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KINETIC PROPERTIES OF HEAVY IONS IN THE SOLAR WIND FROM SWICS/ULYSSES

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Abstract. The kinetic properties of heavy ions in the solar wind are known to behave in a well organized way under most solar wind flow conditions: Their speeds are all equal and faster than that of hydrogen by about the local Alfvén speed, and their kinetic temperatures are proportional to their mass. The simplicity of these properties points to a straightforward physical interpretation; wave-particle interactions with Alfvén waves are the probable cause. With the SWICS sensor on board Ulysses, it is now possible to investigate the kinetic properties of many more ion species than before. Furthermore, the transition of Ulysses into the fast stream emanating from the south polar coronal hole since 1992 allows us to study these properties both in the slow, interstream solar wind, as well as in an unambiguously identified fast stream. We present data from SWICS/Ulysses on the dominant ions of He, C, O, Ne, and Mg. As a result we find that, both in the slow wind and in fast streams, the isotachic property is obeyed even better than it could be determined by the ICI instrument on ISEE-3. The mass proportionality of $T_{\rm kin}$ is also shown to hold for these ions, including the newly identified C and Mg.

Key words: Solar wind – heavy ions – Ulysses

1. Introduction

The solar wind bulk velocity of protons at 1 AU varies between $v_{\rm p} = 300 - 800$ km/s, and their kinetic temperature, $T_{\rm p}$, between $\sim 10^4$ K to a few times 10^5 K. While the velocity stays constant at increasing heliocentric distances, the temperature drops by a power-law in r.

Solar wind helium and heavy ions are known not to be in thermal equilibrium with the protons. Their bulk velocities v_i are equal and vary between $v_{\rm p}$ at low speeds, and $v_{\rm p}+v_{\rm A}$ at high speeds, where $v_{\rm A}$ is the local Alfvén velocity (Marsch *et al.*, 1982). Their kinetic temperatures, T_i, tend to be higher than $T_{\rm p}$ by a factor of the ion's mass, m_i, such that two ion temperatures obey

$$T_i/T_j \simeq m_i/m_j \tag{1}$$

(Schmidt *et al.*, 1980; Ogilvie *et al.*, 1980). H does not normally fit in this rule very well, with a most probable $T_\alpha/T_{\rm p}$ ratio of 2–4 (Neugebauer, 1981), but we will show below that it is well obeyed by He and the heavy ions.

The simplicity of these rules, and the fact that they are observed under nearly all solar wind conditions, point to a straightforward physical interpretation. Wave-particle interactions with Alfvén waves are a candidate cause for both effects,

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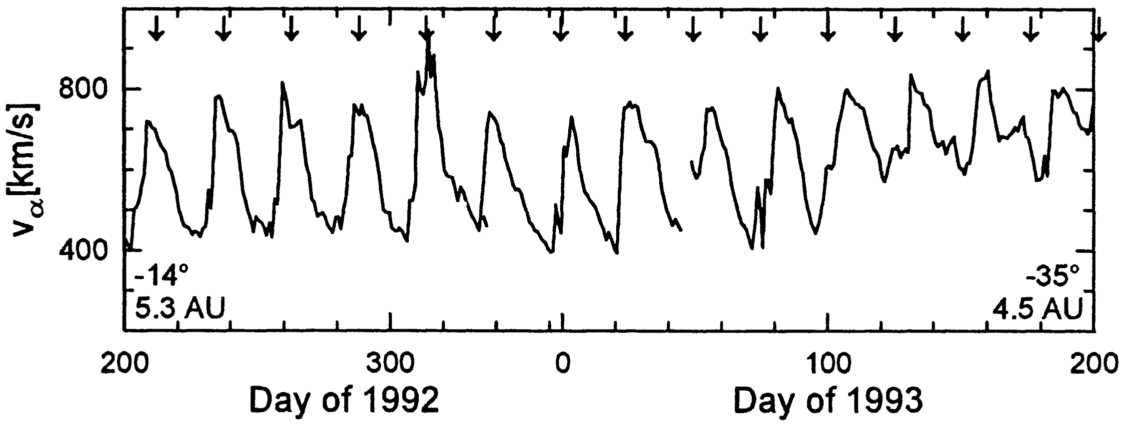

Fig. 1. Overview of the survey period. The solar wind velocity varied between 400 and 800 km/s, with one high-speed stream per solar rotation. The heliolatitude increased from 14° to 35° south, while the heliocentric distance decreased from 5.3 AU to 4.5 AU. Arrows indicate transits of 0° Carrington longitude as seen from Ulysses.

accelerating the heavy ions to speeds in excess of v_p and at the same time heating them to $T_j \propto m_i$. However, a quantitative theory explaining both observations has not been worked out as yet (but see Isenberg and Hollweg, 1983).

