

Kinetic properties of heavy solar wind ions from Ulysses-SWICS

R. von Steiger¹ and T. H. Zurbuchen²

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[1] The kinetic properties of heavy ions in the solar wind reflect the plasma processes governing the solar wind in the heliosphere. We use Ulysses-SWICS data that resolve heavy ions in a wide range of mass-per-charge values, $2 \leq m/q \leq 9.33$, to investigate the heavy ions and their dynamic evolution throughout the heliosphere. While at 1 AU the imprint of Coulomb collisions is known to be present in the slow solar wind, we show that it vanishes by the time the wind has reached 5 AU. All ion species flow with equal bulk and thermal speeds there. This is interpreted as a progressive dominance of wave-particle interactions over Coulomb collisions. **Citation:** von Steiger, R., and T. H. Zurbuchen (2006), Kinetic properties of heavy solar wind ions from Ulysses-SWICS, *Geophys. Res. Lett.*, 33, L09103, doi:10.1029/2005GL024998.

1. Introduction

[2] Heavy ions in the solar wind provide information about its source and its dynamic evolution in the heliosphere. Due to their low relative density and low energy, these ions act as tracers in the solar wind flow. They can be used to infer properties that cannot be deduced from major species (protons, electrons, and to some extent alpha particles) alone. With today's instrumentation, such as Ulysses-SWICS, more than ten different heavy elements from carbon to iron in a total of over 40 specific ions can be observed [Gloeckler et al., 1992], enabling studies relative to the solar wind source and its dynamic evolution [Zurbuchen et al., 2002; von Steiger et al., 2000].

[3] In this paper we focus on the kinetic properties of heavy ions in the solar wind. As opposed to the compositional information, which remains unchanged after the solar wind escapes the near-solar heliosphere, the kinetic properties of heavy ions (a.k.a. heavies) are strongly affected by local processes in the heliosphere [Isenberg and Hollweg, 1983; Gary et al., 2001]. For example, wave-particle interactions may result in nonthermal distributions of heavies. Coulomb collisions, however, tend to evolve particles toward thermal equilibrium in the solar wind rest frame. The observed kinetic properties can thus be interpreted as indicators of these processes and the time scales on which they act.

[4] We report observations of bulk speeds and thermal speeds of 35 ion species measured with the SWICS instrument on Ulysses. They span a mass-per-charge range of $2 \leq m/q \leq 9.33$, or a range in q^2/m (the scaling parameter for Coulomb collisions) of $1 \lesssim q^2/m \lesssim 6$. Ulysses provides

unique access to all types of solar wind and a range of heliocentric distances from 1 to 5 AU. Here we focus on four time periods that cover a representative sample of solar wind, from coronal-hole-associated fast wind to near-ecliptic wind near solar maximum and solar minimum.

[5] The time periods provided in Table 1 are identical to the ones chosen for the comprehensive composition study by von Steiger et al. [2000]. Time periods North and South cover coronal-hole-associated solar wind measured during two Ulysses high-latitude passages, i.e., high-speed streams with an almost constant composition of heavy elements with relatively low charge states and a relatively small enrichment of elements with a low first ionisation potential (FIP). The time periods Min and Max cover near-ecliptic solar wind, i.e., generally low-speed wind with relatively high and very variable charge states and low-FIP element enrichment, during times of low and of high solar activity, respectively.

2. Observations

[6] Since the first observations of heavy solar wind ions at 1 AU it has been known that alpha particles flow at roughly the same speed as the bulk protons [Neugebauer and Snyder, 1966; Bame et al., 1970] and that their kinetic temperatures are nonthermal and approximately mass proportional [Schmidt et al., 1980; Ogilvie et al., 1980]. Bochsler et al. [1985] found small but significant deviations from the simple rule of constant speed: in fast, coronal-hole-associated wind the heavy ions lag behind the lighter ones by tens of km/s at 600 km/s, though all of them propagate faster than protons. Moreover, the kinetic temperatures of these heavy ion species exhibit significant departures from thermal equilibrium and are often approximately mass proportional. Deviations from this mass-proportional scaling are relatively subtle, but significant [Hefti et al., 1998].

