SOLAR WIND MINOR IONS - RECENT OBSERVATIONS

S. J. Bame
University of California, Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

During the years following the Solar Wind Four Conference at Burghausen our knowledge of the solar wind ion composition and dynamics has grown. There have been some surprises, and our understanding of the evolution of the solar wind has been improved. Systematic studies have shown that the minor ions generally travel with a common bulk speed and have temperatures roughly proportional to their masses. It has been determined that the $^3He^{++}$ content varies greatly ; $^3He^{++}/^4He^{++}$ ranges from as high as 10^{-2} values to below 2×10^{-4}. In some solar wind flows which can be related to energetic coronal events, the minor ions are found in unusual ionization states containing Fe^{16+} as a prominent ion, showing that the states were formed at unusually high temperatures. Unexpectedly, in a few flows substantial quantities of $^4He^+$ have been detected, sometimes with ions identifiable as O^{2+} and O^{3+}. Surprisingly, in some of these examples the ionization state is mixed showing that part of the plasma escaped the corona without attaining the usual million-degree temperatures while other parts were heated more nearly in the normal manner. Additionally, detailed studies of the minor ions have increased our understanding of the coronal expansion. For example, such studies have contributed to identifying near equatorial coronal streamers as the source of solar wind flows between high speed streams.

INTRODUCTION

Since the Burghausen Solar Wind 4 Conference in 1978, a number of new observations and studies of solar wind minor ions have been reported. This survey discusses a few of these and some of their implications and mentions others more briefly. Some of the studies are treated in more detail elsewhere in this volume. The topics to be considered are listed below:

1. Abundance of $^4He^{++}$ and its variations.

2. Abundance of $^3He^{++}$ relative to $^4He^{++}$.

3. Minor ion temperatures and velocities.

4. Abundances from E/Q spectra of heavy ions.

5. Iron ions in high speed streams.

6. Ionization temperatures in high speed streams.

7. Ionizationally "hot" transient solar wind flows.

8. Ionizationally "cold" transient flows.

1. ABUNDANCE OF $^4He^{++}$ AND ITS VARIATIONS

Helium abundance variations have been studied using data obtained from Los Alamos plasma instrumentation on IMP 6, 7, and 8 in the years extending from 1971 through 1978. The study documents the association of different average abundance levels with different types of solar wind flows (Borrini et al., 1982a). As seen in Figure 1, low values of abundance are identified with those low speed, interstream flows in which polarity reversals of the interplanetary magnetic field (IMF) are embedded. Intermediate abundances are associated with high speed streams from coronal holes, as previously noted (Bame et al., 1977); abundance variations in streams are small. High abundances, of course, are associated with energetic coronal events; such an association with solar flares has been recognized and documented in many studies during the past 15 years.

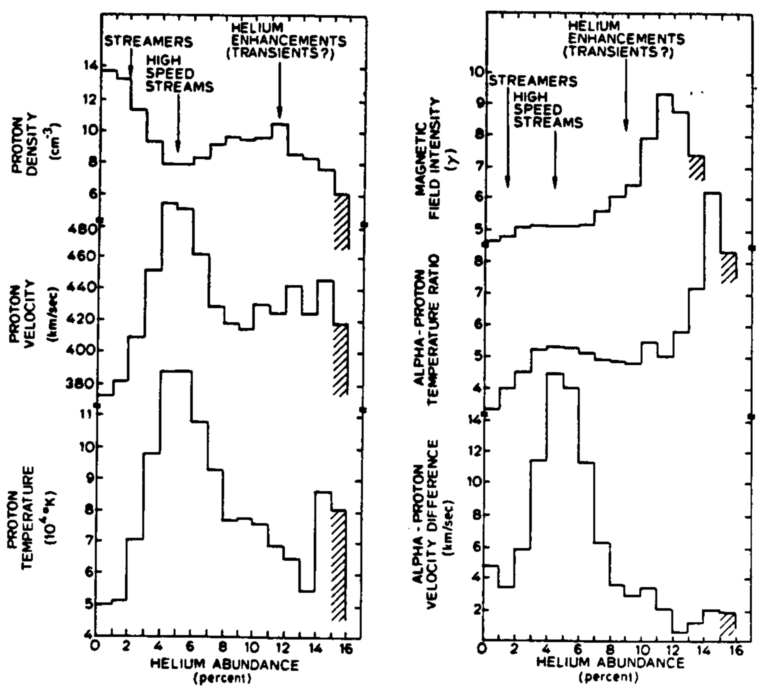

Fig. 1. Interplanetary solar wind flow characteristics associated with varying levels of the helium abundance. Low values of abundance are associated with low speed flows which can be identified with coronal streamers, median values can be identified with high speed streams arising in coronal holes, and high values can be identified with transient flows from various kinds of energetic coronal events.

Earlier studies of the solar cycle variation of the helium abundance (e.g. Bame, 1972; Ogilvie and Hirshberg, 1974; Feldman et al., 1978) have been extended using IMP 6, 7, and 8 plasma results (Borrini et al., 1982a). The IMP data, shown in Figure 2, exhibit a continuing modulation which reached a minimum in 1975-76 and was sharply rising in 1977-78, 11 years after a similar rise observed in 1966-67. An important part of this modulation is due to solar cycle changes in the mix of different types of solar wind, i.e. the low speed interstream flows with low He abundances, the high speed streams with intermediate values, and transient flows from energetic coronal events which have the highest abundances, and which, of course, occur more frequently when the sun is active.

The characteristics of solar wind flows containing helium abundance enhancements, HAEs, previously known to be associated with transient coronal disturbances, have been systematized using a superposed epoch analysis of 73 large events which occurred during 1972-78 (Borrini et al., 1982b). Nearly 50% of the HAEs were associated with interplanetary shocks and/or geomagnetic sudden commencements, but the plasma pattern associated with HAEs occurs whether or not a shock or SC is observed.

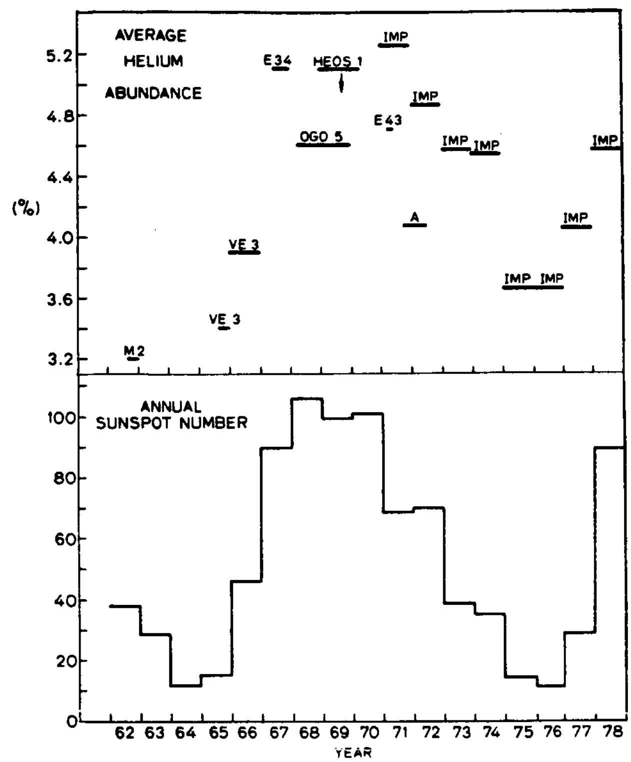

Fig. 2. Solar cycle variation of the solar wind helium abundance. Average values observed with various spacecraft are compared with the annual sunspot number.