In this paper, we report on new data obtained with the SWICS instrument on Ulysses (Gloeckler *et al.*, 1992). These data are particularly suited for a fresh look at the heavy ion velocities and temperatures for two reasons: (1) The mass resolution of SWICS allows to unambiguously identify many more ion species, including those hidden by more abundant species in mass per charge spectra, such as C^{6+} and Mg^{10+}. (2) The post-acceleration (by $\sim$ 23 kV) of ions after the energy per charge selector guarantees that all ions have comparable energies — and thus similar detection efficiencies — in the sensor, irrespective of the original solar wind velocity. This facilitates comparisons of high-speed to low-speed solar wind, with little risk of systematic biases.

In this work, we concentrate on comparing bulk velocities and kinetic temperatures of He and heavy ions among themselves, deferring the comparison of these parameters to those of the main constituent, protons, to a later paper (but see Goldstein *et al.*, 1994).

2. Data Selection and Analysis

For our survey, we have chosen a period of one year duration, from day 200, 1992, to day 200, 1993 (see Fig. 1). During this period, Ulysses traversed the range between 14° and 35° southern heliographic latitude. From Fig. 1, it is evident that the spacecraft encountered a high-speed stream each solar rotation (periodicity 25.7 days, indicated by arrows), emanating from the low-latitude portion of the south polar coronal hole (Bame *et al.*, 1993). Our survey period is thus ideal for comparing the low-speed to the high-speed solar wind.

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Even though SWICS completes one energy per charge (E/q) cycle every 13 minutes, it is not possible to use this time resolution for most heavy ions due to low statistics. We have thus summed over 32 E/q spectra, resulting in a time resolution of $\sim$ 8 hours, of the ions He^{2+}, C^{6+}, C^{5+}, C^{4+}, O^{8+}, O^{7+}, O^{6+}, Ne^{8+}, and Mg^{10+}. Individual ion species were picked from the mass-mass per charge matrix using the ellipse method (von Steiger, 1992), resulting in a distribution function for each species. Each ion spectrum was then fitted to a Maxwellian, from which the two parameters, v_0 and T, were obtained. Only the central portion of the distribution function, consisting of the E/q step with the maximum count rate plus all adjacent steps with count rates $\geq 20\%$ thereof, was used in the fits, in order not to bias the parameters by the possible presence of suprathermal tails. Still, this procedure assumes that the solar wind conditions do not substantially vary over the accumulation period. If they do, the velocity obtained may be regarded as the average over the period, but the temperature is systematically increased by the velocity shift. Note, however, that a velocity shift affects all heavy ion temperatures by the same amount, not disturbing their correlation. Furthermore, since the solar wind velocity is nearly bi-stable, with quick transitions between slow and fast wind, only a small number of spectra are affected by this effect, and their parameters have large error bars, resulting in a low statistical weight in our fitting procedure (see below). We have therefore not cleaned up the data set and include all spectra in the results reported here.

Since the three-dimensional distribution functions are not necessarily isotropic, we need to further characterize the temperature value obtained by our analysis. Since the solar wind is supersonic, the E/q spectra essentially measure T parallel to the bulk velocity. The Parker spiral angle is nearly 90° at the heliocentric distance of our survey period, so this amounts to nearly the perpendicular temperature, $T_\perp$. Assuming that the possible anisotropies are similar and have the same direction for all ion species considered, the temperatures reported here are representative for the full distribution functions.

The above procedure resulted in > 1000 data points for v_i and T_i of nine ion species from He^{2+} to Mg^{10+}. We then correlated the parameters between all ion pairs, using the Mahalanobis method, which is symmetric in the dependent and the independent variable, and which takes into account the errors in both directions (cf. appendix of von Steiger *et al.*, 1992). One such correlogram is shown in Fig. 2. The velocities were fitted with a linear function, while for the temperatures we made two power-law fits, one with both parameters free, and the other with the exponent fixed to one, giving the average temperature ratio.

