SOLAR WIND ION COMPOSITION*

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In addition to the two ion species previously observed in the solar wind, $^1H^+$ and $^4He^{++}$, Vela satellite measurements reveal the presence of ions of $^3He^{++}$, $^4He^+$, various ion species of ^{16}O, and other unidentified heavy ions. From the number ratios of the O^{+7}, O^{+6}, and O^{+5} ion species measured near earth, it may be inferred that the ionization state ratios are established deep within the solar corona at million-degree temperatures.

Expansion of the sun's atmosphere forms the solar wind[1] so it should contain ions representative of the solar materials. However, the solar abundances and solar-wind abundances are not necessarily the same. The various species of ions expand outward with a common bulk velocity, tied together by the magnetic field frozen in the highly conductive plasma. The ion thermal velocities are usually much less than the bulk velocity.

Singly charged hydrogen and doubly charged helium ions, observed with electrostatic analyzers on Mariner 2[2] and other spacecraft,[3-6] are the most abundant solar wind ions. In the measured energy per charge (E/Q) spectra the $^1H^+$ and $^4He^{++}$ ions appear as two groups, with E/Q positions having a ratio of 2.0, and with the number ratios $^4He^{++}/^1H^+$ extending from <0.005 to >0.15. Average number ratios of ~0.045, measured during two time spans,[6,7] seem to fall well below the abundance ratio ~0.09 expected in the sun.[8]

To date, only $^1H^+$ and $^4He^{++}$ have been unambiguously identified in the solar wind; this Letter reports the detection and identification of ions of $^3He^{++}$, $^4He^+$, and various ion species of ^{16}O. Ions of other nuclei such as ^{12}C, ^{14}N, ^{20}Ne, etc., are expected on the basis of solar abundances[9] and abundances of solar cosmic ray nuclei,[10] but, although other heavy ions are observed, they have not been clearly separated from the more abundant ^{16}O ions.

The measurements reported here were made with hemispherical electrostatic analyzers on the earth-orbiting Vela 3A and 3B satellites. Details of orbits and instrument characteristics can be found elsewhere.[6,11] For the present discussion the following facts are pertinent: Ion species with the same velocities appear at positions in an E/Q spectrum which depend on the ion masses and states of ionization. For example, ions of $^3He^{++}$, $^{16}O^{+6}$, and $^4He^+$ appear at E/Q's of 1.5, 2.65, and 4.0 times the E/Q of $^1H^+$, so if the random velocities (or temperatures) are sufficiently low, a high-resolution analyzer can resolve the separate groups. In the Vela analyzers, electron multipliers individually count the ions at three levels of decreasing sensitivity A, B, and C, in such a way that most of the ions are detected at level A, while at level C the fraction detected is highly dependent on, and increases with, ion mass and energy.

The measurements show that heavy ions are usually present in the solar wind, appearing beyond the $^4He^{++}$ group in an E/Q spectrum. When ion temperatures are low, various ion species of ^{16}O can be resolved, as shown by the spectra in Figs. 1 and 2 obtained at times when the proton temperatures were ~10^4 °K, unusually low for the solar wind. The various groups of ^{16}O ions are clearly identified by their E/Q positions and their relative enhancements in the C-counts spectra. Although other unidentified heavy ions are present, the third most abundant species in the solar wind is usually O^{+6} and sometimes O^{+7}. Even when high temperatures prevent their resolution, the presence of the highly ionized ^{16}O ions is shown by comparing the A- and C-counts spectra.

In Fig. 2, resolved ion groups at 1.5 and 4.0 times the $^1H^+$ E/Q are identified as $^3He^{++}$ and $^4He^+$. The $^4He^+$ group probably contains other ions such as O^{+4}, but the C/A ratio indicates that a substantial fraction of the ions produced pulses in about the same pulse-size range as $^4He^{++}$ ions, so we identify this group to be mainly $^4He^+$.

