11

SPACE SCIENCES

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11.1. INTRODUCTION

The adjective "space" in the chapter title loosely means "extraterrestrial" and could include planetology, the study of other solid bodies in the solar system, such as Mars, Comet Halley, or asteroid Ceres. While MS is vital to all planetary exploration, these devices function much the same way as laboratory MS, except that they are remotely operated, use less power, and are considerably more expensive. But "space" can also have the more restricted meaning of "outside the ionosphere of any planet, but inside the solar system," which will be the area discussed in this chapter. The properties and challenges of this region are very different from the lab, although the science turns out to be often the same.

In this region of space, matter is very tenuous, so for example, at 1 AU (AU = astronomical unit = the average distance from the Sun's center to the Earth's center = 149,597,871 km) distance from the Earth the density is approximately three atoms per cubic centimeter, which would pass for ultra-high vacuum in the lab! Furthermore, all those atoms are elemental ions, both because of their likely origin in the solar atmosphere, and because the Sun is a prolific source of ultraviolet, hydrogen Lyman-alpha radiation that rips apart and ionizes molecules. For example, interstellar hydrogen atoms entering the solar system with a 13 eV ionization potential and traveling some 30 km/s can only make it in to about Jupiter's orbit before being ionized by the

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Sun. Helium, with the highest ionization energy of any element, 25 eV, barely makes it to 1 AU before being ionized by the Sun. Therefore, in space, any observation of neutral atoms, or even molecular ions, must be of a temporary population arriving from a nearby planetary body or comet.

Accordingly, space mass spectrometers are different from laboratory MS in that they have no need for an ionizer or a vacuum pump. As we will discuss below, these two advantages are far outweighed by the disadvantages of space, which are responsible for the paradoxical observation that space mass spectrometers costing millions of dollars have only recently achieved a mass resolution of $m/\Delta m = 100$! So the main challenge facing space MS is getting a technology that works and is reliable enough to last 5 to 10 years in a brutal environment without human intervention [1]. But perhaps we should first ask what information a space MS gives us that is important and unique.

11.2. ORIGINS

When the United States launched its first satellite, Explorer I, in 1957, Van Allen's biggest surprise was finding that his cosmic ray experiment saturated in the previously unknown radiation belts surrounding the Earth [2]. Space was full of energetic ions that were dangerous for astronauts and electronics alike. However, what makes them dangerous is primarily their energy, and only secondarily their composition, so mass analysis was not emphasized. Even today, the field of megaelectronvolt ion composition is dominated by cosmic ray "high energy" physicists rather than mass spectrometer "plasma" physicists, with little overlap of techniques, science, or goals of the two communities. So despite the obvious connection to the plasma origin of cosmic rays posed by Fermi a half century ago, we will confine the discussion in this chapter to techniques that measure ions with energies less than 100 keV or so.

In the heady decade of the 1960s, satellites that orbited above the atmosphere but below the radiation belts were found to be useful for communications, weather observations, and of course, intelligence gathering. The United States had a fleet devoted to monitoring nuclear explosions and compliance with nuclear test ban treaties [3]. They quickly found that in this plasma environment, electronvolt ions and photoelectrons caused annoying sparks on nonconductive glass optics, which could easily be mistaken for nuclear explosions. Thereafter, plasma diagnostic packages became standard for nearly all satellites, commercial and defense-related, to monitor the environment. In low Earth orbit (LEO), oxygen often dominates over hydrogen as the main component of the plasma, depending on location, auroral activity, and time of year. So these first plasma environmental diagnostics evolved to become crude mass spectrometers, with a mass resolution of about four to separate the three main constituents of Earth plasmas: hydrogen, helium, and oxygen ions. This type of diagnostic was used to explain the sudden degradation of NASA's Chandra telescope X-ray detectors due to kiloelectronvolt ions, or the Jeans escape paradox of the disappearance of atmospheric helium. (Heavy atmospheric atoms can be lost more easily as ions than as neutrals. Even molecular nitrogen ions have been observed escaping Earth's gravity! [4])

In the decade of the 1960s, satellites explored more of the Earth environment, mapping beyond the radiation belts to the magnetically confined ions surrounding the Earth, the magnetosphere [5]. They discovered the $\sim 1\,\mathrm{keV}/\mathrm{nucleon}$ ions streaming from the Sun, the solar wind [1, 6], and its plasma interaction with the Earth's magnetic field, the magnetosphere.

