Innovations in plasma sensors

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Key Points:

- Most innovations in space plasma instrumentations arise from a mismatch of heritage technologies
- The detection of suprathermal and very low-energy ions are innovation areas of the decadal survey
- Constellations of small spacecraft enable novel and highly constrained plasma measurements .

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This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/2016JA022493

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Abstract

During the history of space exploration, ever improving instruments have continued to enable new measurements and discoveries. Focusing on plasma sensors, we examine the processes by which such new instrument innovations have occurred over the past decades. Due to risk intolerance prevalent in many NASA space missions, innovations in plasma instrumentation occur primarily when heritage systems fail to meet science requirements, functional requirements as part of its space platform, or design constraints. We will review such innovation triggers in the context of the design literature and with the help of two case studies, the Fast Imaging Plasma Spectrometer on MESSENGER, and the Fast Plasma Investigation on Magnetosphere Multiscale. We will then discuss the anticipated needs for new plasma instrument innovations to enable the science program of the next decade.

1. Introduction

Plasma analyzers are some of the most successful and most broadly deployed instruments in solar and space physics. These sensors provide measurements of velocity distribution functions of charged particles to investigate their physical properties, dynamic evolutionary properties and — with suitable additions — their composition and thus their origin or astrophysical context. We routinely use plasma instrumentation to measure solar wind for space weather forecasts and now-casts. Continued development of these critical measurements have opened the door to examine science objectives such as studying the origins of the Sun’s activity, predicting variations in the space environment, and understanding the dynamic coupling of the Earth’s magnetosphere to solar and terrestrial inputs. Furthermore, measurements of pick-up ions

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have provided insights into the interaction of the Sun with the solar system and interstellar medium. Finally, data from plasma analyzers — together with other in situ and remote measurements — have help us discover and characterize fundamental processes within the heliosphere and throughout the universe [*Space Studies Board*, 2013].

Yet the technological advances of plasma sensors that have been driving rapid progress in the understanding of space science have slowed down, and we therefore risk slowing down the speed at which we discover new aspects of our space environment and the solar system. During the development of the most recent decadal strategy for solar and space physics [*Space Studies Board*, 2013], a series of technology studies were undertaken, focused on the most exciting missions imagined by our broad science community. Analyzing all proposed and prioritized missions, as provided in the Appendix of the decadal survey, the report concluded that there were no new instrument technologies needed to enable the proposed strategy. (The study director of The Aerospace Corporation noted: "This is the only NASA decadal survey that does not include really new technologies.") This leads us to pose the question at the heart of this paper: What are the mechanisms that drive innovative and novel space instruments?

Such mechanisms for innovation can occur for two qualitatively different reasons. First, novel and innovative instrument systems and subsystems can be developed because of the availability of new technologies. Alternatively, new instrument technologies can be developed out of necessity, because the traditional heritage approaches prove inadequate for the task.

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There are many reasons why the former motivator – the availability of new technology - rarely leads to the development of new instrumentation. First and foremost, the management philosophy underlying the development of space mission is risk-averse. Part of this risk-aversion is necessary and driven by sound engineering-based arguments: We want our spacebased instruments to do the job, and instrument failure of a strategically important mission can adversely affect an entire research community. As opposed to other laboratory-based research areas, the space community usually has only one chance to get their instruments to work. Even a minor mistake, which could be fixed easily in a laboratory setting, can lead to mission failure, and only a costly re-flight can address a gap arising from a technology mistake. Yet, typically, the ambiguity associated with the first application of new technologies and actual technological reliability are treated the same way: a significantly lower rating on the Technology Readiness Level (TRL) [*NASA*, 2007] during mission selection, and/or an increase of mass, power, and financial reserves to account for any unexpected growth. In fact, in many reviews, risk and TRL level are treated almost synonymously, even though risk has a large number of components that by far exceed the technological readiness of a given system. An additional barrier to innovation comes from reputational risk to the proposer. It is easy for an experienced elder in the community to eliminate a proposal based on inexperience with the technology or the proposer. As a result of these factors, novel instrument designs for the sake of a breakthrough technology rarely occur.