[7] Note that instruments such as SWICS only analyze reduced energy spectra, not three-dimensional distribution functions. These reduced one-dimensional distributions, $f^*(v)$, can be approximated as

$$dn = f^*(v)dv_r = \int dv_{\perp} dv_r f(\mathbf{v}), \quad (1)$$

or,

$$f^*(v) = \int dv_{\perp} f(\mathbf{v}), \quad (2)$$

where $v = |\mathbf{v}|$, v_r and v_{\perp} are the radial and perpendicular velocity components, respectively. The thermal width measured by these reduced distributions is therefore approximately equal to the thermal speed in the radial direction, independent of the magnetic field orientation.

¹International Space Science Institute, Bern, Switzerland.

²Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, Ann Arbor, Michigan, USA.

Table 1. Specification of the Four Time Periods Used in This Study

Name	Time	Range, AU	Latitude, deg
Max	1-Sep-91–30-Jun-92	4.06 ... 5.40	−5.4 ... −13.1
South	1-Jan-94–31-Oct-94	3.83 ... 1.96	−48.3 ... −80.2
North	1-Jul-95–30-Apr-96	1.81 ... 3.73	+80.2 ... +38.6
Min	1-Jul-97–30-Apr-98	5.15 ... 5.41	+8.6 ... −6.7

Keeping this limitation in mind, we now analyze heavy ion distributions all the way to 5.4 AU. The picture we obtain is distinctly different from the one at 1 AU, as reported earlier by *von Steiger et al.* [1995]. However, that first paper was limited to a 1-year period and to a small number of ion species covering only a limited range in m/q .

[8] Consider first the speed distribution. It has been proposed by *Neugebauer* [1981] that there is a tendency of alpha particles to outrun protons by a fraction of the local Alfvén speed. These small velocity differences are generally aligned with the magnetic field. For large heliocentric distances the magnetic field is approximately azimuthal. Hence the reduced solar wind distributions measured by SWICS are expected to show negligible velocity differences.

[9] We find that all heavies flow at approximately the same radial speed, as expected. This is illustrated with two examples in Figure 1, where contour plots of the correlograms of Si^{8+} and Fe^{10+} are given in relation to O^{6+} . In all cases the correlation coefficients are very high, $r > 0.99$.

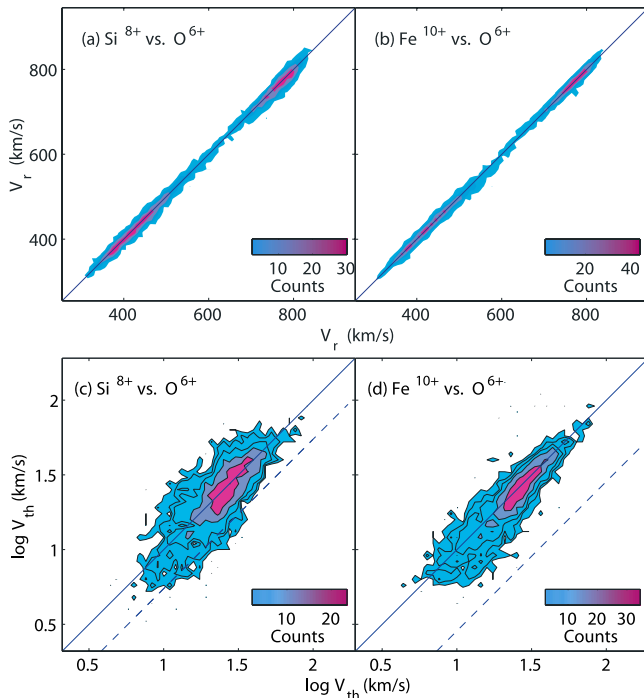


Figure 1. Correlograms of the radial speeds of (a) Si^{8+} and (b) Fe^{10+} vs. O^{6+} from daily averages for Nov. 1990 to Dec. 1999. These species flow at approximately the same radial speed, as expected. (c) and (d) Correlograms of the thermal speeds of the same species and time period; all species have approximately equal thermal speeds, as indicated by the black line, over the complete range observed. Only a small trend to equal temperatures (dashed line) is observed in the slow wind at low temperatures.