The magnetosphere was found to have a sharp boundary at the front, and a long magnetic geotail trailing invisibly behind the Earth like a windsock, many times longer than the distance to the Moon. And most of these discoveries were not predicted, partly because the conditions of space could not be duplicated in the laboratory, and partly because the physics of plasma "magnetohydrodynamics" was more complex even than Navier-Stokes hydrodynamics. Minor details, such as the mass composition of the plasma and its origins, had to wait for the theory to catch up to the gross morphological observations.

Now the composition of the solar wind, like the Sun itself, was expected to be 90% hydrogen and 10% helium, with less than 1% oxygen and minor constituents, all determined telescopically [7]. Optical spectroscopy, however, cannot determine isotopic composition, so that models of nucleosynthesis in the Big Bang, stars, or supernovas could only be tested on Earth rocks, on meteorites, and after 1968, on Moon rocks [8]. This type of extrapolation from meteoritic to galactic composition had built in pitfalls, such as ^{40}Ar being the most common isotope of argon on the Earth (due to radioactive decay), but rare in space. This was shown in the 1970s, when the later *Apollo* missions flew an aluminum foil experiment designed like a window shade that was unrolled on the Moon to collect solar wind noble gases for later isotopic analysis on the Earth [9]. For the majority of the isotopes, however, the largest mass in the solar system, the one that dominates the cosmochemistry chronology of all the planets, the Sun, had never been measured.

The first few decades of space exploration went by without any MS better than $m/\Delta m \sim 4$ because understanding the solar wind flow, its density, its pressure, or its temperature did not require mass resolution. Not until 1984 did a space MS fly with a resolution of about 10 [10], and it was 1994 before that increased to 100 [11]. Suddenly for the first time, the solar wind isotopes of carbon, oxygen, magnesium, silicon, and iron were known, and the models could be tested. Even then, space MS had difficulty measuring rare isotopes, so that it wasn't until 2005 that solar wind samples were returned to Earth inside ultra-pure silicon wafers (the ill-fated *Genesis* mission [12]) to determine the important triple ratios of $^{16}\mathrm{O} : {}^{17}\mathrm{O} : {}^{18}\mathrm{O}$.

Such a measurement can tell us about the chemical evolution of oxygen, such as whether the isotopes differentiated via a thermal cycle in which lighter ^{16}O fractionates from the heavier ^{18}O, much as Vostok ice-core oxygen ratios reveal the Earth's prehistoric climate. From this fixed point of the Sun's oxygen ratios, we can then trace the history of water in other planetary bodies since their birth in the solar nebulae through the subsequent cometary bombardment [13]. In NASA's search for water on the Moon, important for the establishment of a future Moon base, such isotopic ratios will determine whether the water is a vast mother lode or just a recent cometary impact residue.

So we see that space MS functions much as laboratory MS, unlocking secrets about origins, the origin of plasmas, the origin of planets, water, and maybe even the Holy Grail, life itself. Why is this capability unique to mass spectroscopy? Because elemental isotopic ratios are barely affected by the forces that homogenize plasmas or destroy the evidence from the early solar system: the meteoritic bombardment, the atmospheric chemical changes, or the motion of tectonic plates. The same properties that make laboratory MS so useful in forensics also make space MS valuable in NASA's Origins theme. There are, however, yet more uses for mass spectroscopy related to its ability to track dynamic changes.