Low levels of the He abundance are associated with the low speed solar wind, or interstream flows, which in turn are associated with IMF polarity reversals. Noting this, and tracing the low speed wind back to the corona, it is possible to identify the coronal equatorial streamer belt as the source of interstream flows (Borrini et al., 1981; Gosling et al., 1981). In these cool, low speed flows, minimums in the abundance are associated with maximums in proton density, identifying a large fraction of the flows as noncompressive density enhancements, NCDEs, in which polarity reversals often occur. The duration and multiplicity of reversal events are generally correlated, when mapped back to the sun, with the local tilt of the streamer belt to the solar equator.

Another study, making use of Vela 5 and 6 heavy ion measurements, also identifies the streamer belt as the source of interstream solar wind flows (Feldman et al., 1981). It was shown that moderate to high plasma densities and oxygen freezing-in temperatures in interstream flows match similar conditions within coronal streamers close to the sun. It was also shown that high solar wind electron temperatures at 1 AU arise from a lower coronal temperature gradient, rather than from a higher coronal temperature.

2. ABUNDANCE OF $^3He^{++}$ RELATIVE TO $^4He^{++}$

Until recently only a few $^3He^{++}/^4He^{++}$ abundance ratio measurements have been available. Those from ion E/Q analyzers are rare because of the infrequent occurrence of interplanetary conditions appropriate for resolving $^3He^{++}$, using E/Q analysis alone. Values of 1.3×10^{-3} and $\sim 3 \times 10^{-3}$ for measurement periods of ~1 hour have been reported (Bame et al., 1968; Bame et al., 1979); another value of 1.9×10^{-3}, measured during an interval of two days, has been reported by Grünwaldt (1976). Longer term measurements were obtained by exposing Al foils on the moon during 5 Apollo flights, and then analyzing gases released from the returned foils (Geiss et al., 1972). Remarkably similar results were obtained from the 5 flights, yielding an average value of the $^3He/^4He$ number ratio of 4.2×10^{-4}.

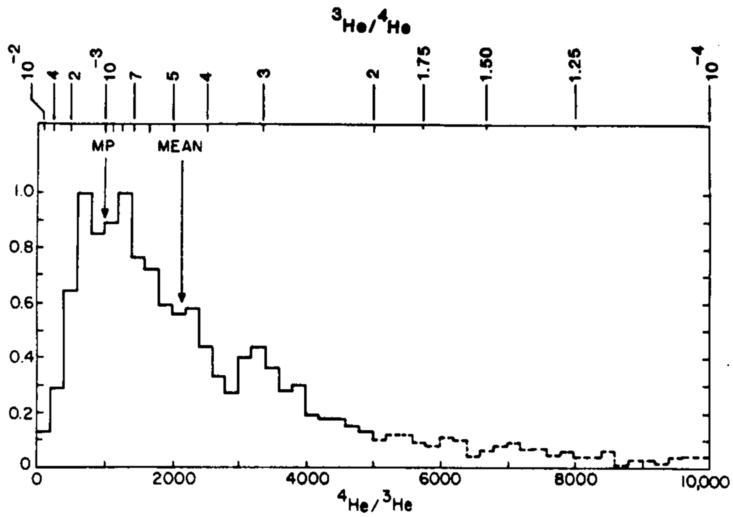

Fig. 3. Abundance level comparisons of ^3He and ^4He ions from 4334 spectra measured over two periods from August 18 to November 24, 1978 and March 24 to August 25, 1979.

Long term measurements reported by Ogilvie et al. (1980a) were made with an M/Q composition analyzer on ISEE 3 (Coplan et al., 1978). As seen in Figure 3, these results show that $^3He/^4He$ is extremely variable, ranging from $<10^{-4}$ to values as high as 10^{-2}. The most probable value measured is $\sim 1 \times 10^{-3}$, very near to the first reported value of 1.3×10^{-3}. Also noteworthy, the average value of these extended observations, 4.7×10^{-4}, is not far different from the average value obtained by Geiss and his coworkers from the five Apollo foil experiments. Another result of the study reported by Ogilvie et al. (1980a) shows that there is a discernible trend for $^3He^{++}/^4He^{++}$ to be lower when the $^4He^{++}$ flux is high.

3. MINOR ION TEMPERATURES AND VELOCITIES

Systematic studies of the local temperatures and velocities of minor ions have been reported by Schmidt et al. (1980), Ogilvie et al. (1980b), and Ogilvie et al. (1982). Briefly, these studies show that on the average the temperatures of minor ions are roughly proportional to the atomic mass of the ion species, i.e. T_i/M_i = constant. However, in individual cases there are significant deviations from this proportionality. In particular, the results obtained with the ISEE 1 M/Q analyzer described by Shelley et al. (1978) show that although the proportionality still holds for He^{++} and O^{6+} at low temperatures, it breaks down for H^+.

Concerning minor ion velocities, the results of the studies show that except for H^+, all ion species have very nearly the same velocities. Speed differences between a minor ion such as O^{6+} and H^+ are then like the well documented differences between He^{++} and H^+ (e.g. Asbridge et al., 1976). Using measurements from the ISEE 3 M/Q analyzer (Coplan et al., 1978), Ogilvie et al. (1982) give examples of He^{++}-H^+ speed differences across several high speed streams. In an unusual case, following an interplanetary shock, the post-shock H^+ ions were found travelling faster than the He^{++} ions for some hours, a reversal of the usual roles of those two ions at high speeds.

4. ABUNDANCES FROM E/Q SPECTRA OF HEAVY IONS

An observation of an enrichment of O^{6+} simultaneously with an abundance increase of He^{++} in the driver gas of an interplanetary shock has been reported by Bonifazi et al. (1980). It seems reasonable to suppose that if there is a helium enrichment, there should also be corresponding enrichments of other heavier elements, and indeed such a result has also been reported for three other transient flows (Zwickl et al., 1982). A note of caution should be given concerning the universality of this result in regard to a single ion species such as O^{6+}. If the ionization temperature of the driver plasma is high enough, the O^{6+} abundance may actually turn out to be lower because the enhanced oxygen will exist principally in the O^{8+} and O^{7+} charge levels. Examples of O^{6+} depletions, occurring on 19 November 1970 and 18 May 1971 have been given by Bame et al. (1979).

