HIGHLIGHTS OF SCIENTIFIC RESULTS FROM SMS THROUGHOUT THE WIND MISSION

The three sensors that comprise the SMS package all provide information on elemental, isotopic abundances and charge states, but each instrument has a different energy range and different measurement strengths. SMS results consist of previously unmeasured abundances as well as improved measurements of solar wind abundances and charge states.

We summarize the most exciting new results. For a more detailed list of results refer to the publication list at the end of this report.

Suprathermal Investigations Using Wind/STICS

Further work using the Wind/STICS dataset has also been conducted. We began by further verifying the dataset for accuracy and in order to increase the number of ions that are available for use. After this, we continued investigating the suprathermal population behavior near solar wind transitions, such as shocks. Early in this process, we noticed an issue. Due to the instrument efficiencies and the low density of the suprathermal populations, long time accumulations on the order of days were required to gather enough statistics for calculation of a distribution function. Long time accumulations are not ideal if one seeks to examine the short transitions between different types of solar wind, or any small-scale (in time) events, like shock fronts. Hence, we incorporate an adaptive cadence scheme into our data processing algorithm.

Suprathermal Heavy Ion Observations during ICMEs

The ionic charge state distribution calculated for a variety of atomic elements is useful in understanding the origin of observed plasma, as illustrated in the work focused on by the previously discussed charge state model. We began a study to investigate the origin of the suprathermal plasma. In order to investigate the origin of suprathermal ions present in ICMEs, we first began by characterizing a number of heavy ions in order to calculate their distribution functions from Wind/STICS data. In addition to protons, we are now capable of producing suprathermal distribution functions for a number of heavy ionic species, namely He^{2+}, He^{+}, C^{4+}, C^{5+}, C^{6+}, O^{6+}, O^{7+}, Fe^{8+}, Fe^{9+}, Fe^{10+}, Fe^{11+}, Fe^{12+}, Fe^{14+}, and Fe^{16+}. These heavy ions suffer from the same intermittent periods of short time accumulation distribution functions. Utilizing the adaptive cadence technique, we were able to determine a number of ICMEs in which short time accumulations suprathermal distribution functions could be obtained for all of the characterized heavy ions.

Figure 1 shows one such ICME, which was determined from the adaptive cadence technique, occurring on day-of-year 150 of 2003. We present a variety of the common plasma observations that illustrate the ICME time period as well as the suprathermal heavy ion data. The top three panels are all measured from the SWE instrument and show the bulk solar wind velocity, proton density, and the thermal velocity. The next two panels show data measured by the MFI instrument. First, we show the magnitude of the magnetic field followed by the direction of the magnetic field vector with the latitude in red and longitude in black. The last three panels are determined from the Wind/STICS distribution functions. First, we show the average oxygen charge state, then the average iron state, and finally the iron ionic distribution. The three vertical bars indicate different time periods occurring during the ICME. The dashed blue line indicates when the ICME-driven shock is observed. While the dashed magenta line indicates the beginning of the ICME plasma and the solid magenta line indicates the end. What is immediately noticeable in the iron ionic

distribution plot is that during the ICME plasma period the suprathermal iron charge states are composed of hotter charge states than outside the ICME period. This behavior is similar to what is commonly observed in the thermal plasma during ICMEs.

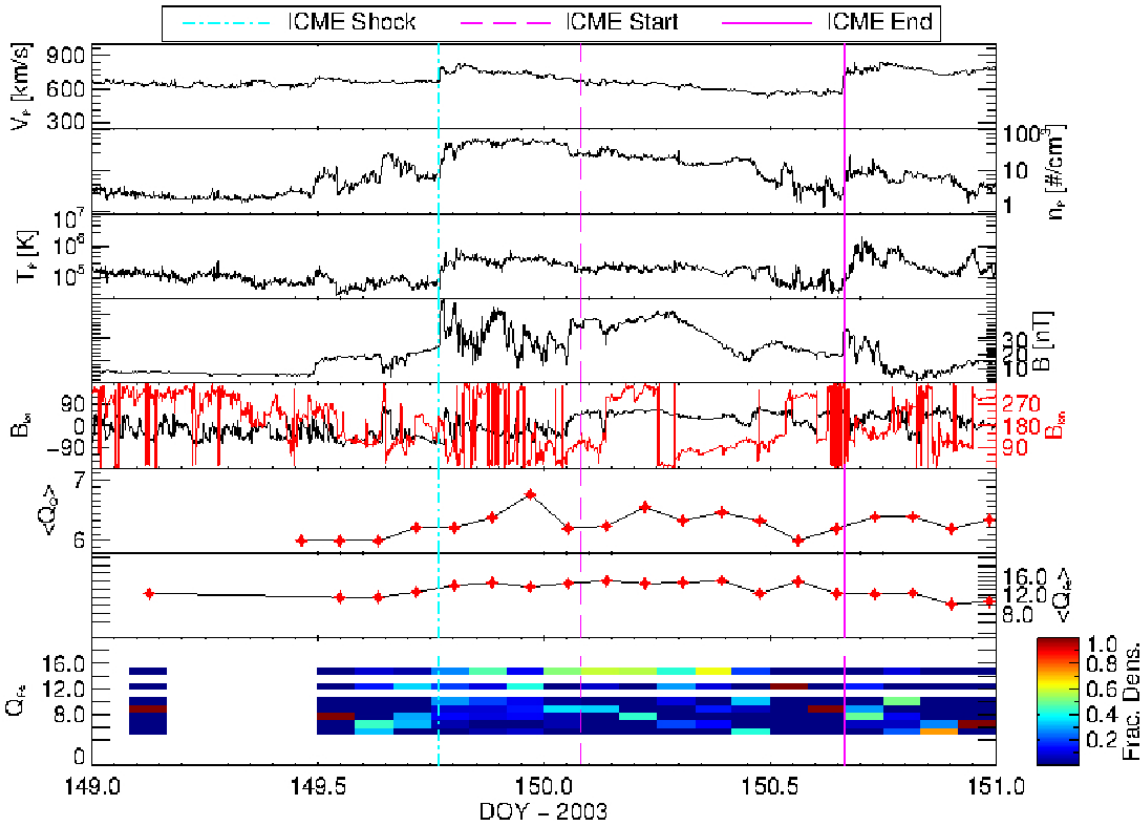

Figure 1. Plasma observations of an ICME observed by the Wind spacecraft on DOY 150 of 2003. From top to bottom we show the bulk velocity, proton density, thermal velocity, magnitude of magnetic field, magnetic field latitude and longitude, average oxygen charge state, average iron charge state and the charge state distribution of iron. The vertical dashed blue line dictates the beginning of the ICME shock, the vertical dashed magenta line dictates the beginning of the ICME plasma and the vertical solid line indicates the end.

For each of the ICMEs for which suprathermal distribution functions can be calculated, we then compare the average iron charge state of the suprathermal plasma to the bulk thermal plasma. Comparing both thermal populations to the suprathermal plasma aids in the constraint of the origination of the suprathermal plasma. As shown in the charge state model studies, the ionic composition is set very close to the Sun. The suprathermal plasma will retain the ionic composition of the thermal plasma from which it originated. The thermal ionic composition is calculated from distribution functions measured by ACE/SWICS. We compare the suprathermal composition to both the co-located local thermal plasma as well as to the thermal plasma located upstream of the ICME driven shock.