We therefore conclude that instrument innovation tends to come from a mismatch of the heritage technologies with system requirements of a new mission — the well-known technology

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just does not do the job, and there is an unmet need to create something new, something creative. Fundamentally, such requirements come in three different flavors [*Wertz and Larson*, 1999]. In the context of instrument design, *functional requirements* are often referred to as measurement requirements, such as the time-resolution, the energy range or the mass-range and resolution of a given instrument. Typically, heritage systems can be adapted for changes in functional requirements, within a factor of 2 or 3, but order of magnitude adaptations are seldom fruitful or even physically possible. For example, the sensitivity of plasma instruments scales with R^2 or even faster, if R is the scaling factor, or electric fields in the sensors become too large for increasingly small scale-factors. *Operational requirements* are also important system requirements, referring, for example, to autonomous operation of a system, or the necessity that an instrument has to run in a significant radiation environment. Finally, instrument requirements also include *constraints*, such as mass-limits, or power-limits, which can render a heritage approach inadequate. It is important to note that one of these three types of requirements — functional or operational requirements, and constraints — can have the same impact on the adaptability of heritage technologies and can render them inadequate or even obsolete for a given application.

Section 2 will provide a short introduction into electrostatic analyzers, an important subset of plasma analyzers, and then discuss two case studies of innovation for plasma analyzers. Section 3 will provide a brief review of the relevant management literature, putting in context our case studies and lessons learned. Section 4 will then address the science priorities of the

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missions ranked by the decadal survey with respect to their innovative potential, and Section 5 will provide concluding remarks.

2. Electrostatic Analyzers and Case Studies

2.1. Introduction

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Electrostatic analyzes serve as front ends to low-energy plasma detectors and are designed to filter particles within a given energy-per-charge band for a given applied voltage. In addition, electrostatic analyzers are also responsible for the suppression of UV/EUV light [*Zurbuchen et al.*, 1995; *Gershman and Zurbuchen*, 2010], which can otherwise cause spurious background counts in the UV-sensitive particle detectors.

For particle populations propagating supersonically and with components with nearly identical speeds, like the solar wind, electrostatic analyzers not only serve to analyze particle distribution functions, but also as a mass spectrometer, as shown in Figure 1a, using data near 1 AU from the electrostatic analyzer of the Fast Imaging Plasma Spectrometer (FIPS), that was part of the MESSENGER payload [*Andrews et al.*, 2007]. Hot solar wind plasma composed of H^+ and He^{++}, as shown in Figure 1b, collected by the same instrument near 0.3 AU, is not as easily mass-separated and the flux in the He^{++} peak gets close to the signal-to-noise ratio of H^+ at its high energy. When adding a linear (or straight-through) time-of-flight section, the ensuing double-coincidence mass spectrometer (i.e., for each ion, this instrument measures both a start and a stop signal) allows a clear separation of the two peaks, even at high temperatures, and also reveals the presence of other species, such as He^+ or heavy ions from the Sun, as shown in Figure

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1c. Detailed solar wind compositional experiments have been pioneered using a triple coincidence technique: each ion passes through the electrostatic analyzer and, after an acceleration in a high voltage, passes through a time-of-flight and is finally measured in a solid state detector. Because of the superb background suppression approach, this measurement technique allows the successful detection of trace ions at dynamic range of 1:10^6 or better [*Gilbert et al.*, 2014].

The most commonly used type of electrostatic analyzer is a cylindrically symmetric top-hat detector with uniform field of view, reaching 360 deg about its symmetry axis, with a relatively small field of view in the polar direction [*Carlson et al.*, 1982]. Examples of such sensors are shown in Figure 2. These top-hat systems have been adapted to a number of applications and have proven versatile due to their near-Gaussian response in energy per charge, compact form factor, and approximate mathematical description of its response function [*Young et al.*, 1988].

Recent applications of top-hat sensors include the use of multiple sensors to increase the effective time-resolution of a spinning spacecraft [*Carlson et al.*, 2001], a creative back-to-back packaging technique for ions and electrons in a double-top-hat design [*Burch et al.*, 2007], and a creative inclusion of RF-driven suppression of protons designed to enhance the dynamic range and focus on heavy ions [*Young et al.*, 2014].

There are, however, alternative designs for electrostatic analyzers that do not use the common top-hat technology. These include a creative electrostatic analyzer with nearly 2pi field

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of view [*Vaisberg et al.*, 1997], a fast delta-function sampling technique of velocity space [*Scudder et al*., 1995], and a spherical analyzer followed by isochronous time of flight that is part of the *Wind* SMS instrument [*Gloeckler et al.*, 1995].

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2.2. A case study for innovation driven by constraints: Fast Imaging Plasma Spectrometer on MESSENGER

The first example provided here is that of the successful Fast Imaging Plasma Spectrometer (FIPS), which was designed to be part of the MESSENGER payload with the goal of measuring the evolution in space and time of Mercury's plasma environment that is composed of a combination of solar wind and planetary ions. All functional and operational requirements of this sensor are very much within the realm of a top-hat enabled sensor with a linear time of flight [see *Andrews et al.*, 2007, for details]. Yet, the desired near 2pi field of view, with an initial mass constraints of 1 kg and a power target of 1 W were considered beyond the reach of a heritage system.