Further observations of heavy ion E/Q spectra have been reported from measurements made with the ISEE 2 solar wind experiment (Formisano and Orsini, 1981) and with the Prognoz 7 plasma spectrometer (Zastenker and Yermolaev, 1981). Unusually high abundances compared to previous measurements were cited in both reports. In the case of the ISEE 2 measurements it seems likely that the high abundance values may be, at least in part, due to counting rate losses in the proton peak. In two of the examples given, the proton peaks are double. If the double peaks were the result of a double stream, such as those observed during the declining phase of high speed streams (Feldman et al., 1973), the He^{++} peaks would probably also be double, as reported by Asbridge et al. (1974). In these examples the resolution is high enough to reveal that double He^{++} peaks are not present. Thus, it seems possible that the dips between the H^+ peaks in the ISEE 2 spectra are due to count rate saturation effects, so the high abundances cited should be viewed with caution. In the case of the Prognoz 7 measurements, which also give abundance values an order of magnitude higher than previous values, not enough information is available to determine whether a similar count rate saturation effect might be responsible for the unusually high results. It is clear that there is a great need for future solar wind composition experiments capable of operating in all types of solar wind flows for extended periods of time, in order to catalogue the extent of abundance variations.

5. IRON IONS IN HIGH SPEED STREAMS

First measurements of the abundance of iron ions in high speed solar wind streams have been reported by Mitchell and Roelof (1980). Abundance determinations from E/Q spectral measurements have not been possible due to the high kinetic ion temperatures in streams and/or insufficient energy range of the electrostatic analyzers which have been flown. Correspondingly, magnetic mass analyzers have not been able to cover the appropriate range due to limitations in available magnetic field strengths.

The results of Mitchell and Roelof come from an analysis of data from the NOAA/JHU energetic particles experiment on IMP 7 and 8 (Williams, 1977) which is sensitive to iron ions at speeds above 600 km s^{-1}. Principal results from this study will be mentioned only briefly here, since the subject is covered more extensively elsewhere in this volume. Estimates of the Fe/H abundance ratio in high speed flows show it to be roughly the same as the nominal coronal abundance. There is evidence that abundance fluctuations in streams may, like those of He, be smaller than in slow and in transient flows, as determined from E/Q measurements. Further results show that the Fe ions generally are faster than H^+, but slower than He^{++} (Mitchell et al., 1981). In general, the Fe distribution parameters (bulk velocity, flow direction, temperature) are found to be similar to the He parameters determined with electrostatic analyzers (Mitchell et al., 1982). There are factor-of-two differences between average abundances determined in recurrent streams from different coronal holes. Similar to the He enhancements seen in flare related flows, Fe enhancements of 4-5 are also observed.

6. IONIZATION TEMPERATURE IN HIGH SPEED STREAMS

Temperatures at which the ionization states of minor ions are established or frozen in during the coronal expansion were reported in a number of early papers (e.g. Bame et al., 1968; 1970; 1974). These determinations, based on measurements of individual minor ion peak intensities in E/Q spectra, are restricted to the slow interstream solar wind in which the local kinetic temperatures are low or to the temperature-depressed drivers of transient flows coming from energetic coronal events (Bame et al., 1979; Fenimore, 1980). It is of particular interest to extend such determinations to the case of high speed solar wind streams arising out of coronal holes, since the holes have been observed to be cooler than other regions of the corona (Krieger et al., 1973). Until recently, it has not been possible to measure the ionization states of high speed flows. In those flows the kinetic temperatures are so high that individual minor ion species such as O^{6+} and O^{7+} can't be resolved in E/Q spectra. The Fe ion distribution has been inaccessible due to limited energy ranges.

This restriction has been overcome with two new experimental approaches. The first of these utilizes the ion composition experiment on ISEE 3, described by Coplan et al. (1978), with which M/Q analyses of some of the minor ions can be performed on high speed flows as well as slow flows. Ogilvie and Vogt (1980) have used ISEE 3 data to investigate the oxygen ion freezing-in temperatures by determining the ratios of ion fluxes at M/Q = 2.29 (principally O^{7+}) to that at M/Q = 2.67 (principally O^{6+}) as a function of solar wind speed, and comparing the ratios with ionization equilibrium calculations. At low speeds ionization temperatures of $\sim 1.6 \times 10^6$ K are inferred, in reasonable agreement with previous determinations using E/Q analyses. However, at speeds above 450 km s^{-1}, i.e. in high speed streams, the measured ratio starts to rise rapidly, suggesting higher freezing-in temperatures in coronal holes. Values above 3×10^6K are inferred for 600 km s^{-1} speeds. The authors suggest that these results might be caused, not by a higher freezing-in temperature, but by electron distributions in coronal holes characterized by a temperature of 1.5×10^6K, but having a non-Maxwellian high energy tail similar to that of a 3×10^6K distribution.

The second experimental approach utilizes the intermediate energy ion composition experiment on ISEE 1, described by Hovestadt et al. (1978). By analyzing the shapes of charge state distributions of CNO ions in diffuse ion events upstream of the bow shock, Galvin et al. (1982) infer ionization temperatures for the types of solar wind flow incident at the bow shock. They find temperatures of $\sim 1.5 \times 10^6$K for slow, interstream solar wind, $\sim 2.5 \times 10^6$K for flare-related transient flows, and $\sim 1.4 \times 10^6$K for coronal hole-associated flows.

Further analysis of the ISEE 3 oxygen charge state data has insured that the high speed data set is not contaminated with shock associated events. The extended study confirms that the M/Q = 2.3 to M/Q = 2.7 ratio rises at speeds above 450 km s^{-1} (Ogilvie, 1982). Some part of this rise may be due to variations in the relative abundances of elements in the CNO region of the spectrum which contribute to the O^{7+} fraction in particular. However, it is concluded that this effect is not large enough to avoid having to infer high coronal tempertures unless a non-Maxwellian shape of the electron distribution in the source region is invoked. It is clear that further work on this important subject is essential.

7. IONIZATIONALLY HOT TRANSIENT SOLAR WIND FLOWS

Following flare-related interplanetary shock waves, driver or piston flows are sometimes observed with very unusual distributions of minor ions in the E/Q spectra measured with electrostatic analyzers. These spectra show that the plasma had a "hot" origin in the solar corona (Bame et al., 1979; Bame, 1981). This is not always the case in driver flows; sometimes the spectrum cannot be distinguished from those found in the slow, interstream solar wind, and sometimes, as discussed in the next section, IP shocks are followed by driver flows which contain ions indicative of a "cold" origin.

In Figure 4 an example of a hot E/Q spectrum is contrasted with a normal spectrum obtained in a slow interstream flow. The hot case was measured with a heavy ion analyzer on Vela 6B and the normal example on Vela 5A. The two spectra have been normalized to E/Q = 2 at the $^4He^{++}$ peaks and are shown plotted on an M/Q scale which assumes equal flow speed for all ion species.

In the upper spectrum from slow interstream solar wind, a typical distribution of ion peaks is evident beyond $^4He^{++}$. Both O^{7+} and O^{6+} are prominent, with unresolved species of C, N, and Ne between them. A fit of the peaks gives a freezing-in temperature of 2.1×10^6K, typical of slow flows. Beyond the oxygen peaks are three peaks, C, D, and E that can be attributed to silicon with an admixture of sulfur. Beyond the Si peaks lies a group of Fe peaks ranging from 12+ to 7+, with a distribution which was formed at $\sim 1.5 \times 10^6$K in the corona, again typical of a slow flow.