3. Results

It is evident from Fig. 2 that (1) the velocities of the individual ion species are equal to a very high degree of accuracy, and (2) the kinetic temperatures are proportional, with those of the heavier species being enhanced by a roughly mass

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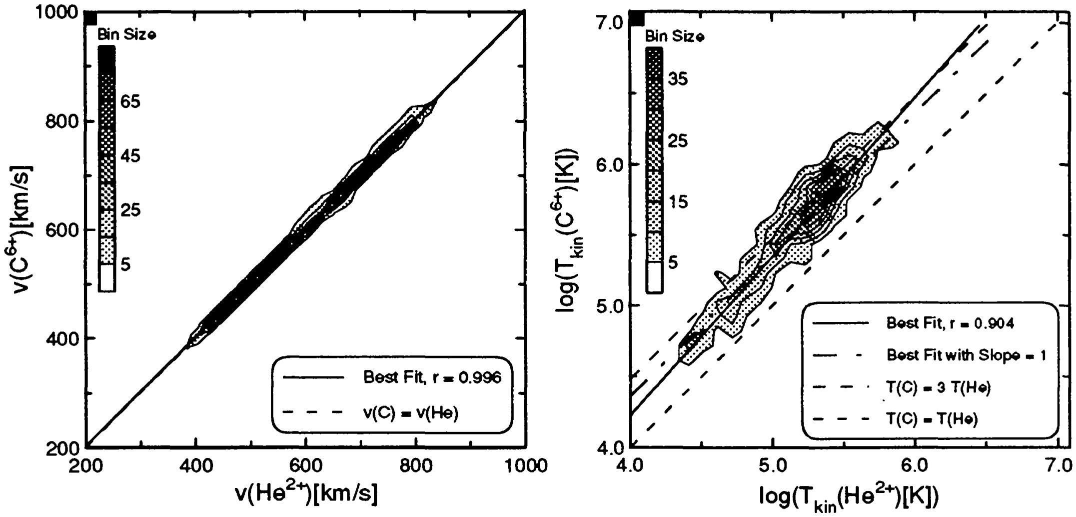

Fig. 2. Correlograms of bulk velocity (left) and kinetic temperature (right) of C^{6+} vs. He^{2+}. While the two velocities are equal over the full range of 400–800 km/s, the temperature of C^{6+} is enhanced over that of He^{2+} by almost a factor of three.

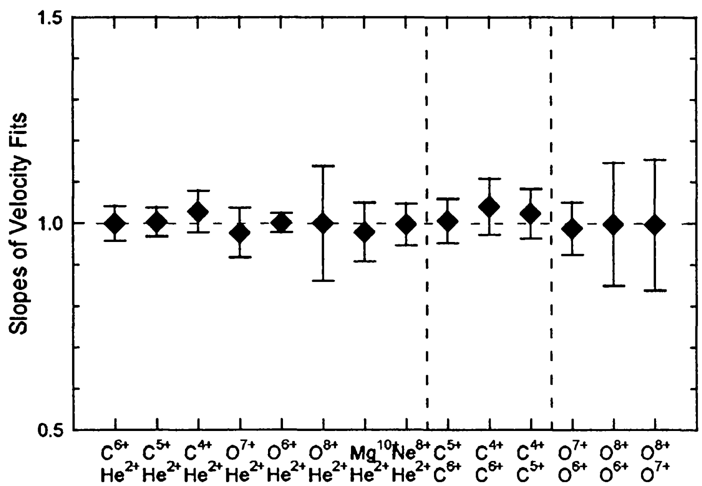

Fig. 3. Slopes of velocity fits as in Fig. 2 for all ion pairs investigated, as indicated on the abscissa. All heavy ion bulk velocities are found to be equal within the statistical errors.

proportional factor. This is, of course, not a new result by itself. Apart from the references cited in the Introduction, it has been found for a mixture of Fe charge states by Schmid *et al.* (1987), and for a mixture of Si charge states by Bochsler (1989), both using ICI/ISEE-3 data. However, our data spans a different range of solar wind velocities, from 400 to 800 km/s, as compared to 300–600 km/s covered by ICI.

In Fig. 3, we plot the slopes of the velocity fits of all ion pairs investigated (indicated on the abscissa). All slopes are found to be equal to unity, indicating that He and the heavy ions all flow with the same speed in the solar wind under all SW conditions encountered in our survey period, since the ordinate intercepts are all zero to within the error bars (not shown).