11.3. DYNAMICS

The European Space Agency's *Ulysses* space probe showed that there are two kinds of solar wind: fast wind coming from the poles of the Sun, and slow wind coming from regions closer to the equator. These two types of wind were analyzed with a space MS with resolution $R \sim 10$ and found to have differing magnesium-to-oxygen ratios, indicative of the differing temperatures of their differing origins in the solar atmosphere [14]. As these two populations leave the Sun, the faster wind piles up against the slower, causing a huge solar system traffic jam referred to as the corotating interaction region (CIR) with copious shock-accelerated ions. Not only do CIRs produce energetic ions hazardous at Earth, but they modify the entire solar system, causing Forbush decreases in the cosmic ray flux, which in turn, modulates the ^{14}C production at Earth [15] (and some have even suggested that it modulates the tropospheric climate). After several decades of study, models are just now being tested that can predict these CIRs starting with optical observations of the Sun. Testing of these models requires far flung spacecraft to pinpoint the CIR boundaries at widely spaced positions in the solar system. Perhaps not surprisingly, plasma measurements of density or magnetic field cannot reveal unambiguously which part of the traffic jam is being observed, whereas composition measurements can. In this case, minor ions in the solar wind act as tracers, like smoke particles in a wind tunnel that reveal the dynamics of the underlying fluid. It was for exactly this purpose that the Active Magnetospheric Particle Tracer Experiment (AMPTE) launched barium and lithium canisters in 1984 to track ion flows with space MS [16].

And because these minor ions have different gyro-radii in the magnetic field carried by the solar wind, they sample different spatial scales and can reveal even greater secrets about the structures in the solar wind: the discontinuous shock interface, the interaction with the Earth's shock, or reconnecting plasma flux tubes. Already we have been able to sort out the structure of a solar eruption that swept past the Earth on January 10, 1997 based on these trace elements [17]. Even greater secrets remain to be revealed when space MS can operate at higher cadence. Currently *Ulysses* requires 13 minutes to complete a mass-energy spectrum, during which time a 400 km/s solar wind has traveled three-quarters of the distance from the Earth to the Moon. Future space MS with cadences of a few seconds will provide the data needed to calibrate the rapidly growing field of MHD space plasma simulations.

11.4. THE SPACE MS PARADOX

As with many things built for space, the first reaction on hearing the cost is surprise that such expensive MS have such limited abilities. One answer is that space is most unforgiving. Many ambitious designs were launched in the 1960's that never returned useful data. In this section we look at some of the unique difficulties encountered by space MS, as well as some of the techniques that have worked.

Solar wind ion densities of 3/cc traveling 400 km/s give respectable fluxes of 120 million/s-cm^2 of solar wind, but this is against a background photon flux about $1.2\,\text{kW/m}^2 = 0.12\,\text{W/cm}^2 \sim 10^{18}\,\text{eV/s-cm}^2 \rightarrow$ 10 billion more photons than particles. Most detectors sensitive to the electronic excitation caused by a 1 keV/nucleon ion traveling just faster than the electron Bohr velocity, would be equally sensitive to a 1 eV electron traveling at the same speed, whose energy corresponds to a solar UV photon. Therefore, the first attempts to measure solar wind saw only photons. Even a carbon black surface with an albedo $<0.1\%$ would require a minimum of three bounces before the UV photon flux were suppressed enough to see the ions. From bitter experience, space MS have electrostatic ion deflection systems that pass the ions through a curved, blackened entrance system designed to reduce the UV flux by about a billion. Such a deflection system naturally selects only ions of the correct energy to pass through the entrance voltages, which makes the instrument both a mass analyzer and an energy analyzer, further reducing the measurable flux.

A second problem not often appreciated in lab MS is the effect of energy spread, which in both TOF-MS (see Section 2.2.1) and magnetic sector MS (see Section 2.2.2), directly degrade the mass resolution. In lab MS, this is solved by the ionizer, which produces ions from cold neutrals with a thermal spread of less than an 1 eV, subsequently post-accelerated up to 1000 eV, resulting in a $\Delta E/E < 0.1\%$. But in space, the solar wind ions come pre-accelerated to 1 keV and at arbitrary angles to the instrument, resulting in energy spreads of $\Delta E/E > 100\%$. Since we extract them from the photon flux with an energy filter, we can pick an energy bandwidth, but the reduction in spread comes with a reduction in sensitivity. As we argue later, this reduced sensitivity limits the typical space MS bandwidth to $\Delta E/E > 5\%$.