The lower spectrum, labelled "hot," in Figure 4 shows a distinctively different shape which has been shown to be due to a hotter than normal origin of the ionization state. This spectrum was obtained in the driver flow of an IP shock which followed a flare, variously reported as importance 1B to 3B, by 64 hours. The typical Fe species in the 12+ to 7+ charge level positions are not present at resolvable levels. Instead, a reasonable analysis shows that the Fe ionization state has shifted to a higher stage, indicative of a freezing-in temperature of $\sim 3 \times 10^6$K. The prominent peak at D in the figure is due to Fe^{16+} ions; the Si ions, normally found in this range are shifted into the Si^{12+} position, near O^{7+}. Another notable feature of hot spectra is that the normally third most prominent peak, O^{6+}, is very subdued, because most of the oxygen ions are in the O^{8+} and O^{7+} charge levels.

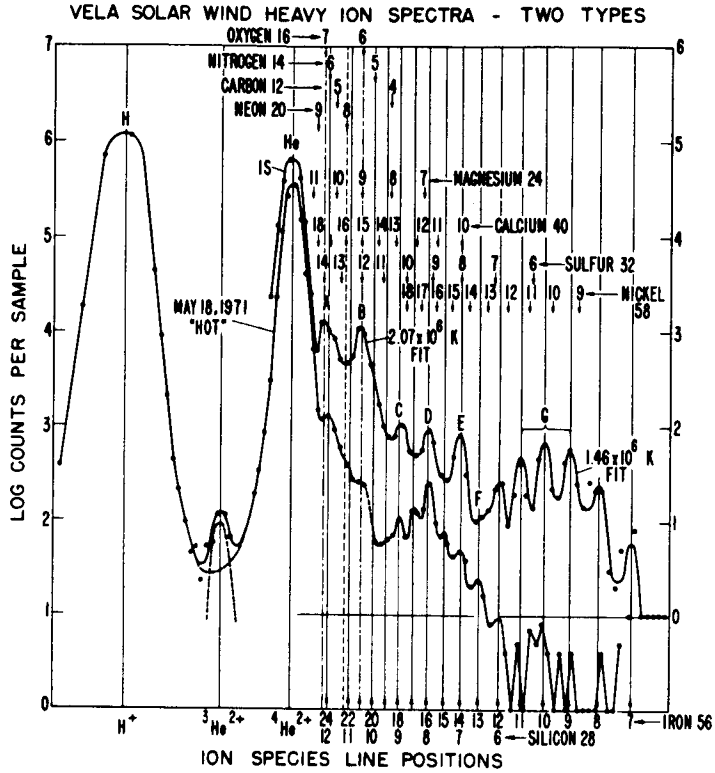

Fig. 4. A heavy ion spectrum from the slow interstream solar wind of June 23, 1969 (upper spectrum) measured with Vela 5A, contrasted with a hot spetrum measured on May 18, 1971 with Vela 6B in a flare induced, post shock, driver gas flow.

A systematic study of the types of solar wind flows associated with hot heavy ions has been reported by Fenimore (1980) using Vela 5 and 6 heavy ion data. Spectra indicating hot coronal conditions ranging from ~1.5 x 10^6K to above 9 x 10^6K are found in approximately 1/7 of the measurements. Hot spectra are found in three types of flows: 1) postshock flows, PSFs, 2) nonshock related helium abundance enhancements, HAEs, and 3) noncompressive density enhancements, NCDEs. The PSFs and HAEs are usually interplanetary manifestations of solar flares. In the case of the HAEs, the flare ejecta reach the Earth even though an IP shock is not observed. The NCDEs with hot heavy ions differ from the PSF-HAEs in several ways, suggesting that they evolve from energetic coronal events that are not flare-related but involve higher than normal coronal temeratures. Active regions, coronal mass ejections, and equatorial streamers are suggested as possible sources for the NCDEs with hot heavy ions.

8. IONIZATIONALLY COLD TRANSIENT FLOWS

The previous section discussed solar wind flows in which the minor ion relative intensity distributions show that the plasma ionization states were established in hotter than usual coronal regions. In the last few years a small number of observations have been reported which show that the opposite also occurs - minor ion distributions have been found which contain ions which could not have survived the usual million-degree temperature coronal expansion.

The first reported solar wind plasma with an anomalously "cold" origin was detected with electrostatic analyzers on HELIOS 1 and described by Schwenn et al. (1980). In the piston gas driving an IP shock on Jan. 29, 1977, very unusual spectra were found with three prominent peaks at relative E/Q positions of 1, 2, and 4 as shown in Figure 5. The peaks at 1 and 2 are readily identified as due to H^+ and He^{++} ions. The peak at 4 seemed too large to be explained by the ion species that usually occupy that position, Si^{7+} and S^{8+}. However, data are available from two different electrostatic analyzers on each of the two HELIOS spacecraft; one analyzer counts ions individually, while the other measures ion current. By normalizing spectra from the two instruments at the charge 1 H^+ peak, as shown in Figure 5, the charge of the second peak was found to be 2, as expected for He^{++}, while the charge of the third peak was approximately 1, instead of a high multiple such as 7. If the third peak had been due to the charge 7 and 8 Si and S ions, which normally occupy this position, the multiply charged ions would have created a sufficiently large current that the peak height in the electrometer spectrum would have been identifiably higher than in the counts spectrum, reaching near the arrow shown in the figure. Thus, the third peak was identified as singly charged He^+, which is at undectably low levels most of the time (Feldman et al., 1974).

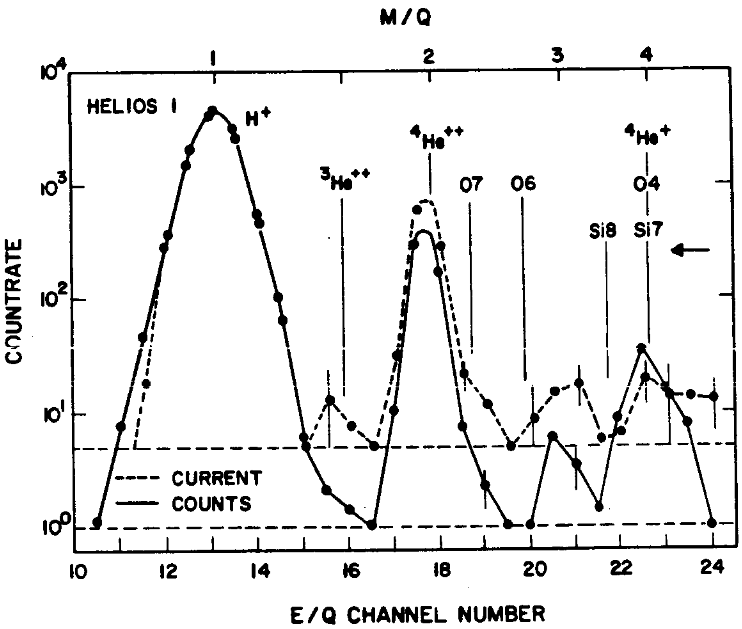

Fig. 5. Spectra measured simultaneously with two electrostatic analyzers on HELIOS 1, plotted together. Comparison of the spectrum determined by counting individual ions with the one using current detection identifies the peak at M/Q = 4 as He^+ rather than Si^{7+} which would produce a peak in the electrometer spectrum at the level shown by the arrow.