The initial design of the FIPS sensor is summarized in Figure 3a [from *Zurbuchen et al.*, 1998], which proposed a symmetrical system with large instantaneous field of view enabled by a novel electrostatic design that involved an imaging back-plane similar to a top-hat design, but extended over nearly the entire active area of the analyzer. This led to necessary changes of the time-of-flight section, starting with a large-area C-foil [*Funsten et al.*, 1994] and a two-dimensional imaging time-of-flight section that required the development of a novel electrostatic mirror with very large fractional transparency. This novel electrostatic analyzer system also had

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a substantially smaller analyzer constant, closer to 1.3 as opposed to 5-10, as is common with thin-gap analyzers, requiring the development of a power supply with significantly higher voltage than heritage systems, and reducing the energy/charge range of the sensors to 20 keV/q. To save mass, a new ASIC-enabled time-of-flight circuit was included [*Paschalidis et al.*, 2002; *Rogacki and Zurbuchen*, 2013]. Thus, the severe mass and power constraints drove changes to almost every single subsystem. Figure 3b shows the design in its flight configuration. Important modifications to the front-end related to the manufacturability of the initially proposed sensor, its initially inadequate geometric factor, and also the UV/EUV leakage that needed to be mitigated.

Figure 4 shows three-dimensional measurements of MESSENGER FIPS averaged over Mercury's northern cusp from a study by *Raines et al.* [2014]. Because of its time-of-flight capabilities and wide field of view, the dynamics of both solar wind-origin (H^+, Figure 4a) and planetary origin (Na^+, Figure 4b) ions can be resolved. A ~60° loss cone is observed in the H^+ indicative of tremendous amounts of space weathering of Mercury's surface by the solar wind. A low-energy population of planetary ions is shown to travel upward along the magnetic field, suggestive of outflow of newly ionized material as a consequence of this precipitation process.

In summary, the FIPS instrument was a novel instrument design for a mission for which mass and power constraints rendered a heritage solution impossible. The driving innovation was the novel electrostatic analyzer design, but that subsystem innovation drove changes throughout the entire instrument design. The novelty did not stop at the construction phase either. Due to

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the open orientation of the time-of-flight section, the noise characteristics of this instrument changed, and novel analysis methodologies had to be developed [*Gilbert et al.*, 2014].

2.3. A case study for innovation driven by functional requirements: Fast Plasma Instrument on Magnetospheric Multiscale

The second example provided here is the Fast Plasma Investigation (FPI) suite for the Magnetospheric Multiscale (MMS) mission (*Pollock et al.*, The Fast Plasma Investigation for Magnetospheric Multiscale, submitted to *Space Sci. Rev.*, 2016). FPI consists of 16 Dual Ion and Dual Electron Spectrometers spread across four spacecraft observatories with the objective of studying the microphysics of magnetic reconnection, a ubiquitous process in space plasma. Typical magnetospheric spacecraft (e.g., THEMIS and Cluster II) deploy plasma analyzers on spinning spacecraft such that the temporal resolution of particle distribution functions is linked to the spacecraft spin period, which is at minimum a few seconds. Such measurement cadences were insufficient to resolve the dynamics in the electron diffusion region at Earth's magnetopause that require full three-dimensional distributions to be measured in ~30 ms.. Furthermore, in addition to improving upon instrument time resolution by an order of magnitude, the sensitivity of MMS's plasma instrumentation needed to maintain the high sensitivity and dynamic-range capabilities present in previous missions.

Because no technology was available to simultaneously meet all of these functional requirements, MMS/FPI adopted a brute-force approach: deploy multiple, identical analyzers across a single observatory to measure the full sky in a small fraction of the spacecraft spin

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period. The key innovation of FPI is not in its configuration, nor necessarily in the design of the sensors themselves, which are high-heritage, top-hat electrostatic analyzers. Instead, the challenge of FPI was to turn space instrument development, which typically consists of the creation of one or two flight-ready prototypes, into a production process capable of producing 32 near-identical ion and electron sensor heads. It is not unusual that two or three copies of a given space instruments are being developed, using one copy for life-time tests, for example, and/or to retain a spare on the ground for support of the flight data. However, for FPI, the manufacturing, assembly, and calibration processes for spaceflight were redefined, and heavy investment was made to develop automated test stations. These stations conducted and recorded results from comprehensive beam tests on each analyzer (see *Pollock et al*., The Fast Plasma Investigation for Magnetospheric Multiscale, submitted to Space Sci. Rev., 2016) and demonstrated that the flight models had matching geometric factors per anode to within ±10% (illustrated in Figure 5). Furthermore, the need for high-fidelity flat-fielding of multiple sensors required the invention and implementation of specialized daily on-orbit calibration and data processing procedures driving innovations in not only the production of sensors but in space plasma data analysis.