A third problem with space MS is the necessity to pack it into a small volume. A rule of thumb for satellite instrumentation is that the final package will have the density of water, 1 gm/cc. Since typical scientific satellite payloads weigh in the neighborhood of 100 kg, and room has to be provided for 5 to 15 instruments, typical weight allotments come out in the 5 to 10 kg range, or 5 to 10 liters of volume. Ten liters is a cube with 21 cm on a side, which has to accommodate not just instrument volume, but power supplies, computer boards, and packaging. Space MS that rely on spatial separation of differing masses, such as magnetic sector MS, would have a maximum lever arm of about 10 cm. This volume limitation proves to be a fundamental limitation for high resolution magnetic MS (Fig. 11.1). For example, in 1994 a state-of-the-art toroidal magnetic sector space MS that tried to pack both UV deflection and a magnet into the same volume with position sensitive multichannel analyzer readout ultimately achieved only mass resolution R $\sim$5 [12].

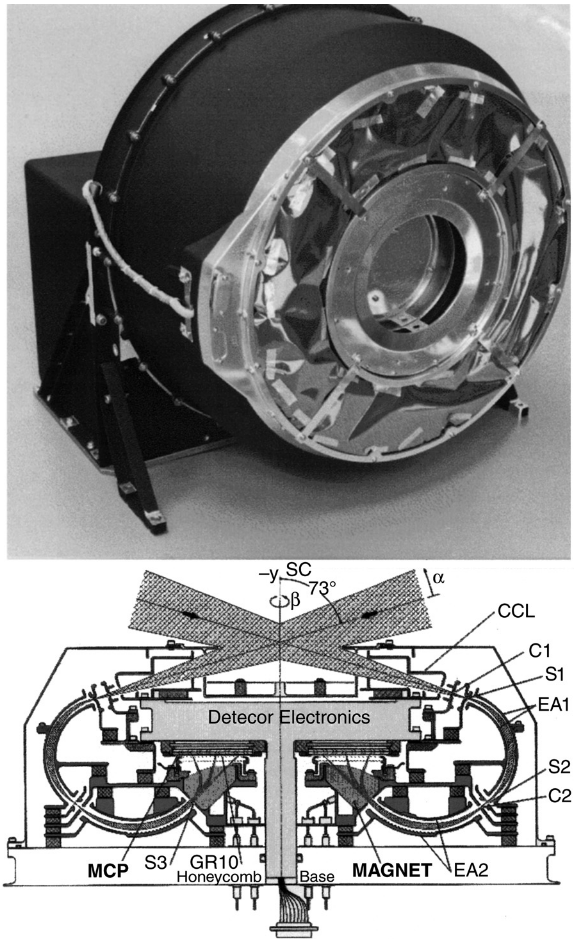

Figure 11.1. POLAR/TIMAS photo and schematic courtesy W. Petersen , NASA.

In laboratory MS, one has a trade-off between sensitivity and mass resolution, so for example, a magnetic sector MS can have increased mass resolution if the entrance slit is made narrower. However, the already low fluxes of space do not allow that solution to the resolution dilemma. Beginning with a 1.2×10^8/s-cm^2 solar wind flux, less than 1% is heavier than helium, reducing the interesting count rate to 10^6/s-cm^2. One must also not permit the hydrogen to create a scattering background to the heavies, which necessitates more collimation and baffles. To filter out the photons in the small distances allowed on a satellite, a cylindrical or spherical deflection system 10 cm across will have a gap or slit only a few millimeters wide. Unlike laboratory MS with capillary feeds, space MS are wide open to the environment, but the collimation and UV suppression make it difficult for a space MS to have more than a few square millimeters of "geometric factor," further reducing the flux to 10^5/s. The solar wind has a much wider energy range than the 5% energy passband resulting in the need to step the deflection plates in voltage so as to sweep through the peak. Duty cycles of 1% to 5% are common depending on details of the energy resolution, reducing the count rate to $10^3/s$. Finally, few space MS have the good fortune to be pointed continuously at the Sun, but are often on spin-stabilized spacecraft, further reducing the duty cycle another factor of 100. With 10 counts per second dedicated to carbon, oxygen, sulfur, magnesium, silicon, and iron, and accounting for the inevitable background of scattered protons, photons, and penetrating cosmic radiation, it is not too surprising that mass spectra require minutes to hours of integration time.