Table I presents ratios of the various ion species, estimated from the data shown in Figs. 1 and 2. The ratios are only approximate because of statistical limitations, resolution, contamination by other species, etc.

<u>$^3He^{++}$ ions.</u>—These observations are the first to show that ^3He exists in the sun of the present epoch.[12] Wagoner, Fowler, and Hoyle[8] have estimated that the present solar $^3He/^4He$ ratio should be ~1.5×10^{-3}. An accurate deter-

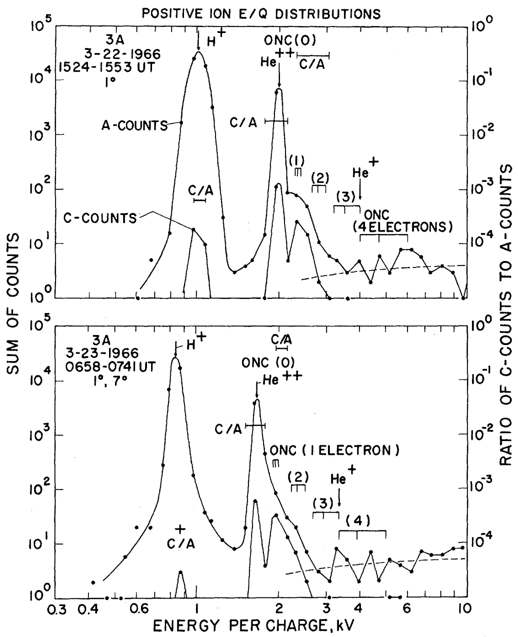

FIG. 1. Energy-per-charge spectra from Vela 3A showing heavy ions in the solar wind. The dates, time spans of data acquisition, and the average angles of the measurements from the solar direction are indicated. C/A ratios of counts in the indicated E/Q ranges are shown by horizontal lines. Vertical lines show the expected E/Q positions of oxygen, nitrogen, and carbon ions having the indicated number of electrons. Dashed curves give the average A-counts background level; C-counts backgrounds are too low to show in the figure.

mination of the solar ratio from the Vela data is likely to be difficult because the $^3He^{++}$ can be resolved only rarely and the relationship between solar abundances and the variable solar wind abundances, for example the $^4He/^1H$ ratios, is presently unknown.

He/O ratio.—This variable ratio can be compared with the 107/1 ratio found in the solar cosmic rays[10] and 136/1 expected in the sun.[8] Biswas, Fichtel, and Guss[10] report the solar cosmic-ray He/O ratio does not seem to be highly variable, which suggests that the solar-

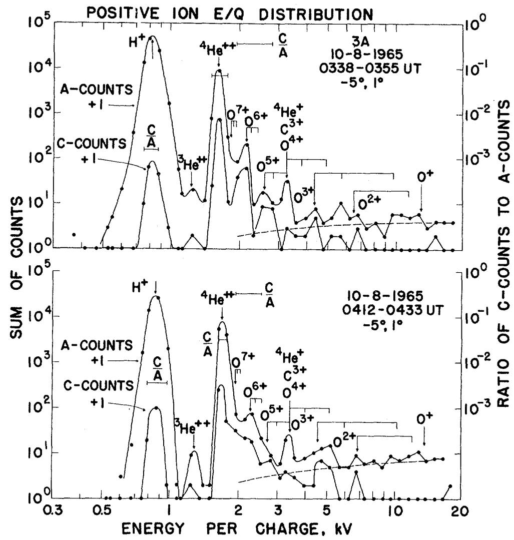

FIG. 2. Energy-per-charge spectra showing groups attributed to $^3He^{++}$, $^4He^{+}$, and various ion species of ^{16}O. Arrows give the expected positions of H, He, and oxygen ion species; the other vertical lines give expected positions for ^{14}N and ^{12}C ions having the same numbers of electrons as the ^{16}O ions. One count has been added to each spectrum point to bring the zero-count points onto the graph. Heavy ions other than the ^{16}O species were apparently present but cannot be as easily identified.

wind abundance fractionation occurs at higher levels in the solar corona than the level of the solar material from which the solar cosmic rays are produced.