3. Innovation of Space Instrument in the Management Literature

Innovation of new technologies breaks down into two distinct activities that need to be coupled for innovation to be impactful [*March*, 1991]. The first activity is one of *exploration*. During the exploration phase, innovation can look disorganized from the outside, and even messy. Many attempts are typically needed until a breakthrough occurs. The culture in which innovative exploration occurs is one that embraces the iterations that are needed to get the

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technology to become useful. Innovative teams need freedom to think and freedom to act and a leadership model that embraces the new and things with high potential. Teams who excel at this first phase of innovation are often strongly purpose and goal focused and constraints often help them create better ideas; they are not just running "open loop".

Furthermore, innovation teams who work in the exploration phase benefit from outside views, especially if they are working on big ideas [*Johnson*, 2010]. Good ideas often come from mixing concepts from different and previously unrelated fields. They can have different characteristics over time — a fast hunch, or a slowly evolving concept one has to grapple with before an "intellectual watershed" is crossed and the innovator sees his/her idea and understands its relation. But, such exploring innovations most often come from relatively small teams, which are rather independent from bureaucracy and top-down management processes.

This exploration phase is followed by one of *exploitation*. Now the new ideas are being integrated into the right instruments, and are being made to work. The key challenge of the exploitation phase is that it stands at the interface of the free, boundless innovator and the processes and structures that are needed to actually turn the innovation into reality. Dealing with this tension between the freewheeling innovator and a process-driven implementation process requires management processed that can deal with these contradictions, and still allow the technology to grow in its right place [*Smith and Tushman*, 2005; *Csikszentmihalyi*, 2013]. In many cases, the exploitation-focused innovators are not the same people as the exploration-

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focused innovators and a communication interface ensues that creates a valley where many good ideas find an abrupt end.

In space science, this interplay between exploration and exploitation phases of innovation is often ineffective [*Szajnfarber*, 2014, and references therein]. First and foremost, many of the best ideas regarding instruments come from outside of NASA, leveraged from a variety of R&D programs. But even within NASA, an over-emphasis on the early exploration stage of new investments followed by a lack of funds focused on maturation creates a highly inefficient process. This results in a situation where only few new and potentially important ideas are moving into flight projects. An over-investment in the exploitation phase, or one that is disconnected from idea-streams of the exploration activities, leads to stagnation and idea-poor programs. There are multiple management strategies on how to deal with this transition, but no consensus exists on how these competing forces should best be managed.

In the NASA space science community, the exploration phase is focused on low-TRL developments, on proof of principle all the way to component and breadboard validation. When proposing space missions, all technologies typically should be above TRL6, a system/subsystem model and prototype demonstration in the relevant environment. If possible, proposers want to rely on TRL7-9, which requires successful system demonstration or operation in flight.

The overall character of innovation cycles summarized previously can be observed with respect to heliophysics missions. The innovation infrastructure leveraged by NASA R&D programs is broadly distributed and includes hundreds of research groups within universities,

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industry, and NASA centers. As pointed out by *Szajnfarber* [2014], the transition to flight-readiness is mired by a series of challenges that are both programmatic, cultural, and even policy related. There are also important differences between Center-led flagship missions and smaller, PI-led missions with respect to their ability to transition such technologies to TRL 9.

The overall conclusion from these analyses is that there are significant and perhaps even insurmountable hurdles that limit technology push — the steady transition from exploration to exploitation — as an innovation strategy. The best examples for such transitions occur when there is technology pull, because the technology is an enabler for a new measurement or new mission architecture.

Finally, we want to add a few comments about risk management. According to the NASA System Engineering Handbook, "Risk is a measure of the inability to achieve overall program objectives within defined cost, schedule, and technical constraints and has two components: (1) the probability of failing to achieve a particular outcome and (2) the consequences/impacts of failing to achieve that outcome." Risk falls into multiple categories, such as technical risk, programmatic risk, etc., to mention only a few. There is value to risk assessment processes that are being used everywhere in NASA and also, in some modified form, in the broader business community [e.g. *Garrick*, 1988].