We have only covered the signal-to-noise problem; several others must be solved simultaneously. Since space is a vacuum, one cannot cool the electronics or power supplies with a fan, but must ensure that thermal contact direct the heat to the spacecraft radiators. Solid state detectors (SSD) (see Section 2.3.5), uncommon in laboratory MS, are often used in space to get an additional energy signal from the ion impact, and these detectors must not go above 30°C. Likewise, fast electronics are often power hungry, and all that power must be dissipated as heat. More than one space MS has failed for thermal reasons.

Not only must space MS be compact, low power, and autonomously operated, but they must survive launch by rocket. The trend over the past few decades has been toward solid-fueled rockets or boosters that have a much rougher ride than liquid-fueled rockets. Over-zealous specifications often require that space MS survive 15 g of random shake acceleration, which is about like lifting the instrument 10 cm and dropping it on the floor repeatedly. All those shims in a magnetic sector MS must be capable of being realigned in space, perhaps with stepper motors, which is what ESA had to fly in its 2011 comet mission [19]. Likewise, carbon foil technology took an additional 10 years to fly after it had been developed in the laboratory, primarily to ensure that it survived launch.

Finally, there are the social limitations of being crammed onto a single satellite platform with ten other science teams. The magnetometer team trying to measure 100 pT fields does not appreciate the stray fields from the mT magnets needed for a magnetic sector MS. The electric field team trying to measure millivolts per meter fields objects to the kilovolts per millimeter sweeping voltages on the deflection plates. And no one wants to be around should that 30 kV post-acceleration voltage arc over. Even with the best social etiquette, and the best measurements, there remains the unavoidable Darwinian telemetry competition for the data sent back to Earth. Just about every space scientist has a "fish story" about the data that got away.

For all these reasons and more, space MS has been an expensive challenge, but one with many accomplishments.

11.5. A BRIEF HISTORY OF SPACE MS

11.5.1. Beginnings

The lowly beginnings of space MS began in the early 1960s with Russian "ion traps" or Faraday cups (see Section 2.3.2) flown on the outside of a satellite [1]. In the United States, these were later outfitted with a grid that could be biased to different voltages, thereby acting as a crude energy filter, or a "retarding potential analyzer [20]." The advantages of Faraday cups were their integral flux measurements, their insensitivity to photons, and their general rugged construction, though they had no mass capability, and produced poor differential energy spectra.

The next step was flying a SSD or channeltron (see Section 2.3.3.2) with deflection plates to eliminate the UV photon flux [21]. These devices gave much better energy spectra, with 1% to 5% $\Delta E/E$ resolution achieved with close spacing between the deflection plates. In "cool" solar wind, the fact that all species travel at nearly the same velocity meant that helium had four times as much energy as hydrogen, permitting these devices to observe helium and sometimes oxygen as a bump on the hydrogen tail [22]. However, shock heated plasma cannot be analyzed this way, nor could rare species that did not rise above the noise in the hydrogen tail, which is a dynamic range limitation of the technique.

Several magnetic sector MS (see Section 2.2.2) were flown, but the small size of the magnets, as well as the desire to keep the spacecraft "magnetically clean," limited the maximum energy analyzed to $E < 15$ keV, and the resolution $R < 7$ [18]. Even with such low resolution, it was still sufficient to separate oxygen from carbon, the third and fourth most abundant species in the solar wind, because they were no longer contaminated by the long thermal tail on the hydrogen peak. Nevertheless, the real revolution in mass resolution awaited TOF-MS (see Section 2.2.1). Because this instrument revolutionized space MS in such an elegant fashion, it deserves more careful study.