A few examples of the sporadic appearance of He^+ peaks in solar wind spectra were reported much earlier (Bame et al., 1968; Bame, 1972), but in those cases the He^+/He^{++} number ratios were much smaller than in the spectrum observed by Schwenn et al. (1980). No viable explanation for these sporadic appearances was set forth until the report of Schwenn and coworkers.

A second case of high flux levels of He^+ ions which occurred on July 29, 1977 was found in IMP 8 data and reported by Gosling et al. (1980). The interplanetary conditions associated with this event are illustrated in Figure 6 which shows a time sequence of E/Q spectra starting at 2358 UT on July 28, extending beyond 1444 UT on July 29. During this time period an IP shock passed IMP 8, leaving the spacecraft immersed in the heated ambient plasma. At

1224 UT the temperature-depressed driver gas arrived, in which the peaks of H^+ and He^{++} are sharply resolved. About 1 hour after the arrival of the driver gas, a third prominent peak appeared in the spectrum at an E/Q position four times that of H^+. The abundance of this peak is much too high to be explained plausibly by an ion species other than He^+. The He^+/He^{++} number ratio reached values as high as 0.3 during the event.

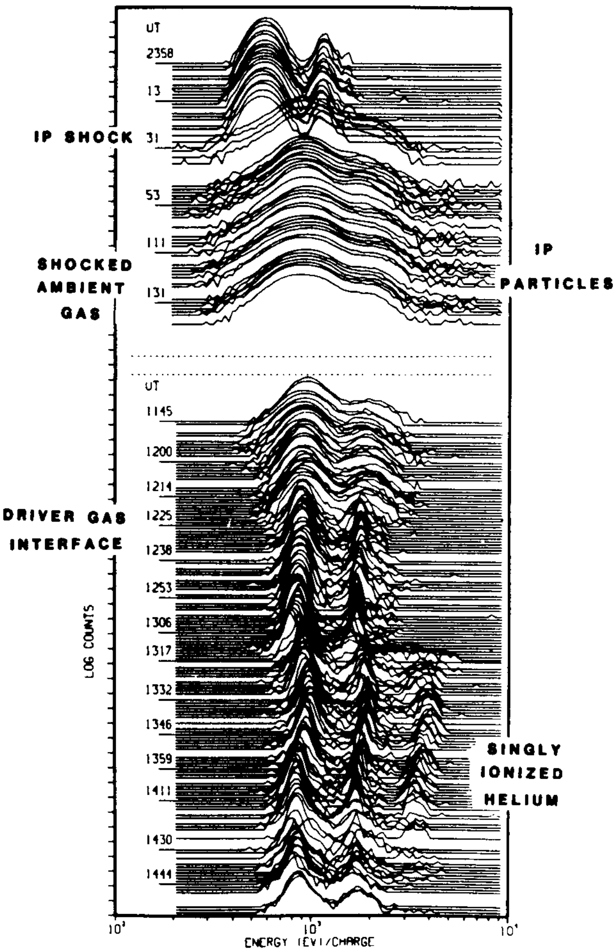

Fig. 6. Interplanetary conditions during the July 28-29, 1977 period. An IP shock heated and accelerated the ambient flow. Interplanetary ions associated with the shock passage are evident in the heated flow, creating the noise-like traces at low and high energies surrounding the H^+ and He^{++} peaks. The arrival of driver gas is marked by the sudden appearance of cold plasma with very well resolved H^+ and He^{++} peaks. About an hour later a strong third peak, due to He^+ ions, appears in the spectra.

An ion spectrum from this event, obtained by summing many of the individual spectra together is shown in Figure 7. Notable features of the spectrum in addition to the prominent third peak are the resolved peak of O^{6+} ions and the broadness of the He^+ peak compared to the He^{++} peak. No reason has been found for why the He^+ ions in this example should have a higher kinetic temperature than those of He^{++}, as they apparently do.

A study of a large number of heavy ion spectra obtained with the Vela 5A, 5B, 6A, and 6B analyzers during 1969-1975 has yielded some seven events with anomalously high numbers of counts at the M/Q = 4 position (Bame, 1980) Many more events would have been observed if fuller telemetry coverage in the solar wind had been available. The numbers of He^+ ions in these Vela events were small in comparison to the numbers in the large events mentioned above.

A systematic search of Los Alamos IMP and ISEE data received between October 1972 and February 1980 found two more events in addition to those already mentioned (Zwickl et al., 1982). The IMP and ISEE experiments were designed with sensitivities for standard solar wind ion measurements rather than for detecting low countrate exotic ions. More events would certainly have been found with more sensitive instrumentation and more complete telemetry coverage.

The most recent large He^+ event was found in HELIOS 2 data of May 29, 1979 (Schwenn, 1980; 1982). In this case, a charge 1 peak was again found at an E/Q position 4 times the position occupied by H^+.

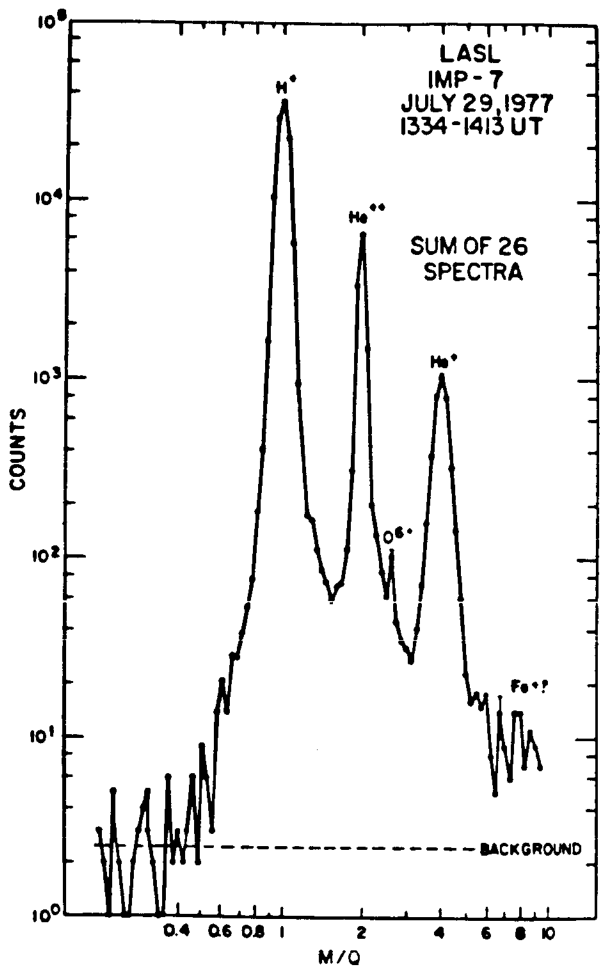

Fig. 7. Summed IMP 7 spectra showing the strong third peak of He^+ ions at M/Q = 4.