[10] Correlograms for the thermal speeds of the same three ion species are also given in Figure 1. Due to the predominantly azimuthal orientation of the magnetic field, these thermal speeds measure the perpendicular temperature of the solar wind species. The correlation coefficients are good, $r > 0.75$. The contours are aligned with the main diagonal of the plots indicating equal thermal speeds, or mass-proportional kinetic temperatures. Specifically, there is hardly any tendency toward equal temperatures in slow solar wind. This is in contrast to the situation at 1 AU, where *Hefsti et al.* [1998] clearly observed such a trend.

[11] Figure 2 summarizes the kinetic properties of all ions identified by Ulysses-SWICS. Average values of the bulk speed and the thermal speed of 35 ion species, obtained during the four time periods defined in Table 1, are plotted versus their q^2/m in units of e^2/amu . The main point of Figure 2 is the absence of (nearly) any systematic trend with q^2/m in the bulk speeds, as described by *Zurbuchen et al.* [2000].

[12] Interestingly, we still observe a small systematic trend in the slow-wind periods (Max and Min) to higher thermal

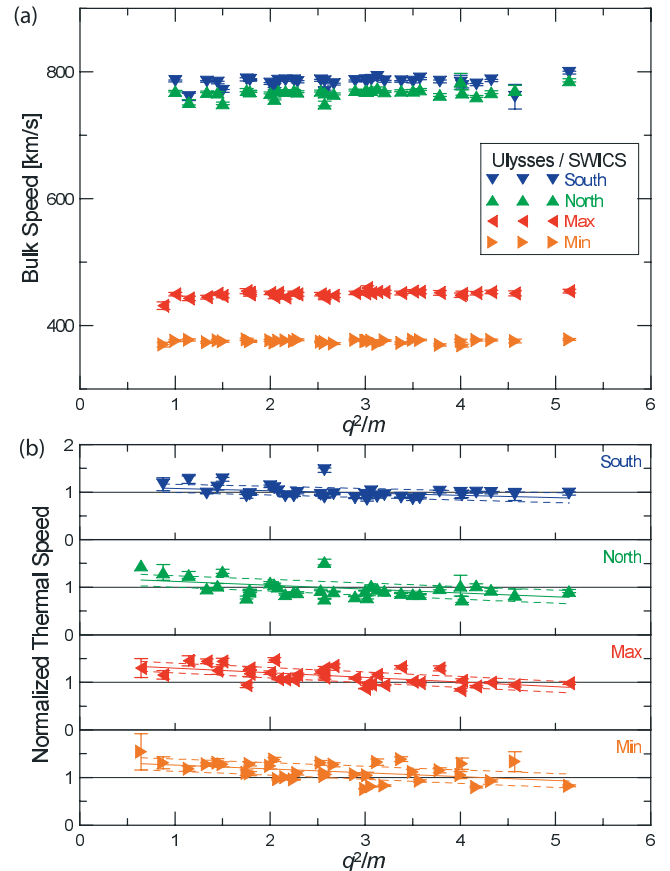


Figure 2. (a) Average radial speeds and (b) thermal speeds of 35 ion species, obtained during the four time periods defined in Table 1. The thermal speeds were normalized by the thermal speed of alpha particles in order to remove any radial or latitudinal trends. Each data point represents the mean of ~ 300 daily averages, and the error bars indicate the standard error of the mean. Linear regression lines are given (solid color) together with their confidence intervals (dashed colour).

speeds with decreasing q^2/m . This is in qualitative agreement with the result described by *Zurbuchen et al.* [2000] for SWICS data around 2.5 AU and SOHO-CELIAS data at 1 AU [*Hefi et al.*, 1998]. A quantitative comparison of the results in these papers shows that the trend is decreasing with increasing distance from the Sun. On the other hand, the coronal-hole-associated wind (periods South and North) show no significant dependence on q^2/m , again in agreement with *Hefi et al.* [1998] and *Zurbuchen et al.* [2000].