11.5.2. Linear TOF-MS

In 1984, the AMPTE mission launched the first carbon-foil TOF-MS into space, which would have been the second, had the *Challenger* shuttle disaster not delayed the *Ulysses* launch until 1991 (Fig. 11.2) [23]. The photons were filtered out by a traditional blackened deflection system, which directed the ions toward the 2 $\mu g/cm^2$ thick foil mounted on an 85% transparent grid almost a square centimeter in area. The grid provided the support needed to survive the launch. The foil thickness permitted >2 keV/nuc ions to pass through and hit a SSD some 10 cm away. To ensure that the ions made it through the foil and also through the "dead layer" on the SSD (caused by the upper electrode), the foil and the entire TOF section were floated at $\sim$20 kV to post-accelerate the ions. Electrons sputtered off the carbon foil became the start, whereas electrons sputtered off the SSD became the stop pulse for the TOF.

These sputtered electrons were detected by multichannel plate detectors (see Section 2.3.3.2) having a pulse width of about 1 ns, which when combined with a 3 ns variation due to C-foil location, gave a timing error in the $\sim$70 ns flight time of $<$5%. Since time-of-flight is proportional to the square root of the mass, this doubles the mass uncertainty to 10%, for a resolution of $R \sim 10$. Lowering the post-acceleration would increase the TOF, which helps the mass resolution, but would also increase the "straggle" from energy loss in the foil, so that there is an optimum voltage roughly in the tens of kilovolts region. Making the foil thinner would reduce the straggle, but at the cost of producing fewer start electrons, so that the 0.5 $\mu g/cm^2$ foils flown on later space MS returned no signal for hydrogen [24]. Once again, 1 to 2 $\mu g/cm^2$ C-foils appear about ideal.

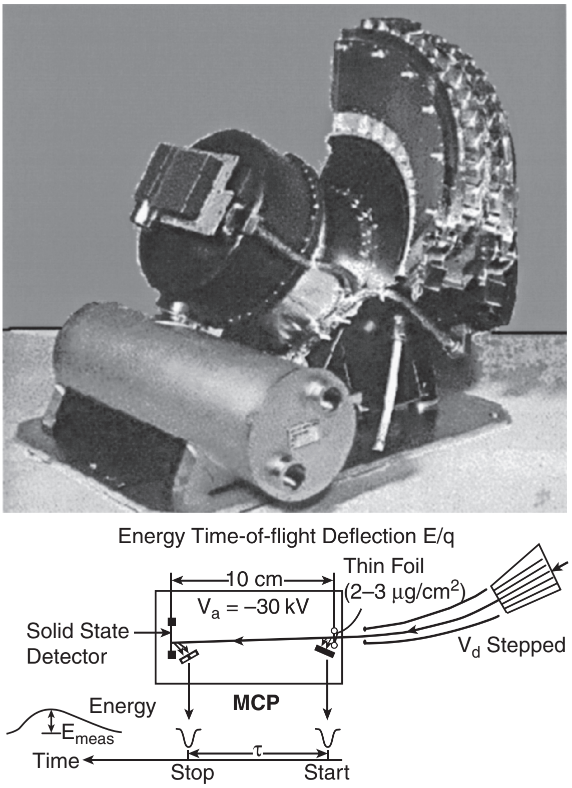

Figure 11.2. ULYSSES/SWICS photo/schematic courtesy G. Gloeckler, NASA.

Since the voltage on the deflection plates determined the energy per charge of ions, E/Q, a TOF measurement giving the velocity could be combined to give the mass per charge, m/z. Unlike laboratory MS, ions in space can have many different charge states, so that there remains an essential ambiguity in the signal. For example, the second, third, and fourth most abundant species in the solar wind will overlap, with He^{2+} having the same m/z ratio as C^{6+} and O^{8+}, to within a few tenths of a percent. This was solved by measuring the total energy with the SSD with a resolution of 10%. Despite the increase in noise caused by having to subtract off the large post-acceleration voltage, the fact that charge is a small integer permitted an accurate determination of both charge and mass. Plots of M versus m/z clearly resolved solar wind species up to magnesium and silicon, effectively doubling the mass resolution to twenty or so (Fig. 11.3).