Figure 4 gives the fit parameters of the temperature fits, revealing the proportionality of T for all ion pairs. Exponents are between 0.9 and 1.1 (top panel),

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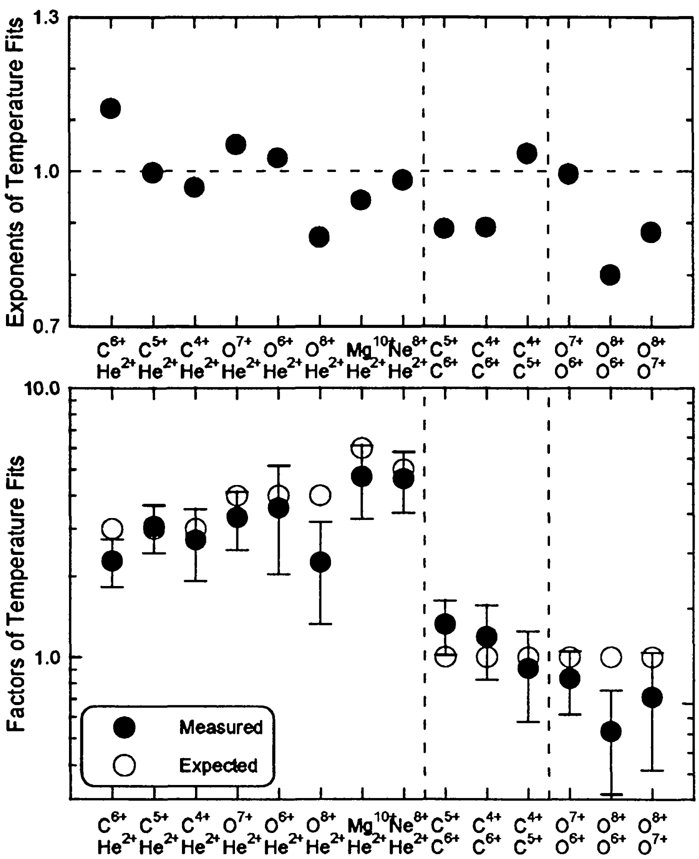

Fig. 4. Exponents of temperature fits as in Fig. 2 (top), and average temperature ratios (bottom) for all ion pairs investigated, as indicated on the abscissa. All heavy ion temperatures are found to be proportional to each other, but not equal. Their ratios agree with the mass ratios of the ions (indicated by open dots) within the statistical errors (see text for the case of O^{8+}).

and the average temperature ratios, calculated as the factor of the temperature fit with exponent fixed to one, are all found to agree with the mass ratios within the error bars (bottom panel), as expected from Eq. (1). The bad correspondence for the ratios including O^{8+} is probably caused by the difficulty to identify this ion even with SWICS, since it may be contaminated by the neighbouring and more abundant C^{6+}.

4. Discussion

We have demonstrated that the well-known isotachic property of the solar wind heavy ions is obeyed to a very high degree of accuracy for solar wind velocities between 400–800 km/s, and that the mass proportionality of their kinetic temperatures is obeyed also by ion charge states previously unavailable. These results are seemingly at variance with those obtained by ICI/ISEE-3 in two respects:

(1) Schmid *et al.* (1987), and Bochsler (1989) found that the heavier ions, Fe and Si, are lagging behind He at high bulk velocities (up to 600 km/s), while in our data no such difference is apparent up to the highest velocities of 800 km/s. A possible interpretation may be that the acceleration of the heavy species to the He speed is not yet fully developed at 1 AU (the distance of ISEE-3), but only at 5 AU (the distance of Ulysses), due to the longer expansion time. This

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view is supported by the observation of a bimodal distribution of He–Si velocity differences by ICI, with a narrow peak at $\Delta v = 0$ superimposed to a broader distribution with $\Delta v > 0$. At 1 AU, the relative number of $\Delta v = 0$ observations increases with decreasing v, i.e. with increasing expansion time. It may thus be that, during the transition from 1 to 5 AU, the solar wind speed is further equalized, leading to more $\Delta v = 0$ observations at larger distances, and thus to a smaller $|\Delta v|$ on the average.

(2) Bochsler *et al.* (1985) found a deviation of the mass proportionality in T towards equal temperatures at low solar wind velocities. We could not observe such a deviation, but this is simply due to the fact that the lowest velocities in our data set are of the order of 400 km/s, while the isothermal solar wind was only observed at the extremely low velocity of $\sim$ 300 km/s by ICI. Our data set is thus not well suited to search for isothermal solar wind, which is limited to instances of very low velocity, combined with high density, resulting in enhanced Coulomb friction equalizing T.

In summary, we find that the solar wind velocities of He and heavy ions are equal and that their kinetic temperatures are mass proportional up to the highest bulk velocities observed. These rules are obeyed to a high degree of accuracy. Furthermore, previously unobservable ion species such as C^{6+} and Mg^{10+} fully support this picture. It is hoped that these results will trigger a new effort in theoretical modelling of the solar wind expansion, which eventually will result in understanding the cause of these simple observational rules.

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