3. Discussion

[13] We now discuss these data in the framework of qualitative expectations from models addressing ion interactions in the solar wind [e.g., *Dusenbery and Hollweg*, 1981; *Isenberg and Hollweg*, 1983; *Marsch et al.*, 1982]. Recent observations by SOHO [e.g., *Cranmer et al.*, 1999; *Tu et al.*, 1998] indicate preferential heating of heavy ions close to the Sun, especially in coronal-hole-associated regions, emphasizing the importance of electromagnetic waves or turbulence. However, it is difficult to conclusively relate these remote observations from UVCS to theoretical predictions because of the lack of constraints on plasma characteristics, such as the nature of the plasma turbulence. The kinetic properties of heavy ions discussed here are therefore a test case of many theories to explain the preferential heating in the solar corona.

[14] In a simple picture, the kinetic properties of the solar wind heavy ions in the heliosphere far away from the Sun are determined by the competition between Coulomb collisions and wave-particle interactions: (1) Coulomb collisions are constantly pushing the heavy ions toward thermal equilibrium in the rest frame of the solar wind with identical bulk speed and equal temperature. The collision frequency scales as q^2/m and typical collision times at 1 AU are as long as ~ 3 days [*Livi and Marsch*, 1987]. The timescale is therefore $\tau_c^{q,m} \propto q^2/(mr^2)$. (2) Wave-particle interactions which tend to scatter heavy ions in the rest frame of the waves. Nondispersive MHD waves propagate along the magnetic field with $\sim v_A$, the Alfvén speed. It is therefore assumed the interactions naturally result in a positive differential speed of v_A , and a thermal speed which is equal for all species, also v_A . The heavy ions are “surfing” the waves, and are heated since they are scattering to isotropy in the rest frame of these waves [*Marsch*, 1991].

[15] It has been pointed out that this picture is oversimplified [*Dusenbery and Hollweg*, 1981; *Gary et al.*, 2001]. For example, in quasi-linear theory particle scattering can only occur if the resonance condition $\omega = \Omega_c + k_{\parallel}v_{\parallel}$ is fulfilled [*Dusenbery and Hollweg*, 1981], where $\Omega_c = qB/m$ is the gyro-frequency of the heavy ion. Generally, the m/q dependence of this scattering term is rather large because of the fast drop-off of the wave power-spectrum at high frequencies near the dissipative range [*Leamon et al.*, 1999]. *Dusenbery and Hollweg* [1981] have also pointed out that there are resonance gaps which limit the efficiency of wave-particle interactions. These scattering processes have been studied in detail using self-consistent wave-particle interaction theories [*Marsch*, 1999]. These theories still predict differences between different particle species interacting in the solar wind, but tend to smooth out resonance gaps.

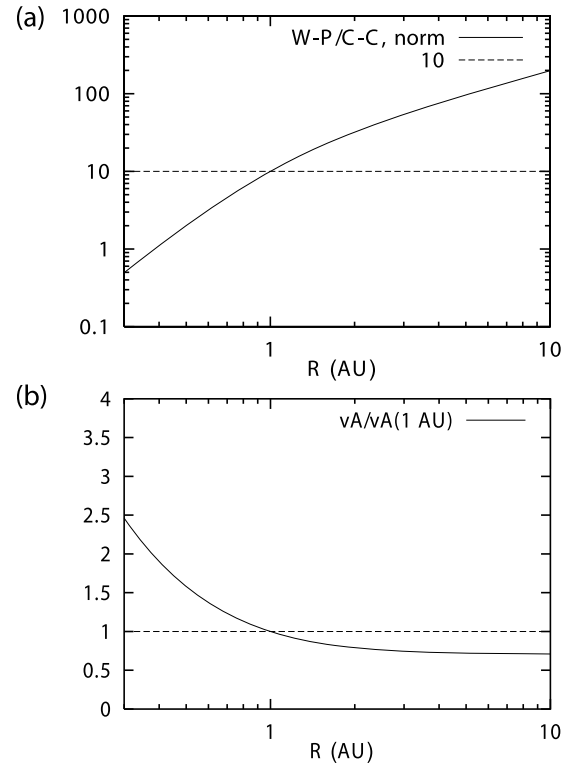


Figure 3. (a) Normalized ratio of wave-particle interaction and Coulomb collision rates as a function of heliocentric distance. The scaling law has been arbitrarily normalized to a value of 10 at the heliospheric distance of 1 AU. (b) Alfvén speed as a function of heliocentric distance. A Parker spiral field has been assumed; the curve has been normalized to 1 AU.