Although the SSD could not be used for TOF determination because the pulse height analysis used to extract the energy from the SSD had a shaping constant of around a microsecond, the presence of a SSD signal along with a start and stop signal permitted triple coincidence logic to virtually eliminate background electronic noise. This was crucial in enabling the instrument to collect spectra in the heart of the Van Allen radiation belts, as well as during solar energetic particle events that follow solar

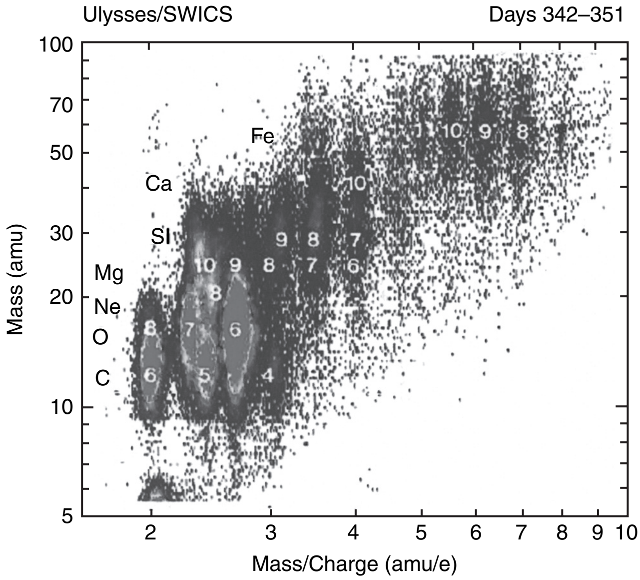

Figure 11.3. SWICS M vs M/Q analysis to enhance R, courtesy G. Gloeckler, NASA.

flares. In addition, these three rates permitted internal calibration of the instrument, so that MCP efficiencies, age degradation, or carbon foil damage could be tracked as well.

Also note that carbon foils are excellently suited for the low density space environment, using an asynchronous timing technique capable of measuring every rare particle that enters. Such a technique will saturate only when the count rate exceeds the reciprocal "window" time, the maximum time allowed for a stop signal before resetting the trigger. In the solar wind, the heaviest ions were expected to be iron, or about eight times slower than hydrogen. This converts to a $\sim$350 ns window, for a saturation rate of 3 MHz. The SSD shaping amplifier had a "pulse pile up" saturation at a slightly lower rate, around 300 kHz. With a few square millimeters of geometric factor, and an energy sweep of 32 steps, AMPTE only began to saturate in the highly compressed region behind the Earth's bowshock, the magnetosheath, where the density peaked around 50/cc [25].

11.5.3. Isochronous TOF-MS

These instruments were so well optimized that it became clear no further improvements were possible using more advanced materials or electronics. Much attention was directed to the C-foil, and the inherent energy straggle that directly reduced the mass resolution. Despite extensive testing of metals, plastics, and composites, resulting in several theory papers, nothing was found that had better energy straggle properties [26]. But if the TOF could be made independent of energy, then perhaps the straggle could be finessed. In the laboratory, TOF-MS "reflectrons" had been demonstrated that achieved first-order correction in the energy (see Section 2.2.1). But Laplace's equation for a vacuum electric potential Φ, $\nabla^2\Phi = 0$, says that if one dimension is reflecting with a positive second derivative, one or both of the other dimensions must be diverging, with a negative second derivative. In practice, this means that the ions in a reflectron must be highly collimated to avoid being diverted into the walls by the reflecting field. However, collimation is inversely proportional to energy spread, so the C-foil destroys both! Would it be possible, we reasoned, to place the C-foil as close as possible to the reflectron to minimize the divergence of the beam?

