates much faster than a wide maxwellian of uniform temperature. Obviously, this needs further investigation of selected cases, for which both, proton and iron distributions, have been determined simultaneously. Undoubtedly velocity distributions with large anisotropies can become unstable, thereby creating various types of waves. Jian et al. [12] have recently reported observations of ion-cyclotron wave events (ICWs) in the solar wind with STEREO. A preliminary inspection of two short periods with strong anisotropies of iron ions, however, has not revealed any association of ICWs in the relevant frequency range for iron ions. One possible explanation is that the ICWs observed by Jian et al. [12] have their source near the Sun and are damped as they move outwards to 1 AU, while the contribution of waves generated locally from unstable distributions of rare ions are much weaker.

ACKNOWLEDGMENTS

The authors thank all the individuals who designed and built the PLASTIC instruments for STEREO at the University of New Hampshire, the University of Bern, the Max-Planck-Institute für extraterrestrische Physik, and the University of Kiel. The authors took benefit from helpful discussions with Justin Kasper. We acknowledge support by NASA STEREO contract NAS5-00132.

REFERENCES