Figure 2 shows this comparison using the iron charge states. Along the x-axis of both panels we show the average charge state of the thermal plasma, while along the y-axis we show the average charge state of the suprathermal plasma. In both panels the suprathermal plasma is

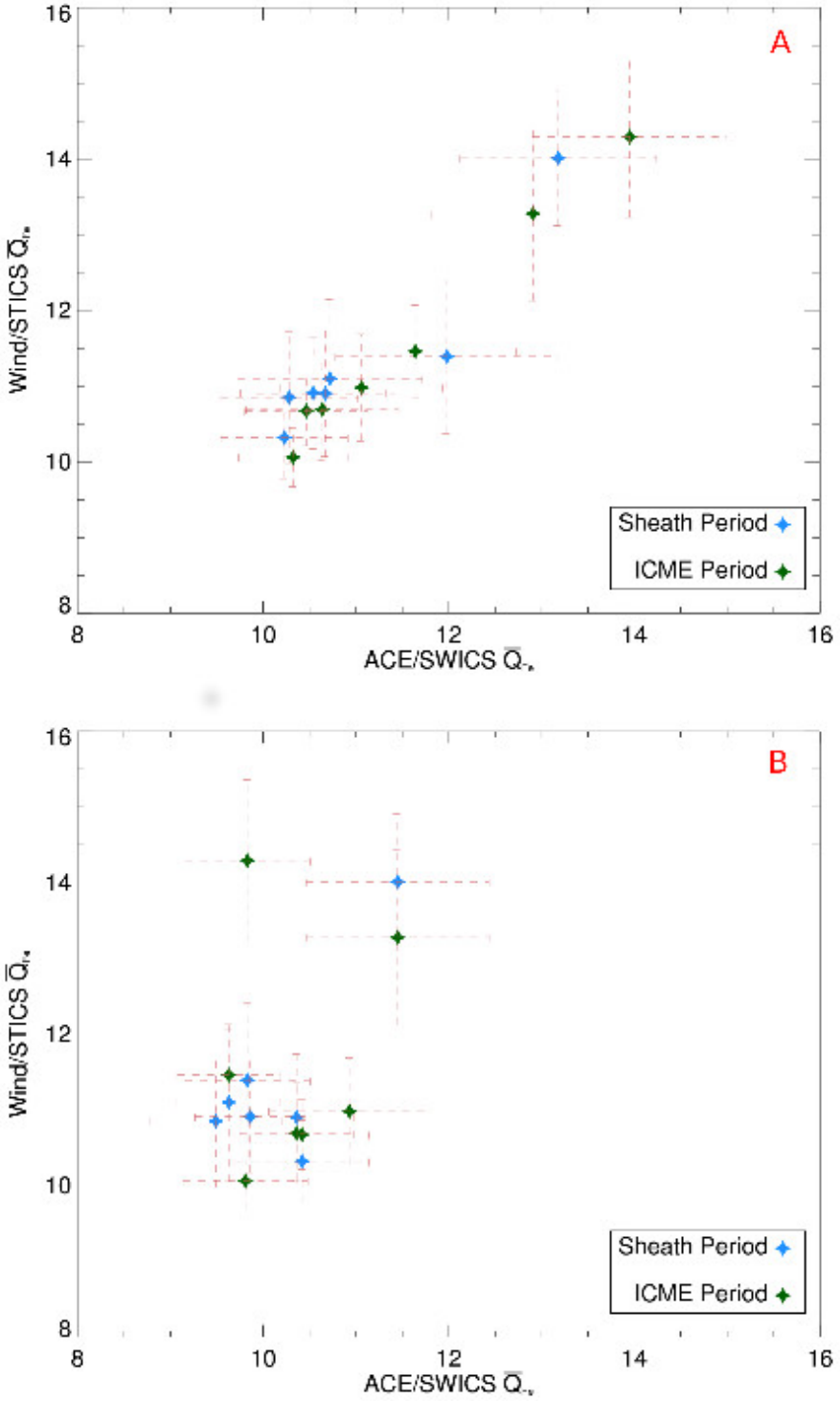

Figure 2. The average charge state of iron calculated for the thermal population from ACE/SWICS data along the y-axis, and suprathermal population from the Wind/STICS data along the x-axis. The top panel shows suprathermal data in the ICME compared to the local thermal plasma. The bottom panel shows the ICME suprathermal data compared to thermal plasma located upstream of the driven shock.

calculated during the ICME time period, denoted by green diamonds, or between the driven shock and the ICME plasma, denoted by the blue diamond. In the top panel, the thermal plasma is calculated during the same time periods as the suprathermal plasma. The bottom panel shows the thermal charge state calculated from a time period upstream of the driven shock. We can readily see that the suprathermal composition is very closely related to the co-located thermal plasma and not very related to the upstream plasma. This implies that the suprathermal plasma is being accelerated from the local thermal plasma and not being accelerated out of the surrounding thermal plasma through which the ICME shock is propagating. This work has been submitted for publication.

Time Variations of the Suprathermal Distribution as observed by WIND/STICS

Shocks are known to be a primary source for the acceleration of very high energetic particles (such as SEPs and ACRs). Recent studies have begun to look at the role of shocks in the acceleration of the suprathermal particle population in the solar wind (Ebert et al., 2011; Fisk and Gloeckler, 2012). The SupraThermal Ion Composition Spectrometer (STICS), onboard the Wind spacecraft, enables observations of these suprathermal particles at much higher time resolution than previous suprathermal studies using ACE, Ulysses, etc. In addition, the long mission duration of Wind allows investigation of the suprathermal population throughout an entire solar cycle, for which we find that the average suprathermal flux for H^+, He^{2+}, and O^{6+} remain steady, with minor modulation by large-scale changes from the solar cycle. From an investigation of the suprathermal flux at small-scale events (i.e., SIRs), we find that the majority of these shocks only act to enhance the low-energy ($V< 5V_{sw}$) suprathermal particles, while others have little impact on their suprathermal fluxes, implying that SIRs may not be strong drivers of suprathermal particles near 1 AU.

The key findings of this study include the following:

- The long-term evolution of the average suprathermal flux from three separate species, H^+, He^{2+}, and O^{6+} has been determined. **The flux remains very steady over the solar cycle, showing minor modulation by solar cycle**. **The decreasing trend could be attributed to the unusually large depression of solar wind density (~30% decrease) and magnetic field (~23% weaker) during the most recent solar minimum (Jian et al., 2011), as shown in Figure 3.**
- Although care was taken to reduce the amount of magnetospheric plasma sampled, the presence of leaked material cannot be discounted in the years before 2004.
- Short-cadence observations of suprathermal protons were made during 26 SIR shocks. A dramatic low-energy enhancement was observed >50% of the time, while other times the shock was seen to cause little to no change in the suprathermal density.
- **A low-energy enhancement is consistent with a broadening of the solar core plasma into the observation range of STICS.** Fluid compression of the shock would heat the core plasma causing the distribution to broaden (Fisk et al., 2006; Fisk and Gloeckler, 2012).
- Flux enhancements show little organization with compression ratio or shock angle.
- **SIR shocks may not be efficient accelerators of suprathermal particles at 1 AU.**

This work was presented at the 2012 SHINE meeting in Hawaii and work towards publication is ongoing.