[16] For simplicity, we approximate the wave-particle interaction time scale by $\tau_w \propto (q/m)^2 I(m/q)(\delta B/B)^2$ [*Isenberg and Hollweg*, 1983]. Here, $I(m, q, v_{\parallel})$ stands for the relative wave-intensity resonantly interacting with the particle, B and δB are the average and the turbulent magnetic field. As a standard baseline, let us take a WKB approximation, where $(\delta B)^2 \propto 1/r^3$. This assumption can be justified for relatively low frequencies, which contain most of the energy, but it may not be good for high-frequency waves. Figure 3a shows the radial scaling of the ratio of ω_w/ω_c , or τ_c/τ_w , with the additional assumptions of an average Parker field configuration, and no r -dependence of the shape of $I(m/q)$ and v . The normalization is arbitrarily set to 10 at 1 AU. Figure 3b shows the radial evolution of the Alfvén speed under the assumptions described above. Note that there is only a very small radial dependence of the Alfvén speed outside 1 AU.

[17] The observations can now be discussed in the framework of these qualitative scaling laws. The observed radial evolution of the thermal speed as a function of heliocentric distance is in qualitative agreement with Figure 3: The larger the heliospheric distance, the smaller the influence of Coulomb collisions. Based on the radial evolution of v_A , one would expect a very small dependence of the thermal speed on heliocentric distance. In particular, the radial dependence should be smaller than the radial dependence of the proton thermal speed, as is also observed.

Generally, the magnetic field will tend to be more azimuthal for increasing distance, resulting in a smaller radial component of the differential speed, as is also observed.

[18] There are, however, some issues that are not easily explained by this simple formalism and require more detailed treatment. First, it is not obvious how the weak collisional coupling to 1 AU manages to affect heavy ions in the heliosphere. On average they only encounter a few collisions between the Sun and 1 AU. It is therefore surprising that the data of *Hefti et al.* [1998] so clearly show a signature of Coulomb collisions. Second, it is not obvious from quasi-linear wave-particle theories why there are almost no differences between the kinetic properties of these ions. Using a quasi-linear interaction scenario for the large m/q range of these particles, one might expect noticeable differences. These are not observed in the entire heliospheric distance range observed so far.

4. Conclusions

[19] We have presented Ulysses-SWICS data characterizing the kinetic properties of heavy ions in the solar wind over a large range of heliospheric distances. These data clearly indicate an increasing dominance of wave-particle interactions for increasing heliospheric distance. This can be understood as a result of the fast density decrease compared to the typical r -scaling of the solar wind turbulence.

[20] The apparent collisional signatures in the low-speed solar wind are not easily understood and require a more detailed analysis. It is also noticeable that there is no m/q dependence in any of the cases where wave-particle interactions dominate. Such m/q dependencies might be expected based on the differences of the resonant interaction processes.

[21] The anticipated m/q dependencies are not observed. This may be a feature of a more subtle aspect of quasi-linear wave-particle interactions. However, our experimental results might also indicate that these interactions are not well described using the assumptions of quasi-linear theory. It is worth pointing out that these difficulties with quasi-linear predictions may be related to the well-established observation of a long mean free path of pickup ions which exceeds the quasi-linear prediction by over two orders of magnitude [*Gloeckler et al.*, 1995]. The range of v_{\perp} of the pickup ions with close to 90° pitch-angle is very much comparable to the parallel speed of the heavy ions compared here.

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R. von Steiger, International Space Science Institute, Hallerstrasse 6, CH-3012 Bern, Switzerland. (vsteiger@issii.unibe.ch)

T. H. Zurbuchen, Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, 2455 Hayward St., Ann Arbor, MI 48109, USA. (thomasz@umich.edu)