One other He^+ event, detected with the Vela 3A plasma analyzer on January 13, 1967 (Bame, 1980), is shown in Figure 8. The measured E/Q spectra are shown in time sequence vertically. The first spectrum shows a plasma flow with uncommonly well resolved H^+ and He^{++} peaks; most likely this flow is an anomalously cool driver gas from an energetic coronal event. In the second spectrum, a peak at an E/Q position 4 times that of H^+ shows the presence of He^+ ions in the flow. At 1150 UT a small amount of He^+ is still present. At 1207 UT an IP shock had passed the spacecraft leaving the ambient gas accelerated and heated. In succeeding spectra the continued presence of He^+ is evident, although the high temperature of the gas prevents complete resolution of He^+ from He^{++}. In the later stages of the event, the proton bulk speed in the shocked gas was appreciably higher than that of the He ions; another case of H^+ ions travelling at a higher speed than He^{++}, following a shock passage, has been reported by Ogilvie et al. (1982). At 1839 UT, the He^+ number density is roughly 50% that of He^{++}. By 0027 UT on January 14 a new body of gas, the driver for the January 13 shock, had arrived. In this driver, which can be associated with a 3B flare, there is no longer a component of He^+. Instead, a well resolved peak at a relative E/Q position of 3.5 shows that this driver contained Fe^{16+} ions originating in a hot coronal region (Bame et al., 1979).

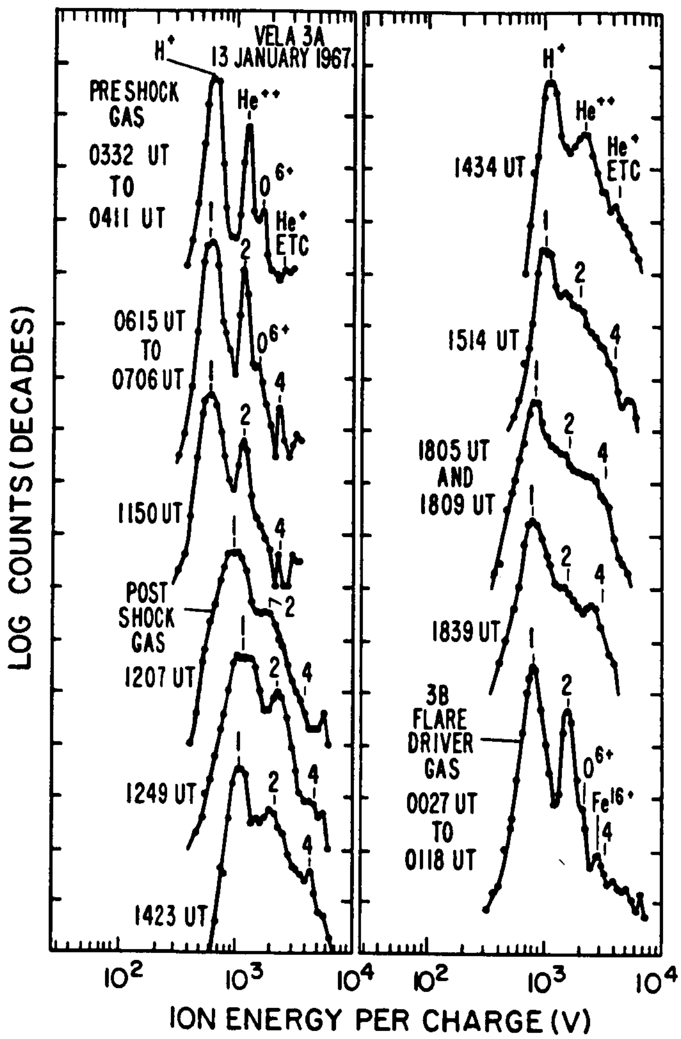

Fig. 8. Sequence of spectra from Vela 3A and 3B showing the appearance of a small narrow peak of He^+ ions early on January 13, 1967. Following an interplanetary shock at about noon, the He^+ abundance in the ambient plasma increased to levels high enough that the presence of He^+ ions is evident, even though the ion temperature is too high to permit full resolution. At 1839 UT the spectrum indicates that the He^+/He^{++} number ratio is roughly 50%.

The sources of ionizationally cold flows seem well established as energetic coronal events, generally without a flare association. Including the seven small He^+ events found in Vela heavy ion data and the other events mentioned above, there is strong evidence of a correlation of the events with phenomena which are associated with impulsive coronal events, i.e. mass ejections. Many, but not all events followed IP shocks and most are associated with Forbush decreases. There is a strong association with Type II and IV radio emissions, but there is no association with flares for several of the large events. Schwenn et al. (1980) suggest the possibility of direct ejection of cool chromospheric plasma into the solar wind via eruptive prominences (disappearing filaments when observed against the solar disk). Indeed, correlations of eruptive prominences with He^+ events are found for the events of January 29, 1977, July 29, 1977, May 29, 1979, and January 13, 1967. There are possible associations for some of the remaining 10 events; in the others there is not enough information to make a determination. There are flare associations with some of the events which is perhaps not surprising since an association between flares and disappearing filaments has been noted.

The spectra of two of the He^+ events discussed above also show the presence of oxygen ions in low stages of ionization. Schwenn (1980; 1982) reported the observation of two E/Q spectra on May 9, 1979 which exhibited four strong peaks at E/Q values of 1, 2, 4, and 8 relative to H^+, as shown in Figure 9. Comparing the spectrum obtained by counting individual ions with one obtained by measuring the charge deposited by the analyzed ions, it was possible to show that the ion charges of the four peaks were 1, 2, 1, and 2, identifying the ions as H^+, He^{++}, He^+, and O^{2+}. This spectrum was obtained in a transient flow which was very well associated with a nonflare-related explosive prominence.

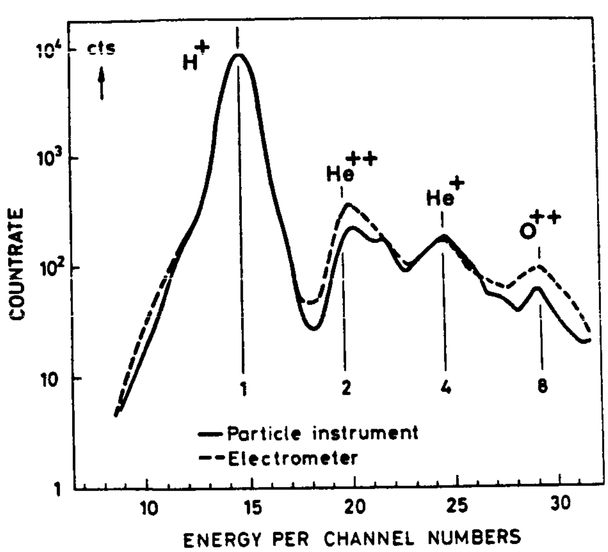

Fig. 9. Spectra measured simultaneously with two electrostatic analyzers on a HELIOS spacecraft. Comparison of the particle counting spectrum with that obtained by measuring current shows that the peaks at 4 and 8 are He^+ and O^{++}.