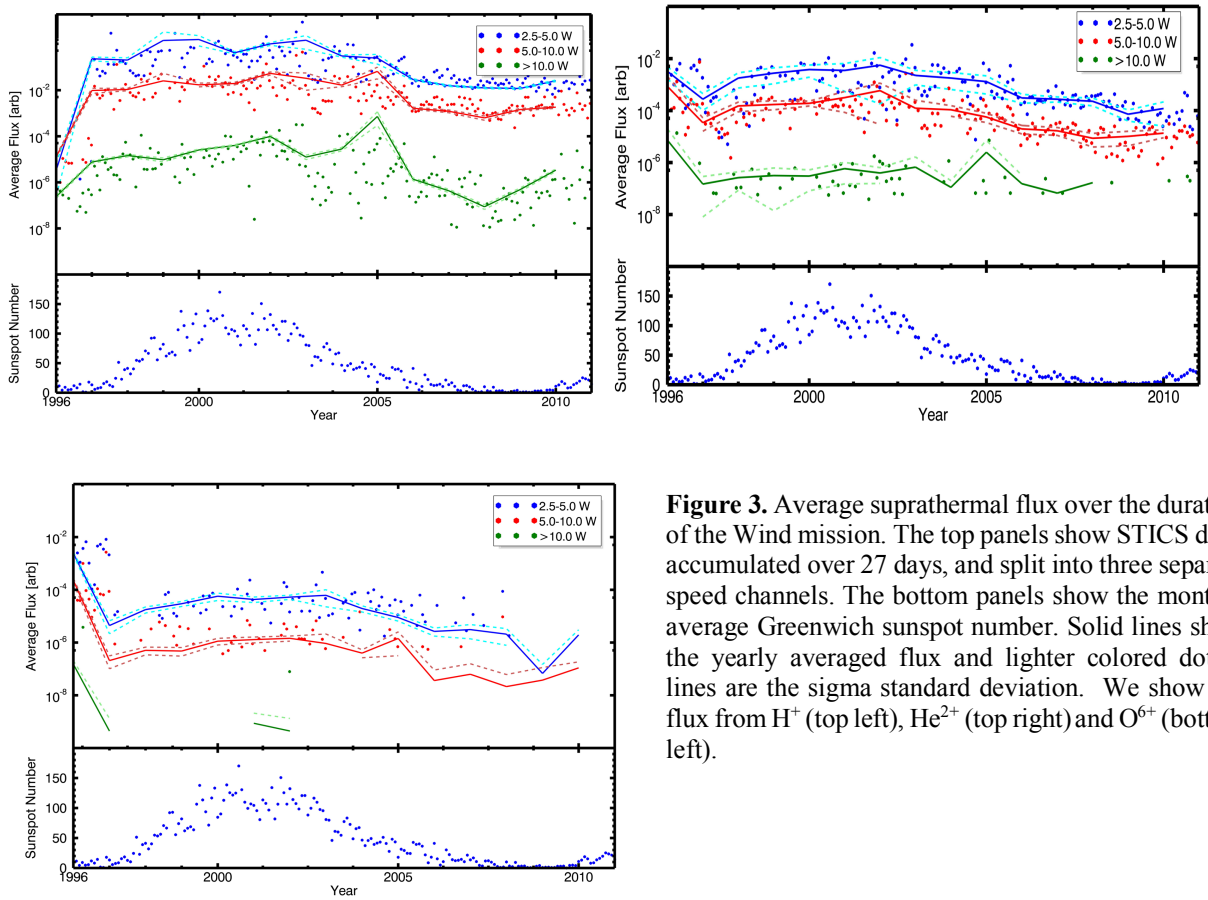

Figure 3. Average suprathermal flux over the duration of the Wind mission. The top panels show STICS data, accumulated over 27 days, and split into three separate speed channels. The bottom panels show the monthly average Greenwich sunspot number. Solid lines show the yearly averaged flux and lighter colored dotted lines are the sigma standard deviation. We show the flux from H^+ (top left), He^{2+} (top right) and O^{6+} (bottom left).

First in-situ measurements of a highly fragmented comet: WIND STICS and ACE SWICS measurements

While many of the characteristics of comets and their local plasma environment are obtained using remote sensing via spectroscopic methods, mass spectrometers onboard spacecraft allow us a unique opportunity to directly sample cometary material in-situ. To date there have been only a handful of in-situ spacecraft encounters with comets, such as 1P/Halley, 103P/Hartley, 81P/Wild and others. Comet 73P/Schwassmann-Wachmann started to disintegrate in 1995, two major components, B and C, were recovered in 2001, and it burst into more than 36 pieces during its passage near the Earth in 2006 (e.g, Crovisier et al., 1996; Boehnhardt et al., 2002; Fuse et al., 2007; Reach et al., 2009). Serendipitously, some very distant fragmentation members, well-separated from the major identified fragments, passed between the Earth and Sun, so that cometary pickup ions and possibly recombined solar wind minor ions convected past the Earth in late May 2006 and were observed by both the ACE/SWICS and WIND/STICS mass spectrometers located in halo orbits around the Earth-Sun L1 Lagrange point. Most of these observations took place a few days after the comet passed through the ecliptic when their orbits crossed the spacecraft-Sun line, suggesting additional pieces lagging far behind the main fragments. We present the first in-situ observation of these pieces that passed very close to the spacecraft (<0.07AU) and conduct a comparative analysis of composition and characteristics of pick-up ions originating from a number of the cometary fragments. We find that the pickup ions extend over a much larger range of distances than orbits of fragments (scattered over ~0.52AU). This suggests a trail of smaller

objects lagging behind the ~66 observed fragments. We also observe the distribution functions of the pickup ions as ring distributions, indicating very recent pickup due to a local source. The ion composition shows evidence of dissociated water. This paper was published as Gilbert et al. 2015.

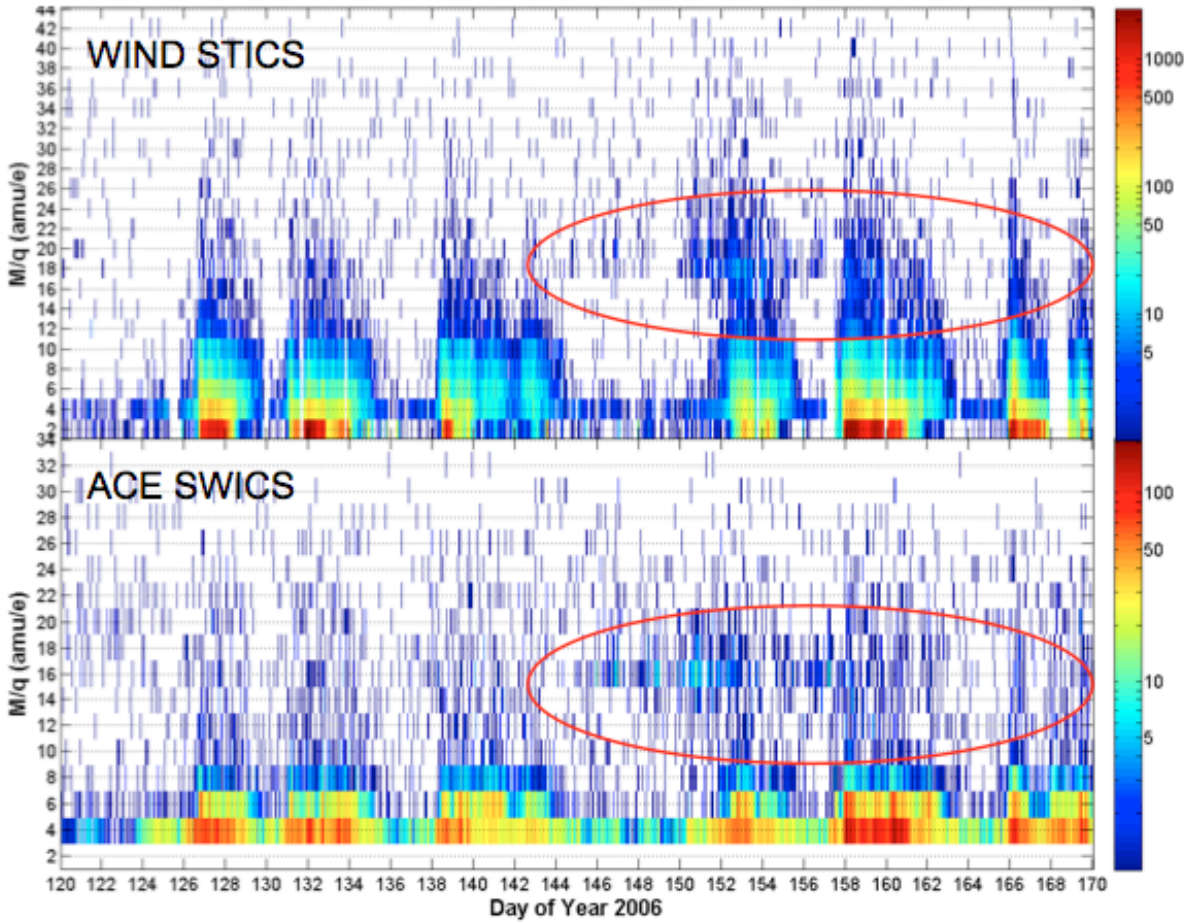

Figure 4. The WIND/STICS and ACE/SWICS M/Q histograms for the period during which cometary material was observed. The signature of the comet can be seen in the enhancement in molecules and ions related to water. For example, there is a strong enhancement in the O^+ flux (M/Q=16) as well as OH^+ and H_2O^+ (M/Q =17,18) around days 150-154 as well as during other periods.