In this case, the mirror should be a parabolic electric field, so that like Galileo's chandelier the period of oscillation would be independent of the energy amplitude, $\Phi = z^2$. As it turned out, two simple solutions to Laplace's equation exist, $\Phi = z^2 - y^2$ in planar geometry, and $\Phi = 2z^2 - (x^2 + y^2)$ in cylindrical geometry. Both of these solutions diverge badly, but a computer glitch saved the day. The first, planar solution is seen to be the equation for a hyperbola, so one quarter of a hyperbola consisting of a "V" held at ground, and a "U" at positive 20 kV was simulated on an ancient HP2000 computer (Fig. 11.4). The computer had only 64 k of memory, and was unable to store the entire model in memory at once. As a consequence, particles often did not collide, but passed through potential structures. When we started particles from the point of the "V" upward toward the "U," they reflected and scattered, passing through the "V" potential until ultimately striking the bottom of the simulation box. Surprisingly, it had very little effect on the TOF; the isochronicity of the particles was preserved. When we analyzed the effect, we found that the greatest contribution to the TOF came at the closest approach to the "U," not down near the point of the "V." Galileo's chandelier, after all, wasn't swinging in a parabola but in a circle, yet it made little difference to the TOF. With this insight, we stopped worrying about the scattering of the particles, put in a transparent grid on the "V" and collected them wherever they went, thus making the first practical application to an isochronous TOF and achieving a R $\sim$100.

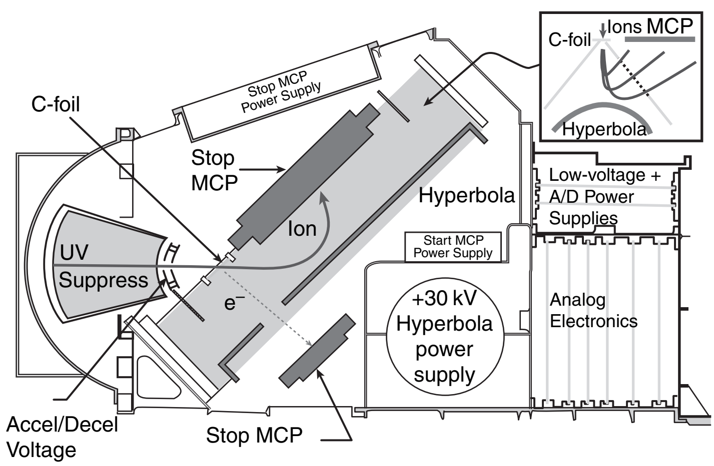

Figure 11.4. WIND/MASS schematic courtesy R.Sheldon, NASA.

11.6. GENESIS AND THE FUTURE

This instrument flew on three missions: SOHO, WIND, and ACE, where it has returned information about solar wind isotopes confirming the meteoritical abundances for the proto-solar nebulae [27], as well as identifying boundaries in the solar wind. With more than enough resolution to detect ^{17}O, why then was the GENESIS mission funded to return samples of the solar wind [22]? Well, the problem turned out to be the C-foil once again.

When the ions penetrate the foil, they achieve an equilibrium charge state that depends on their speed. The 2 to 10 keV/nuc achieved in solar wind plasmas, even after post-acceleration, resulted in an exit population that was more than 90% neutral. These neutralized ions did not reflect, but impacted the hyperbola and produced electrons, ions, or just scattered around inside the instrument. This created a high background that we could suppress only slightly, so that there always existed a long TOF "tail" to every peak. A rare isotope to the right of the main peak was then invisible, and the effective dynamic range for an isotope such as ^{17}O was about 1%, but its abundance was only 0.1% of ^{16}O. Consequently GENESIS was conceived as a sample-and-return mission to solve the rare abundances in the laboratory [29].

The future, perhaps, is exemplified by the ROSETTA mission, which uses an ion trap and electrostatic gating rather than carbon foils to achieve a R $\sim$3000. While the foils are excellent in producing nanosecond timing on fast particles with very simple electronics, advances in power supplies and switching means that future instruments will be capable of both the nanosecond gates and the kilovolt energies without the C-foils. Then all the advantages of C-foils will be obtained without the energy straggle, scattering, or neutralization disadvantages. We are developing such instruments in our lab, and foresee space MS that can exceed R $>$5000.

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