Oxygen ion species.—The ratios of the ^{16}O ion species measured near earth are related to the solar wind formation deep within the corona. O^{+5} is consistently less abundant than O^{+6} which is usually more abundant than O^{+7}. Examination of the scale times for collisional ionization of O^{+6} and radiative and dielectronic recombination of O^{+7} shows that these times are much longer than the coronal expansion time beyond a heliocentric distance of ~1.7 solar radii. Thus the ratio of O^{+6} to O^{+7} (or any other ion pair), formed deep in the

Table I. Ion species ratios estimated from the data shown in Figs. 1 and 2.

Date	$^3He/^4He$	$^4He^+/^4He^{++}$	He/O	O^{+7}	:	O^{+6}	:	O^{+5}
3-22-66	$\leq 4\times10^{-4}$	$\leq 10^{-3}$	80	2		1		0.1
3-23-66	$\leq 2\times10^{-4}$	$\leq 10^{-3}$	50	3		1		$\leq$0.1
(1) 10-8-65	1.3×10^{-3}	$\approx 3\times10^{-3}$	25	$\leq$0.2		1		0.1
(2) 10-8-65	1.3×10^{-3}	$\approx 3\times10^{-3}$	66	0.3		1		0.1

corona, will not change significantly in transit to the earth.[13] The observed state of ionization is consistent with that expected in the corona for a temperature of $\sim 10^6\,°K$.[14] It is important to note that the solar wind near earth can be quite cool ($\sim 10^4\,°K$ proton temperature) at times when the O^{+7} to O^{+6} ratio implies coronal temperatures in excess of $2\times 10^6\,°K$.

$^4He^+$ ions.—These ions are only occasionally observed above background levels and when detected they have been less abundant than O^{+6}. Ionization equilibrium calculations[14] for $1\times 10^6\,°K$ give $^4He^+/^4He^{++} = 3\times 10^{-6}$, so the occasional appearance of $^4He^+$ with $^4He^+/^4He^{++} \approx 3\times 10^{-3}$ and with $O^{+6}/O^{+5} > 1$ is not readily explained.

A Pioneer 6 electrostatic analyzer spectrum measured on 26 December 1965 showed a $^4He^{++}$ group with an elevated tail which was interpreted[5] as being due to $^4He^+$ ions with $^4He^+/^1H^+ = 0.001$. We would identify the cause of the tail as oxygen ions for the following reasons: Vela 3A observations bracketing the time gave the same solar wind speed and direction as the Pioneer measurements, but found $^4He^+/^1H^+ < 0.0002$, and showed that the O^{+5} and O^{+6} fluxes were higher than those of $^4He^+$. The Pioneer analyzer measures current rather than counting particles, so the oxygen ion currents were enhanced by factors of 5 and 6 over the $^4He^+$ currents, thereby producing the elevated tail.

Ion species temperatures.—For solar wind in the normal temperature range $\geqslant 3\times 10^4\,°K$ there is a tendency for $^1H^+$ and $^4He^{++}$ random velocity distributions to have similar widths, implying $^4He^{++}$ temperatures ~4 times the $^1H^+$ temperatures.[6,7] There are clear indications in the Vela data that the various ion species have more nearly equal temperatures when the solar wind is cold ($\sim 10^4\,°K$), as would be expected if the isothermal relationships deep within the corona have not been greatly perturbed by nonthermal processes as the plasma expanded outward. Thus, normal-temperature solar wind has presumably undergone extensive nonthermal heating in interplanetary space,[15,16] the heating processes tending to cause different ion species to have nearly the same random velocity distributions. If this concept is correct, the temperatures of the ions near earth ordinarily bear little relationship to the solar-wind-formation conditions deep within the corona. Thus, a valid picture of the elemental composition and states of ionization deep within the corona may well be established with extended measurements at times of cool solar-wind conditions, using instruments as simple as high-resolution electrostatic analyzers.

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