Magnetic Clouds

Unusual average charge composition in the January 10 magnetic cloud: We have reported that the ionic charge states of the solar wind in the 3-hour, high-density pulse at the end of the 10-11 January 1977 magnetic cloud have a number of highly unusual features. The composition, measured with the SWICS, MASS, and STICS instruments, shows a large enhancement of low-FIP elements but at the same time is enriched in $^4He^{++}$. Our charge state measurements reveal the presence of the extremely rare $^4He^+$, O^{5+}, and $^{56}Fe^{5+}$, indicating very low (~<0.5 x 10^6 K) freeze-in temperatures. C, N, Mg, and Si have charge states corresponding to temperatures between l and 1.6 x 10^6 K. The most remarkable characteristic of this solar wind in the relatively short, high-density pulse is the unusually high abundance of $^3He^{++}$. These data provide important information about the properties and formation of the CME [Ho, 1998].

Unusual isotopic composition of a magnetic cloud in January 1997: During the January 1997 magnetic cloud event, MASS made some peculiar and unusual measurements. Within the high-density pulse at the end of the magnetic cloud in January 1997, MASS discovered a mixture of both hot and cold solar wind plasma [Ho et al., 1997]. In addition, MASS also found the He^3/He^4 =0.4=+0.1%, which is extremely high compared to a normal solar wind value of 0.04% [Ho et al., 1997, 2000]. An ongoing study has also found that the increased He^3/He^4 ratios in CMEs are typically high.

Unusual composition of the November 1997 event: This event is of interest because it was associated with a large flux of energetic particles. Based on WIND/MASS data, it could be shown that some of the compositional patterns for energetic particles and for solar wind plasma were surprisingly similar. This either indicates a rather local acceleration process or a relatively long-lived flux tube of a certain composition from which the energetic particles are accelerated [Wimmer et al., 1999a,b].

Comparative composition measurements on WIND and Geotail can be used to trace matter through the magnetosphere: The oxygen $O^{7+,8+}/O^{6+}$ ionization temperature measured by SWICS during the January 1997 magnetic cloud event was compared with that measured by the STICS instrument onboard Geotail showing different temporal behavior of the ionization temperature. Since the WIND and Geotail spacecraft were located at different positions when the magnetic cloud swept through them, this has implications for the entry, acceleration, and residence time of the solar wind plasma in the magnetosphere.

Elemental Abundances

Long-term averages of elemental abundances from MASS data are consistent with previous measurements: Abundances of other elements have been determined under a variety of conditions. Long-term average abundance ratios for ^4He, ^{20}Ne, and ^{16}O were determined from MASS data [Collier et al., 1996]. The ratios were found to be $^4He/^{20}Ne$ = 566 ±87, $^{16}O/^{20}Ne$ = 8.0 ±0.6, and $^4He/^{16}O$ = 70 ±7, consistent with previous measurements. In the slow solar wind the relative abundances of He, C, 0, Ne, Mg, Si, S, and Fe were also measured by the MASS sensor. The abundances compared to photospheric abundances were well ordered by the element's first ionization potential (FIP), as expected. Later studies will include elements such as Ca and Al not often measured in the solar wind.

Slow solar wind is released out of magnetically confined loops: The elemental abundance measurements of slow solar wind have been studied in connection with its source region, the solar corona. The enrichment of the abundances of elements with low FIP very likely occurs in closed magnetic structures in the low-latitude corona [Fisk et al., 1998, 1999; Schwadron et al., 1999; Zurbuchen et al., 1999].

Isotopic Abundances

First direct determination of Mg isotope ratio: Data from the MASS sensor is of such high mass resolution that isotopes can be readily measured. The results for the isotopes of magnesium are: ^{24}Mg: ^{25}Mg: ^{26}Mg = (0.792 ±0.006): (0.095 ±0.005): (0.113 ±0.005) [Bochsler et al., 1997]. This is the first determination of isotopic abundances for a solar wind element other than a noble gas.

First determination of Ne isotope ratio: Another isotopic abundance determination was made in the slow solar wind using MASS data. The $^{20}Ne/^{22}Ne$ abundance ratio was determined to be 0.073 ±0.028 [Hamilton et al., 1996]. This result is consistent with the results of the Apollo

SWC Foil Experiment (0.073 ±0.002) [Geiss et al., 1972], and with the SAMPEX SEP results made at substantially higher energies. The SAMPEX value of 0.076 ±0.008 from the Oct/Nov 1992 SEP events was reported by Selesnick et al. [1993]. In addition, the $^{16}O/^{18}O$ isotopic abundance ratio was determined to be 522 ±149 using MASS data [Collier et al., 1997]. The result is consistent with the SEP events (526 +474, -222) as reported by Mewaldt and Stone [1989].

First determination of Si isotope ratio: For the first time, measurements of the isotopic composition of Si in the solar wind were performed. The data were obtained with the MASS instrument aboard the WIND spacecraft and accumulated in exceedingly cold and slow wind. Such wind is often associated with large superradial expansion factors and with current-sheet crossings, which, in turn, are associated with the most efficient isotopic fractionation processes in the solar wind acceleration region. We detect little or no isotopic fractionation between the solar surface assumed to be of meteoritic composition and the solar wind. This constrains solar wind acceleration models and puts stringent limits on possible secular changes in the isotopic composition of the outer solar convective zone, the solar atmosphere, and the solar wind [Wimmer et al., 1999].

First determination of Fe isotope ratio: This ratio has been determined for the first time. Deviations from the meteoritic value are of enormous importance due to the predominant role Fe has in the formation of stars. The determined Fe ratio is found to be consistent with the meteoritic value, within statistical limits. It is worth noticing, however, that the WIND-MASS value could also be consistent with slightly different abundance ratios [Oetliker et al., 1997]. It is therefore very important to do this analysis with improved statistics.

He isotopic enhancements occur in closed magnetic structures: The slow solar wind is observed at a slightly larger He^3/He^4 abundance ratio than the fast, coronal-hole-associated wind [Gloeckler and Geiss, 1998]. Additionally, the charge and elemental composition of the slow solar wind is observed to have large systematical variations on all temporal scales. These two observations have been interpreted in a slow solar wind model. In this theory, slow solar wind is released out of previously confined magnetic loops [Zurbuchen et al., 1998; Fisk et al., 1998].

Injection into CIR Shock Acceleration

Extended velocity distribution functions at 1 AU up to MeV energies are measured for the first time: Data from the STICS and STEP sensors on WIND were used to obtain a combined He^+ and He^{++} spectra over a large energy range in the fast solar wind. Because of the broad energy ranges that all three sensors measured, we are able to cover the energy range from a few keV to MeV [Chotoo et al., 1998, 2000; Chotoo, 1998; Gloeckler et al., 1998]. These data severely constrain processes that inject data into shock acceleration in CIRs.