There are some risks that are quantifiable, and some — especially in new or lesser-known technology areas — are much more strongly based on perception and therefore not founded in reality [*Slovic*, 1987]. There are also factors of risk that are very difficult to quantify but tend to

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be more important than things that are easily measureable. For example, reviews of the Mars Program in 2000, especially the Mars Climate Orbiter, point to the importance of a well-functioning team, good systems engineering, and communications for mission success. Few mission failures result from low TRL.

4. Innovation Opportunities for Plasma Instruments during the Next Decade

Decadal surveys are community based strategic planning activities by the National Academies that provide a review of research and applications reflecting the status of the field, list key science questions that should drive investments in the next decade, and also recommend specific research programs, missions, and ground-based facilities to address these science questions [*Space Studies Board*, 2015]. The proposed science program is “realistic”, in a sense that the program fits within a notional and pre-prescribed budget envelope.

Because of this budgetary boundary condition, a process for cost and technical evaluation (CATE) was devised which allows estimating the cost for proposed new missions. The requirement for such estimates was added as part of the 2008 NASA Authorization Act (Congress of the United States, National Aeronautics and Space Administration Authorization Act of 2008, Public Law 110-422, Section 1104b, October 15, 2008), which required an independent cost estimate and is not driven by mission advocates who tend to create highly optimistic or even unrealistic cost estimates. The CATE estimate is based on analogies and historic data for performance of each space instrument and subsystem [*Space Studies Board*, 2015]. Cost reserves are then added based on a probabilistic analysis [see, chapter by *Apgar* in *Wertz and Larson*, 1999]. Typically, more complex systems with a small amount of heritage will

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require a larger fraction of cost reserves than a system that is largely a rebuild of what already exists and has flown in space. Similar, although not identical, cost estimation strategies are used during proposal selections.

The most recent decadal review [*Space Studies Board*, 2013] recommended a number of important programs that include plasma instruments, as summarized in Table 1. Each program or mission that implies the use of plasma sensors is summarized there, together with a short description of the plasma sensor needed for that particular mission.

There are at least three important opportunities for innovation during the next decade, as implied by Table 1, which are small spacecraft and multi-spacecraft constellations, and suprathermal plasma and composition instruments, as well as low-energy ionospheric plasma and composition sensors. These will now be addressed in the following subsections.

4.1. Small spacecraft and multi-spacecraft constellations

Small spacecraft have been important research platforms for a number of years. Consider the Advanced Composition Explorer (ACE) [*Stone et al.*, 1998] and the Time History of Events and Macroscale Interactions during Substorms (THEMIS) [*Angelopoulos*, 2008], two Explorer missions that have had tremendous impact transforming a field of research. ACE carried composition instruments that have set the standard in solar wind and suprathermal particle distributions. For example, the Solar Wind Ion Composition Spectrometer (SWICS) on ACE [*Gloeckler et al.*, 1998] provided the most comprehensive dataset of the solar wind composition to date. As a sister instrument to the Ulysses sensor with the same name, ACE SWICS benefits

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from enhanced data rates and near-solar distances to provide complete ionic charge distributions for solar wind ions and pickup ions, a feat that had not been achieved previously [*Gilbert et al.*, 2012]. Similarly, the Solar Wind Electron Proton and Alpha Monitor (SWEPAM) [*McComas et al.*, 1998] has been providing real-time solar wind data for space weather predictions, the first solar wind sensor to do so.

The THEMIS mission has provided definitive measurements of substorms, especially during their onset and expansion phases. THEMIS consists of five identical micro-satellites that carry a rather complete payload. Due to their unique orbital design, the THEMIS probes could detect substorm onsets and other magnetospheric phenomena *as a distributed measurement system*. At launch, each probe weighed 134 kg, including 49 kg of hydrazine, providing nearly 1 km/sec of delta-V. In many ways, the success of THEMIS, a mass- and budget-constrained constellation, has never been surpassed.

In cost models for instruments and spacecraft, as previously discussed, THEMIS systems are outliers, much cheaper than other heritage instruments. Although there may be a variety of reasons for this, the differences undoubtedly relate to the fact that this mission was built using very different and innovative approaches, in both instrument development and also testing of the system. THEMIS used a smaller spacecraft and managed to develop instruments that were good enough for the task at hand. Even though instruments with more capacity and more complexity could have been built, they would not have created mission success within the constraints.

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There is wisdom in looking at the direct relationship of small spacecraft and the ability to fly constellations, like GDC in Table 1. To create a dense set of measurements of the magnetosphere, and also several other multi-scalar plasma phenomena, the number of spacecraft available needs to be large compared to 5 to achieve breakthrough research. Yet an evolutionary trajectory that uses heritage systems leads to multibillion dollar missions for such designs. It is therefore critical to develop “disruptive innovations”, as defined by *Christensen* [1997]: technological innovations that can surpass heritage systems that have seemingly exceeding qualities.