The second case of a spectrum with oxygen in low ionization stages was reported by Zwickl et al. (1982) and is shown in Figure 10, contrasted with a more normal high density flow. In the upper panel, envelopes which reasonably encompass the Si peaks and Fe peaks are shown. Generally, these minor ion groups in spectra measured in slow solar wind can be fitted rather well with smooth envelopes which are somewhat broader than an isothermal fit would predict. The greater broadness has been attributed to the fact that the ratios of adjacent pairs of ion species are established at different heights in the corona and hence different temperatures (Bame et al., 1970). In the lower, anomalous spectrum, reasonable envelopes for the Si and Fe species have been drawn. It is apparent that three of the peaks are far outside of the envelopes and can best be explained as being due to He^+ (with some O^{4+}), O^{3+}, and O^{2+}. Another ion indicative of a colder than normal origin is prominent, C^{4+}, and

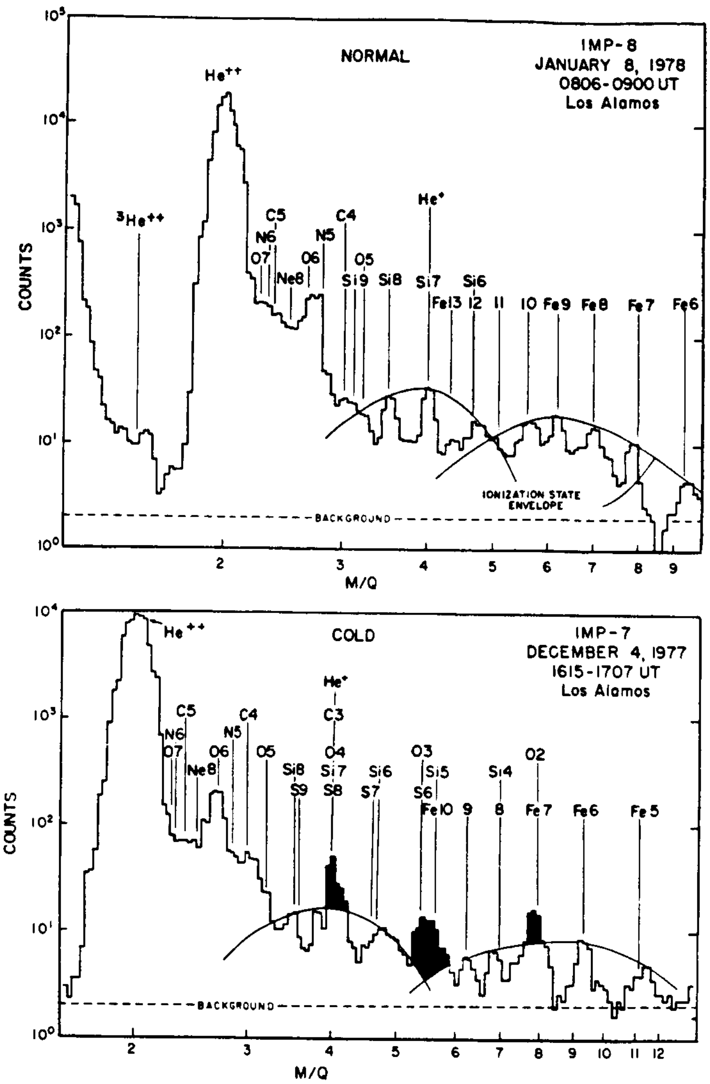

Fig. 10. Two spectra from IMP 7 and 8 obtained by adjusting for speed changes and summing E/Q spectra together. The upper normal spectrum is a somewhat cool example since C^{4+} ions are present. Well-behaved ionization state envelopes can be fit to the Si and Fe species peaks in the normal spectrum. In the lower cold spectrum C^{4+} ions are again present, but in addition reasonable ionization state envelopes do not encompass three prominent peaks. The surplus ions in these peaks can be best identified as He^{+} (with some O^{4+}), O^{3+}, and O^{2+}.

possibly N^{5+} and O^{5+}. There is evidence of some C^{4+} in the January 8, 1978 spectrum in the upper panel, as well, and indeed this spectrum, although not cold like the lower spectrum, is somewhat cooler than most of the minor ion spectra which have been obtained in low speed flows. The December 4, 1977 cold spectrum was possibly associated with a disappearing filament. It was not associated with an IP shock.

ACKNOWLEDGMENTS

This report was prepared under the auspices of the U.S. Department of Energy.

References

- Asbridge, J. R., S. J. Bame, and W. C. Feldman, Abundance Differences in Solar Wind Double Streams, Solar Phys., 37, 451, 1974.
- Asbridge, J. R., S. J. Bame, W. C. Feldman, and M. D. Montgomery, Helium and Hydrogen Velocity Differences in the Solar Wind, J. Geophys. Res., 81, 2719, 1976.
- Bame, S. J., Spacecraft Observations of the Solar Wind Composition, in Solar Wind, edited by C. P. Sonett, P. J. Coleman, and J. M. Wilcox, NASA SP-308, p. 535, 1972.
- Bame, S. J., Vela Observations of He^+ Ions in the Solar Wind, Workshop on Ion Composition of Space Plasma, Deutsche Forschungsgemeinschaft and Max Planck Society, Göttingen-Lindau, West Germany, August 26-29, 1980.
- Bame, S. J., Solar Wind Heavy Ions from Energetic Coronal Events, in Solar Wind Four, edited by H. Rosenbauer, Report No. MPAE-W-100-81-31, Max Planck Institut für Aeoronomie, Max Planck Institut für Extraterrestrische Physik, 1981.
- Bame, S. J., A. J. Hundhausen, J. R. Asbridge, and I. B. Strong, Solar Wind Ion Composition, Phys. Rev. Lett., 20, 393, 1968.
- Bame, S. J., J. R. Asbridge, A. J. Hundhausen, and M. D. Montgomery, Solar Wind Ions: Fe^{+8} to Fe^{+12}, Si^{+7}, Si^{+8}, Si^{+9}, and O^{+6}, J. Geophys. Res., 75, 6360, 1970.
- Bame, S. J., J. R. Asbridge, W. C. Feldman, and P. D. Kearney, The Quiet Corona: Temperature and Temperature Gradient, Solar Phys., 35, 137, 1974.
- Bame, S. J., J. R. Asbridge, W. C. Feldman, and J. T. Gosling, Evidence for a Structure-Free State at High Solar Wind Speeds, J. Geophys. Res., 82, 1487, 1977.
- Bame, S. J., J. R. Asbridge, W. C. Feldman, E. E. Fenimore, and J. T. Gosling, Solar Wind Heavy Ions from Flare-Heated Coronal Plasma, Solar Phys., 62, 179, 1979.
- Bochsler, P. and J. Geiss, Cross- and Autocorrelations of Speeds and Kinetic Temperatures of Minor Ions in the Solar Wind, Trans. Am. Geophys. Union, EOS, 63, 424, 1982.
- Bonifazi, C., A. Egidi, and G. Moreno, Observation of Oxygen-Enriched Plasma in the Driving Piston of a Flare-Generated Shock Wave, Lett. al Nuovo Cimento, 28, 39, 1980.
- Borrini, G., J. T. Gosling, S. J. Bame, W. C. Feldman, and J. M. Wilcox, Solar Wind Helium and Hydrogen Structure Near the Heliospheric Current Sheet: A Signal of Coronal Streamers at 1 AU, J. Geophys. Res., 86, 4565, 1981.
- Borrini, G., J. T. Gosling, S. J. Bame, and W. C. Feldman, Helium Abundance Variations in the Solar Wind, Solar Phys., to be published, 1982a.
- Borrini, G., J. T. Gosling, S. J. Bame, W. C. Feldman, Helium Abundance Enhancements in the Solar Wind, J. Geophys. Res., 87, 7370, 1982b.
- Coplan, M. A., K. W. Ogilvie, P. A. Bochsler, and J. Geiss, Ion Composition Experiment, IEEE Trans. Geosci. Electron., GE-16, 185, 1978.
- Feldman, W. C., J. R. Asbridge, S. J. Bame, and M. D. Montgomery, Double Ion Streams in the Solar Wind, J. Geophys. Res., 78, 2017, 1973.
- Feldman, W. C., J. R. Asbridge, S. J. Bame, and P. D. Kearney, Upper Limits for the Solar Wind He^+ Content at 1 AU, J. Geophys. Res., 79, 1808, 1974.
- Feldman, W. C., J. R. Asbridge, S. J. Bame, and J. T. Gosling, Long-Term Variations of Selected Solar Wind Properties: IMP 6, 7, and 8 Results, J. Geophys. Res., 83, 2177, 1978.
- Feldman, W. C., J. R. Asbridge, S. J. Bame, E. E. Fenimore, and J. T. Gosling, The Solar Origins of Solar Wind Interstream Flows: Near-Equatorial Coronal Streamers, J. Geophys. Res., 86, 5408, 1981.