Anisotropies of low-energy particles are not field-aligned: STICS data have been used to calculate particle anisotropies at STICS-type energies. This is about one order of magnitude lower than any previous study. It was shown that the surprisingly CIR-accelerated particles exhibit anisotropies that are not field-aligned. This result must be of great importance since it contradicts all current injection theories. The physical interpretation is currently not understood [Chotoo et al., 1999; Chotoo, 1998].

Low-energy particle acceleration at CME shocks: STICS data have been used to determine the energy spectra of H, He^+, and He^{2+} for CME shock-accelerated particles. The spectral shape, the spatial dependence, and the M/Q dependences are in qualitative agreement with a prediction by Lee et al. [Matsuoka et al., 2000].

Heliospheric Studies

Suprathermal Tails: Substantial research has been done on the acceleration of energetic particles in the heliosphere. The observations have become clear: the spectral shape of low-energy particles has a common spectral shape: it is a power law in particle speed with spectral index of -5 when expressed as a distribution function. This spectral shape is observed in particular downstream from shocks, on average throughout the heliosphere, and most consistently in the heliosheath where the spectra seen by both Voyager spacecraft have locked onto the common spectral shape, with effectively the same absolute intensity.

The usual acceleration theories — diffusive shock acceleration or stochastic acceleration by diffusion in velocity space — cannot account for these observations. Diffusive shock acceleration, in particular, fails at observed heliospheric shocks since the observations require a -5 spectrum downstream independent of the shock compression ratio, contrary to the standard prediction of diffusive shock acceleration theory.

We have as a result invented a new acceleration theory, a pump mechanism, which can account for the observations. Energetic particles are pumped out of a core distribution of particles through a series of compressions and expansions. The pump mechanism naturally yields the -5 tails, independent of the plasma conditions. It also has the advantage that it contains a first-order acceleration that competes successfully with diffusive shock acceleration.

During the funding period we have written a series of papers, and delivered several talks at international meetings and in seminars, which have provided a compelling derivation of the governing equation of the pump acceleration mechanism that answers some criticisms that have been made of this mechanism. A paper by Fisk et al. [2010] appeared in ApJ, and additional papers will appear in meeting proceedings.

With the theory now on a firm theoretical foundation, we are applying the pump acceleration mechanism to the acceleration of energetic particles in CMEs in the solar corona, and to the acceleration of Galactic Cosmic Rays in the interstellar medium.

Magnetospheric Studies

ACE and WIND composition experiments can be used to trace data within the magnetosphere: During the magnetospheric phases of the WIND orbit, the composition data of SMS and ACE can be used to trace solar wind matter through the magnetosphere. This study also includes Geotail and Polar data. A first publication proving this concept is by Perry et al. [2000]. We continue to study this more recently using STICS data. Preliminary results show the penetration of solar wind O^{6+} into the magnetosphere and leakage of O^{+} out of the magnetosphere (see Figure 5). We are currently working on a bow shock fitting program to allow detailed examination of suprathermal tails and ion composition over many bow shock crossings.

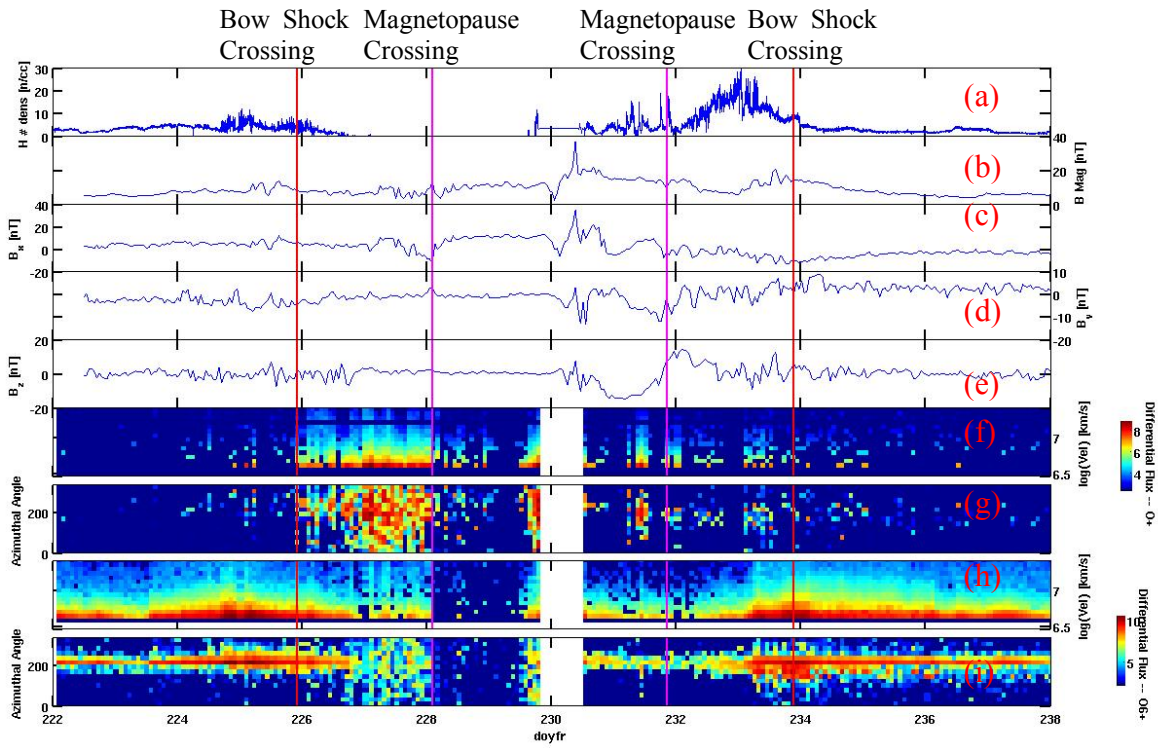

Figure 5. STICS observations from WIND's passage into and out of the magnetosphere. WIND SWE plasma properties are plotted in the top 4 panels. Panel (a) show the proton density, panel (b) shows the magnitude of the magnetic field, (c) shows Bx, (d) shows By, panel (e) shows Bz. The bottom 4 panels show WIND STICS data. Panel (f) show the differential flux intensity of O^+ vs. time and energy, and panel (g) show the azimuthal dependence of the O^+ flow. Panel (h) shows the differential flux of O^{6+} and panel (i) shows the azimuthal dependence of the O^{6+} flow. It is evident here that O^+ is leaking out of the magnetosphere in small amounts, while O^{6+} is penetrating into the magnetosphere.

Collaboration with ACE

Suprathermal electron temperatures correlate with the O freeze-in temperature: It has commonly been accepted that there are two in-situ measures of coronal temperatures. First, suprathermal electrons propagate nearly collisionless out of the corona, and secondly, the freeze-in process of solar wind charge states imprints coronal properties in solar wind minor ions. Using WIND and ACE data, these two tracers have for the first time been connected. In many cases these tracers directly correlate [Hefti et al., 1998].

First cross-calibration results: Using data from late 1997 and 1998 when ACE and WIND were both close to the Lagrangian libration point L1, composition data from ACE/SWICS and WIND/SWICS are used to cross-calibrate the two sensors and improve the instrument models used for the data analysis. First results from this study were presented during a WIND meeting in Berkeley. These results suggest that CNO/He can be successfully compared for WIND and ACE data and the small-scale structure of composition boundaries can be determined [Reinard et al., 1999].