CubeSats and other pico-satellites [see, *Heidt et al.*, 2000; *Fleeter*, 2010 and references therein] are such disruptive platforms that have the potential to become parts of large magnetospheric constellations. Yet important instrument and spacecraft technological innovation has to occur to provide the necessary measurements within constraints and to be consistent with the functional requirements implied by a large and distributed constellation of spacecraft.

It should be noted that there are physical constraints that limit the ability to shrink the size of certain instruments. For example, the count rate of particle sensors is generally directly proportional to their aperture area, and shrinking the sensor reduces their count-rate and thus their scientific value. As mentioned in section 2.2, some of these constraints can be addressed with instrument innovations, such as adding angular range to make up for smaller aperture size. But other factors provide rather stringent constraints on the minimum size a scientifically useful instrument can have.

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4.2. Suprathermal plasma and composition instruments

Suprathermal plasmas are composed of particles at energy ranges intermediate to thermal energies and particle energies of 100 keV or higher. This energy range is of importance because it appears to contain the critical energy range for particles and injection into shock acceleration. This energy range within heliospheric plasmas also contains pickup ions, which carry critical compositional information about their galactic or planetary sources (see Table 1).

Depending on required time resolution and mass resolution, suprathermal particle measurements are ripe with opportunities for innovation because their densities are very small compared to thermal plasmas. Furthermore, these low densities occupy a large volume in phase-space, leading to very small count rates in a given observational pixel of energy and angular range. These small count rates limit the time resolution of current instrument techniques, but also set important constraints on the signal-to-noise requirements of the measurement technique, such as provided by triple coincidence techniques [*Gilbert et al.*, 2014].

4.3. Very low-energy ions

Finally, high-resolution measurements of cold, low-energy particles near the Earth's exobase region are crucial to understanding ionosphere-thermosphere-magnetosphere coupling (i.e., MEDICI/DYNAMIC). Very high energy and angular resolutions are required to measure the detailed pressure tensor of ions, in particular the partitioning of perpendicular and parallel energy that may be critical to obtain a complete picture of the physics that drive ionospheric outflow. Thermal and suprathermal electron measurements also provide crucial insight into

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coupling processes. These measurements are further challenged by spacecraft charging, sheath and small particle gyroradius effects [e.g., *Whalen et al.*, 1994; *Pollock et al.*, 1998; *MacDonald et al.*, 2006] that demand the miniaturization of technology to enable packaging on small satellites or onto deployable booms.

5. Summary and Discussion

We have focused on innovations of plasma sensors during the past decades and have argued that the most important process for innovation or the advancement of a technology most often results from need – from a pull of technology, and not a technology push. When functional requirements, operational requirements, or constraints imposed by upcoming missions are no longer satisfied by the status quo, then new ideas are required. We visualized these processes using two case studies, then put it into the broader context of innovation theory, and applied prevalent risk assessment methodologies. We concluded that risks from novel technologies might be overstated relative to other important factors, such as team composition and cohesion, communication processes, and programmatic focus, etc., which have historically had a major impact on mission success. (Often, experienced investigators refer to programmatic focus as TLC ("tender loving care"), the ability to get to know the instrument inside-out, focus on its performance and its measurements, and address any performance issues that inadvertently show up during the lifetime of an instrument.)

We identified key opportunities for instrument development during the next decade, using proposed programs and missions in the decadal review. These opportunities come from science questions that push the limits of the status quo, but also from constraints from small

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systems, such as CubeSats and other pico-satellite platforms for which heritage instruments are typically not a good match or even woefully inadequate.

The apparent dearth of innovation in plasma sensors and other space instruments constitutes a challenge to our community at large. For heliophysics to remain a vital and exciting field for us and the next generation to come, we need to ask difficult science questions and be comfortable with experiments to answer them that reach beyond the status quo. The worst thing we could do as scientists is to discourage such developments or even brand an instrument as “high risk” during a review just because we do not recognize its look or the PI on the proposal. The next decade provides ample opportunities for breakthroughs — we better not miss them.

Acknowledgments

THZ acknowledges the support of the International Space Science Institute where much of this work was performed. There is no new data presented in this paper.

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Table 1. Summary of recommendations for missions from the *Space Studies Board* [2013] using abbreviations provided in the report, a bullet-like description, and a summary of the anticipated needs for plasma instrumentation for each recommendation.