- Fenimore, E. E., Solar Wind Flows Associated With Hot Heavy Ions, Astrophys. J., 235, 245, 1980.
- Formisano, V. and S. Orsini, Quiet-Time Solar-Wind Ionic Composition, Nuovo Cimento, 4C, 682, 1981.
- Galvin, A. B., F. M. Ipavich, and G. Gloeckler, Solar Wind Ionization Temperatures Inferred From the Charge State Analysis of Diffuse Ion Events, Trans. Am. Geophys. Union, EOS, 63, 4242, 1982.
- Geiss, J., F. Bühler, H. Cerutti, P. Eberhardt, and C. Filleux, Apollo 16 Preliminary Science Report, NASA SP-315, Nat. Aeoronaut. and Space Admin., p. 14-1, 1972.
- Gosling, J. T., J. R. Asbridge, S. J. Bame, W. C. Feldman, and R. D. Zwickl, Observations of Large Fluxes of He^{+} in the Solar Wind Following an Interplanetary Shock, J. Geophys. Res., 85, 3431, 1980.
- Gosling, J. T., G. Borrini, J. R. Asbridge, S. J. Bame, W. C. Feldman, and R. T. Hansen, Coronal Streamers in the Solar Wind at 1 AU, J. Geophys. Res., 86, 5438, 1981.
- Grünwaldt, H., Solar Wind Composition from the Helios 2 Plasma Experiment, Space Research, XVI, 681, 1976.
- Hovestadt, D., G. Gloeckler, C. Y. Fan, L. A. Fisk, F. M. Ipavich, B. Klecker, J. J. O'Gallagher, M. Scholar, H. Arbinger, J. Cain, H. Höfner, E. Künneth, P. Laeverenz, and E. Tums, The Nuclear and Ionic Charge Distribution Particle Experiments on the ISEE-1 and ISEE-C Spacecraft, IEEE Trans. on Geosci. Electron., GE-16, 166, 1978.
- Krieger, A. S., A. F. Timothy, and E. C. Roelof, Solar Phys., 29, 505, 1973.
- Mitchell, D. G., and E. C. Roelof, Thermal Iron Ions in High Speed Solar Wind Streams: Detection by the IMP 7/8 Energetic Particle Experiments, Geophys. Res. Letters, 7, 661, 1980.
- Mitchell, D. G., E. C. Roelof, W. C. Feldman, S. J. Bame, and D. J. Williams, Thermal Iron Ions in High Speed Solar Wind Streams, 2. Temperatures and Bulk Velocities, Geophys. Res. Letters, 8, 827, 1981.
- Mitchell, D. G., E. C. Roelof, and S. J. Bame, Solar Wind Iron Abundance Variations at Solar Wind Speeds >600 km s^{-1}, 1972-1976, Trans. Am. Geophys. Union, EOS, 63, 1088, 1982.
- Ogilvie, K. W., Coronal Temperatures and Oxygen Charge States, Trans. Am. Geophys. Union, EOS, 63, 1088, 1982.
- Ogilvie, K. W. and J. Hirshberg, The Solar Cycle Variation of the Solar Wind Helim Abundance, J. Geophys. Res., 75, 4595, 1974.
- Ogilvie, K. W., M. A. Coplan, P. Bochsler, and J. Geiss, Abundance Ratios of $^4He^{++}/^3He^{++}$ in the Solar Wind, J. Geophys. Res., 85, 6021, 1980a.
- Ogilvie, K. W., P. Bochsler, J. Geiss, and M. A. Coplan, Observations of the Velocity Distribution of Solar Wind Ions, J. Geophys. Res., 85, 6069, 1980b.
- Ogilvie, K. W., and C. Vogt, Variation of the Average 'Freezing-In' Temperature of Oxygen Ions with Solar Wind Speed, Geophys. Res. Letters, 7, 577, 1980c.
- Ogilvie, K. W., M. A. Coplan, and R. D. Zwickl, Helium, Hydrogen, and Oxygen Velocities Observed on ISEE-3, J. Geophys. Res., 87, 7363, 1982.
- Schmidt, W. K. H., H. Rosenbauer, E. G. Shelly, and J. Geiss, On Temperature and Speed of He^{++} and O^{6+} Ions in the Solar Wind, Geophys. Res. Letters, 7, 697, 1980.
- Schwenn, R., Observations of Unusual Solar Wind Heavy Ions, Workshop on Ion Composition of Space Plasma, Deutsche Forschungsgemeinschaft and Max Planck Society, Göttingen-Lindau, West Germany, August 26-29, 1980.

- Schwenn, Rainer, Direct Correlations Between Coronal Transients and Interplanetary Disturbances, presented at the Fifth International Symposium on Solar-Terrestrial Physics, Ottawa, Canada, May 1982.
- Schwenn, Rainer, Helmut Rosenbauer, and Karl-Heinz Mühlhäuser, Singly Ionized Helium in the Driver Gas of an Interplanetary Shock Wave, Geophys. Res. Letters, 7, 201, 1980.
- Shelley, E. G., R. D. Sharp, R. G. Johnson, J. Geiss, P. Eberhardt, H. Balsiger, G. Haerendel, and H. Rosenbauer, Plasma Composition Experiment on ISEE-A, IEEE Trans. on Geosci. Electron., GE-16, 266, 1978.
- Williams, D. J., The Ion-Electron Magnetic Separation and Solid State Detector Detection System Flown on IMP-7 and 8, NOAA Tech. Report ERL 393-SEL40 (U.S. Department of Commerce), October 1977.
- Zastenker, G. N., and Yu. I. Yermolaev, Observations of Solar Wind Stream with High Abundance of Heavy Ions and Relation with Coronal Conditions, Planet. Space Sci., 29, 1335, 1981.
- Zwickl, R. D., J. R. Asbridge, S. J. Bame, W. C. Feldman, and J. T. Gosling, He^+ and Other Unusual Ions in the Solar Wind: A Systematic Search Covering 1972-1980, J. Geophys. Res., 87, 7379, 1982.