Collaboration With Ulysses

Coronal-hole-associated streams are seen from both Ulysses and WIND: The timing of the WIND launch allowed significant collaborations between SMS and the SWICS instrument on Ulysses. While Ulysses was traveling from the south to the north pole of the Sun, it obtained data

from many of the same solar wind streams seen by WIND. One study in particular examined coronal-hole streams seen by both spacecraft (while Ulysses and WIND were on opposite sides of the Sun). The distribution of solar wind sulfur charge states was determined from MASS data on WIND and SWICS data on Ulysses. Results indicate a coronal temperature of ~1.5 MK where sulfur charge states freeze in [Cohen et al., 1996a].

Kinetic temperatures of O and He are not strictly mass proportional: Another collaboration with Ulysses/SWICS involved kinetic temperature ratios of O^{6+} and He^{2+}. Data from the MASS and Ulysses/SWICS sensors yielded very similar results even though the two data sets are obtained using different measurement techniques, at different phases of the solar cycle, and at different radial distances. It appears that the temperature ratio often deviated from the expected mass-proportional value of 4. The ratio also appears to be a function of the solar wind velocity. This velocity dependence was also evident in $^{2O}Ne/^{4}He$ kinetic temperature ratios determined from over 6 months of MASS data [Cohen et al., 1996b].

WIND data were used as part of the Whole Sun Month study: Solar wind composition and velocity observations were being correlated with those of Ulysses and other spacecraft in two projects: in the Inter-Agency Consultative Group Campaign 4 "Ulysses Fast Latitude Scan" covering the 1995 time period, and in the "Whole Sun Month" campaign, covering August through September,1996 [Galvin et al., 1997].

Suprathermal O6+ behavior associated with suprathermal shocks

During the validation of the new STICS data set, we found new behavior of suprathermal O6+ associated with interplanetary shocks. We have identified 10 intervals based on features in the O6+ energy spectra for selected shock-associated periods in the solar wind. These ions are observed transitioning from hot to cold distributions while maintaining isotropy for many shock lengths, until collapsing into a beam coming from the Sun (Figure 6). In other cases, O6+ ions in the same energy range were also observed in beam-like distributions moving to progressively lower energies and narrower beam opening angles (Figure 7). O6+ progressive energy drop appears related to ICME bulk plasma velocity profile. Further analysis is underway.

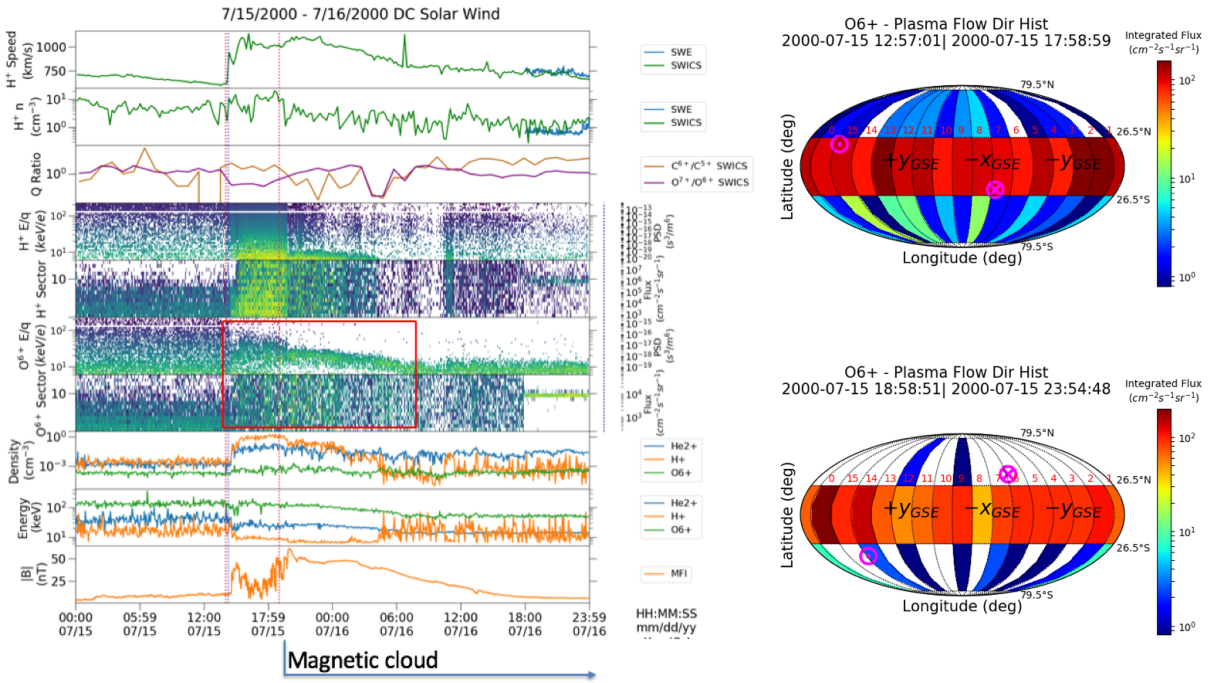

Figure 7. Hot, isotropic O6+ (left) being hot then cools and moves to progressively lower energies. Distribution is isotropic in equatorial plan in both periods, but has additional spread in elevation while hot (right top) as compared to when the energy is progressively lowering (right bottom).

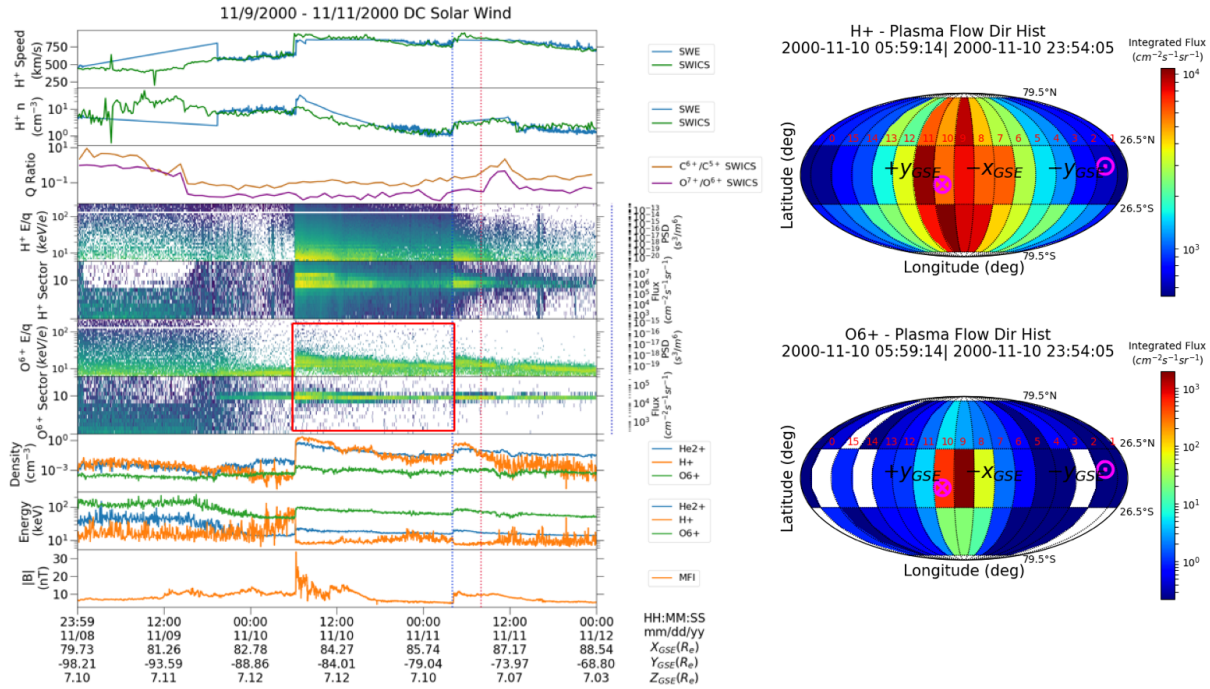

Figure 8. O6+ becomes beam-like after shock, with beam opening angle dropping as the distribution moves to progressively lower energies (left). The proton flow angle distribution

(right top) is more intense by similar in angular width to the O6+ (right bottom) just after the shock.