Program/ Mission	**Recommendation**	**Plasma Sensor**
DRIVE	Expand small mission capability using CubeSats or other platforms.	Various, focus on small and constrained platforms
Explorers	Explorer Programs, which have been key contributors to solar and space physics	Various, including constellations
IMAP	An interstellar mapping probe with both ENA remote sensing and in situ data	Focused on suprathermal ions and especially pickup ions to 100 keV/e
DYNAMIC	A mission focused on the dynamics of neutral atmosphere –ionosphere coupling	Focused on ion velocity meter and ion neutral mass spectrograph
MEDICI	A multi-spacecraft mission aimed at analyzing the magnetosphere-ionosphere-thermosphere system	Ion and electron plasma sensors
GDC	A global dynamics constellation designed to transform our understanding of the magnetosphere through multi-point measurements	Electron and ion plasma and composition sensors

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Figure 1. Solar wind measurements in the heliosphere by the Fast Imaging Plasma Spectrometer (FIPS). (a) Raw data of counts as a function of energy/charge measured near 1 AU. He^{2+} and H^+ are readily separable. (b) Equivalent measurements near 0.3 AU where such a separation is no longer easy. (c) The same data resolved in both E/q and time of flight, allowing an easy separation of the two components.

Figure 2. Heritage sensors for top-hat designs in a variety of applications. For detailed discussion, refer to text.

Figure 3. The initial and flight designs of the Fast Imaging Plasma Spectrometer. Both designs foresee a large field of view and imaging time-of-flight section with post-acceleration. But the initial design did not have enough sensitivity and needed to be adapted. Figures adapted from *Zurbuchen et al.*, [1998] and *Andrews et al.*, [2007].

Figure 4. Proton and Na^+ velocity distributions measured in Mercury's cusp plasmas adapted from *Raines et al.* [2014]. The distributions show a large loss cone for the solar-wind-borne protons and an upwelling Na^+ population indicative of a low-altitude source of energized planetary ions. Figure adapted from *Raines et al.*, [2014].

Figure 5. Results of beam calibration of the Dual Electron Spectrometers on MMS adapted from *Pollock et al*. (The Fast Plasma Investigation for Magnetospheric Multiscale, submitted to Space Sci. Rev., 2016). Each unit was placed in a cradle (top left) with a nearby Retarding Potential Analyzer / Faraday cup assembly to enable near real-time beam monitoring. Automated test

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stations generated energy-angle plots (right) for each of 16 anodes in 32 sensor heads. The assembled flight models produced geometric factors per anode within ±10% (bottom left).

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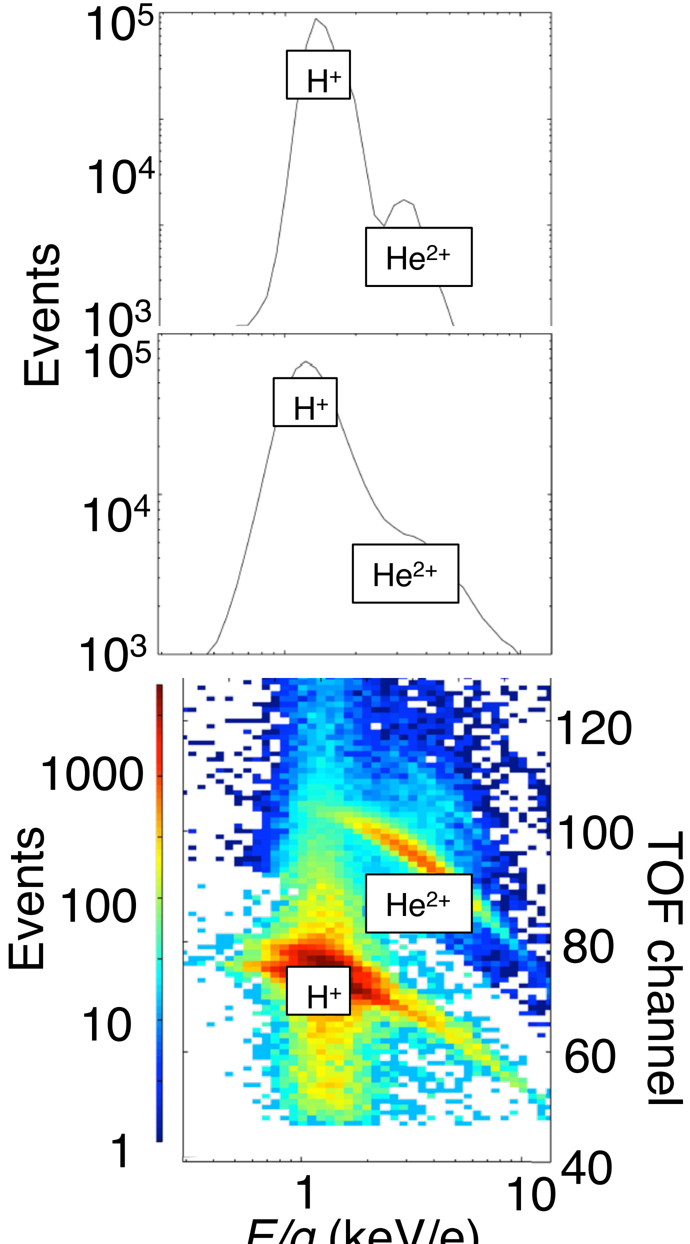