Recently Completed Work

A brief list of the tasks completed is given below. A few of these have been expanded upon in detail in the following sections.

- Successfully designed, coded and tested software to produce all proposed data products
- Performed consistency checks, such as flat field tests, to ensure that map products were properly normalized
- Identified appropriate time resolutions for the data
- Identified appropriate coordinate systems and their transformations
- Chose magnetospheric and heliospheric validation cases
- Validated data for above cases
- Assembled boundary list and wrote software to separate data into magnetospheric and heliospheric regional subsets.
- Produced full set of data products for several of the mission years, separated by region
- Validated data statistically by confirming that obviously unphysical values were not present in the tested years
- Documented validation in detail
- Designed and implemented output file formats for the public data
- Delivered all data to NASA SPDF. Only finalization of CDAWeb interface and release notes remains to be done.

Software

We have designed, coded and tested the software system which produces the data to be delivered. In a departure from previous systems that were written in C++ and IDL, this system was written in Python, making use of the SciPy, Matplotlib, and associated libraries. We chose Python for three main reasons. First, Python is an efficient, object-oriented language which can easily handle the modest demands which will be placed on it by this sort of data system. Since most of the hard work is done by our existing C++ system [*Gruesbeck et al.*, 2015], the new processing is only of moderate computational complexity. Second, this Python analysis system appears to be on its way to becoming a world-wide standard system for scientific data analysis, gaining substantial ground each year on the established Matlab and IDL. Finally, because the system is free, use of any plotting routines that we may distribute with the data (if appropriate) will not be restricted to researchers who can afford the substantial licensing fees of the other systems.

We have developed Python code to ingest 3D velocity distribution functions (VDFs) in spacecraft coordinates output by the Gruesbeck code, and transform them into 2D and 3D data products in GSE and HCI coordinate frames. We have assembled and ingested lists of Earth bow shock crossings (1995 – 2004), which are input to this code to allow separation of the data into heliospheric (outside the bow shock) and magnetospheric (inside the bow

shock) regional subsets. Multiple single-ion runs are ingested by this code to produce convenient files for analysis. Quality filtering has also been implemented.

Heliospheric validation periods

We chose two types of periods to scientifically validate the data produced.

First, we compared our new STICS 3D velocity distribution functions with a preliminary version that were used a scientific study [*Gilbert et al.*, 2015]. In this work, *in situ* plasma measurements from the ACE and Wind spacecraft were used learn about the composition of fragmented comet 73P Schwassmann-Wachmann, as it passed between the spacecraft and the Sun. Under these conditions, ions formed near the comet fragments, either by photoionization or by charge exchange with the solar wind, get picked up into the solar wind and carried away from the Sun. Some of these fragments are too small to be observed optically, so these observations provided a unique opportunity. They found a large enhancement in water group ions (mass-per-charge ratios 16-18) when downstream of the fragments, which provided strong evidence that they were still actively sublimating. For this work, 3D velocity

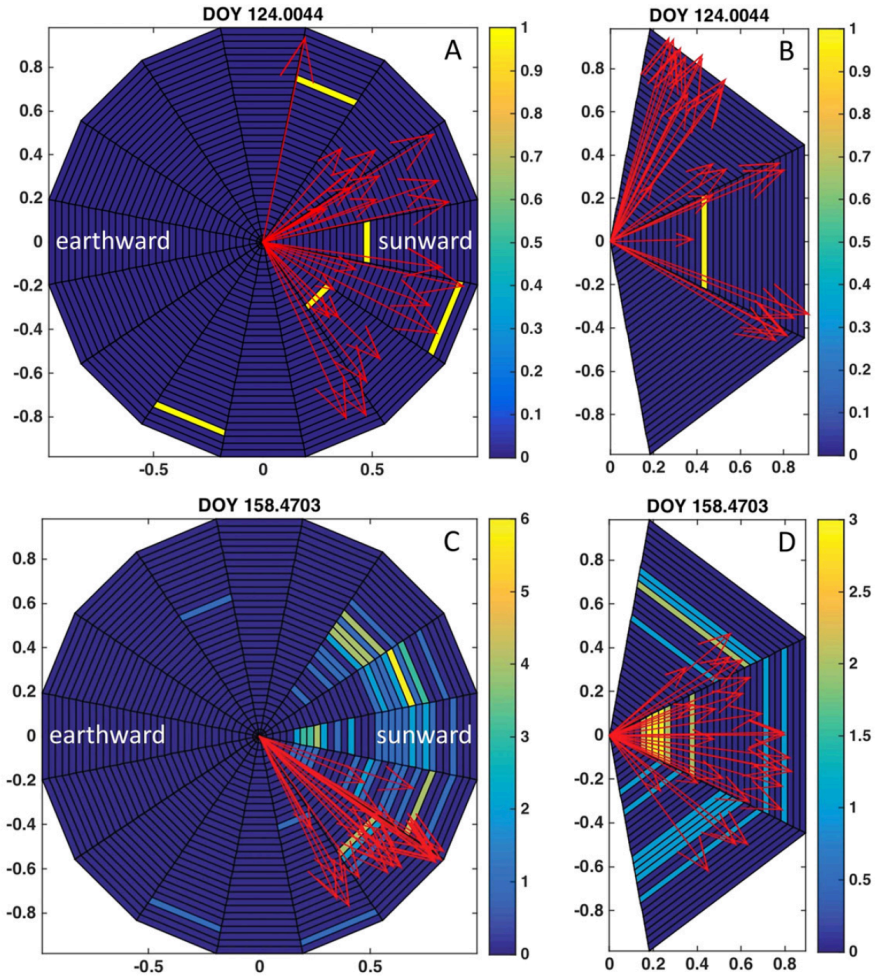

Figure 1. Newly developed preliminary 3D velocity distribution functions for Wind/STICS data, shown as 2D projections into the *X-Y* plane. *Adapted from Gilbert et al. [2015].*

distribution functions for O^+ from STICS were constructed for two cases, during (Fig 1, C-D) and outside of the comet passage (Fig 1, A-B). One can clearly see the enhancement in ions originating in the Sunward direction (Fig. 1 C-D) during the comet passage, as opposed to the much lower counts observed outside that period (Fig. 1, A-B). The ability to observe both the anti-Sunward *and* Sunward directions with Wind/STICS supplies key evidence that the enhanced water group ions originated at the comet. Though not needed for these solar wind speeds, the high energy maximum of STICS allows tracking of ions such as these during higher speed solar wind streams than other instruments. This example illustrates the value of the STICS 3D observations which will be made public through the work funded by this grant.

Our second type of heliospheric validation periods are times surrounding transits through the interstellar helium focusing cone. As our solar system passes through the galaxy, neutral atoms of the interstellar medium are free to pass through out solar system since they do not

feel the effects of the heliospheric magnetic field. As they encounter the gravity of the Sun, they are focused into a downstream region that is opposite the direction of solar system motion. Sun-orbiting spacecraft, such as Wind, pass through this region every year. When photoionized, these interstellar ions (now) can be detected by sensitive plasma instruments. Looking for this focusing cone in the new STICS data provides a high-level, end-to-end test of the processing. In Figure 2, we show total counts of He^+ over a 6 year period, 2007-2011. Repeated, sharp enhancements in these counts, as marked on the plot, indicate passage through the focusing cone and correct operation of the instrument and data processing system.

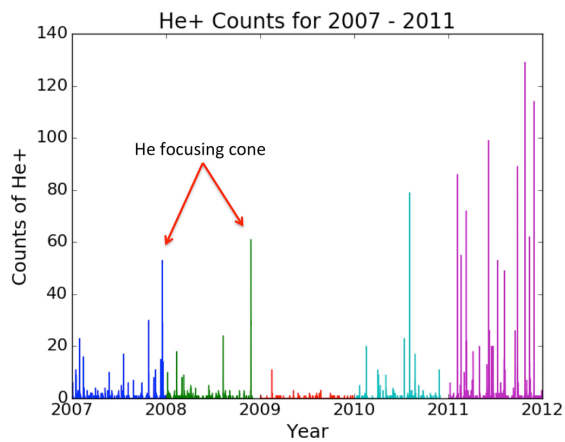

Figure 2. STICS He+ counts for years 2007-2011. Peaks (labeled) indicate passage through the interstellar He focusing cone. These intervals can be easily used for validation since they have been observed in other instruments (at lower energies).

Magnetospheric validation periods

Within the magnetosphere, regions of high plasma flux are a good first place to test new data. In particular, the central plasma sheet, which surrounds the magnetic equator in the magnetotail, is a region of hot, very often isotropic plasma (Figure 3). We have identified several plasma sheet crossings from the data, some of which have been previously studied using other instruments [e.g. *Parks et al.*, 2001]. The isotropic nature of this plasma has provided a good test of the relative calibration of angular bins in STICS: the isotropic plasma appeared in each angular bin with nearly equal intensity, indicating if that the response in each of these bins is well calibrated. Furthermore, since the Earth's plasma sheet has been studied extensively, we have been able to cross

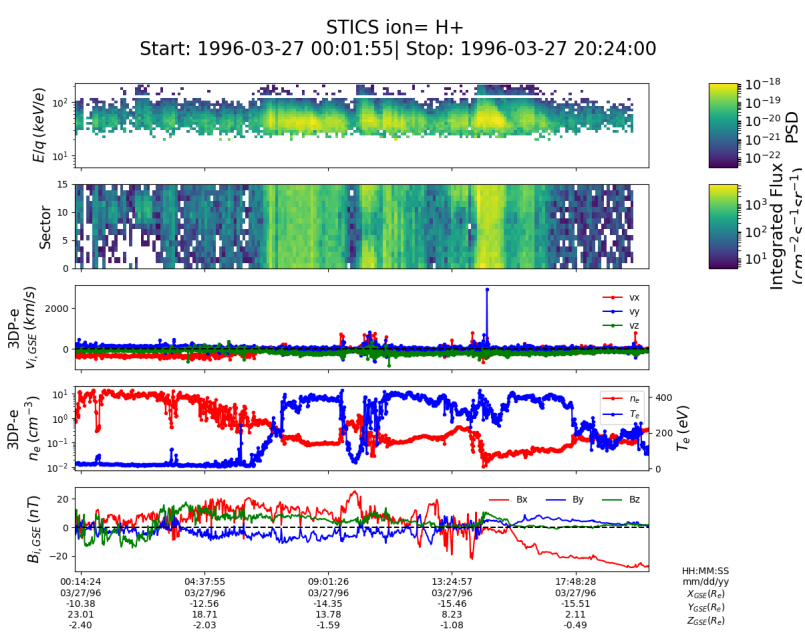

Figure 3. Wind crossing of Earth central plasma sheet. Sector panel shows nearly equal intensity across each angular bin, indicating the expected isotropic plasma. This is an example of the numerous crossings examined.

calibrate STICS moments with other instruments during these periods. In addition, we have compared approximate densities derived from STICS in these periods with accepted averages. Few other instruments in measure the suprathermal tail like STICS does, but we were able to confirm that the retrieved STICS densities were consistent with those expected in the tail from published thermal densities.

Selected time resolutions

Through examination of the above validation periods, we were able to choose the most appropriate time resolutions for public data. Furthermore, our runs of several years of data have allowed us to estimate the amount of time required for a given time resolution. Surprisingly, we have found that we can produce data all products at the full 3 min STICS time resolution for the entire mission.

EDUCATION AND PUBLIC OUTREACH

The WIND EPO project has been implemented at the Detroit Science Center (DSC) (See Figure 6). We currently have three movies that showcase the Sun and the effects of coronal mass ejections and the solar wind on the near-Earth space environment. We are currently updating the exhibit to switch to using a 3D TV for visualizing the movies as well as incorporating a sonification portion which will use an audio component for data interpretation.

Figure 6. A view of the Detroit Science Center (Courtesy the DSC).

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Zurbuchen, T. H., S. Hefti, G. Gloeckler, L. A. Fisk, N. A. Schwadron, Solar wind composition variations as a signature of fractionation processes in the solar corona, *EOS Transactions*, *80*, S237, 1998.

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Zurbuchen, T. H., L. A. Fisk, G. Gloeckler, and P. Bochsler, High time-resolution composition data: a new look at the highly structured corona, *EOS Transactions*, *79*, F709, December 1998. Invited talk.

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Zurbuchen, T. H., Solar composition: A status report, LANL, Seminar of the Space Science Group, February 1999. Invited presentation.

Zurbuchen, T. H., Acceleration of particles in the solar wind, Departmental Seminar, Physikalisches Institut, University of Bern, June 1999. Invited presentation.

Zurbuchen, T. H., S. Hefti, G. Gloeckler, L. A. Fisk, and N. A. Schwadron, Solar wind composition variations as a signature of fractionation processes in the solar wind, Spring AGU, June 1999. Invited presentation.

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Zurbuchen, T. H., CME Identifiers, Space Sciences Seminar, University of Michigan, September 1999.

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Fisk, L. A., Gloeckler, G. Schwadron, and T. H. Zurbuchen, Statistical acceleration in the solar wind, ACE-2000, January 2000. Invited presentation.

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Zurbuchen, T. H., Solar wind composition experiments: Status of technology and recent results, Presentation at Micro-devices Laboratory, January 2000.

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Zurbuchen, T. H., N. A. Schwadron, L. A. Fisk, and G. Gloeckler, Non-thermal properties of heavy ions in the solar wind, ACE-2000, January 2000. Invited presentation.

Zurbuchen, T. H., Solar wind signatures of CMEs, CME Workshop in Elmau, Germany, March 2000. Invited presentation.

Zurbuchen, T. H., Solar wind composition: A review, European Geophysical Union Meeting, Nice, France, March 2000. Invited presentation.

Zurbuchen, T. H., Constraints on particle transport from solar wind composition data, Departmental Seminar, Physikalisches Institut, University of Bern, June 2000. Invited presentation.

Zurbuchen, T. H., Solar activity cycle, Public Lecture for the Michigan Amateur Societies in their Annual Astronomy at the Beach, Kensington Park, July 2000. Invited presentation.

Zurbuchen, T. H., Heliospheric magnetic field configuration and its coronal sources, International Astronomical Union Symp., 203, 55Z, 2000.

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Neugebauer, M. C., and P. C. Liewer, Determining the sources of solar wind using potential field models and in situ measurements, 2005 Joint Assembly (AGU Spring Meeting), abstract SH13A-04, New Orleans, LA, May 2005.

Posner, A., F. Allegrini, M. I. Desai, G. C. Ho, S. Livi, and D. J. McComas, Interplanetary shock forecasting with suprathermal ions: Solar cycle dependence, abstract SH14A-04, AGU Fall Meeting, San Francisco, CA, Dec. 2005.

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Zurbuchen, T., Coronal effects on FIP fractionation of the solar wind?, Symposium on the Composition of Matter, Grindelwald, Switzerland, Sept. 11-15, 2006, invited talk.

Zurbuchen, T. H., Connecting the Sun and the heliosphere, AGU Fall meeting 2006, abstract SH21B-01, San Francisco, CA, Dec. 2006.

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