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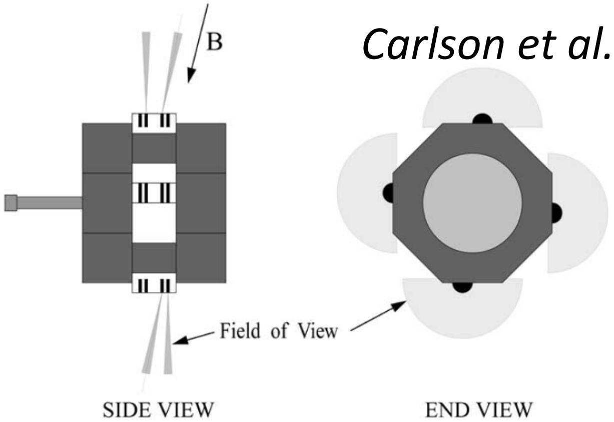
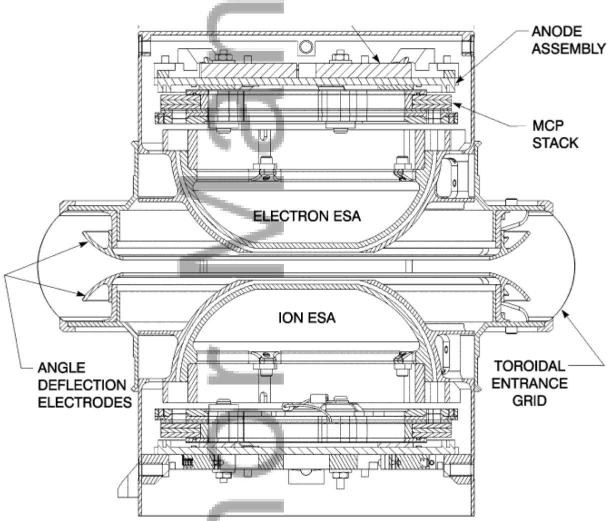
Use of multiple sensors to increase effective time-resolution
ESA (FAST), FPI (MMS)



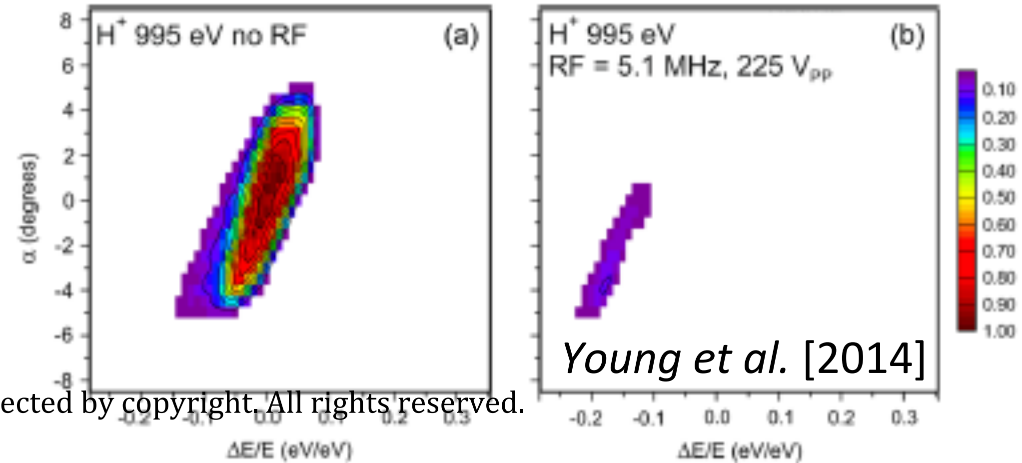
Carlson et al. [2001]



Shared deflectors for electron and ion sensors
IES (Rosetta)

Burch et al. [2007]

RF-driven ESA reduces H^+ fluxes
HPCA (MMS)



Young et al. [2014]

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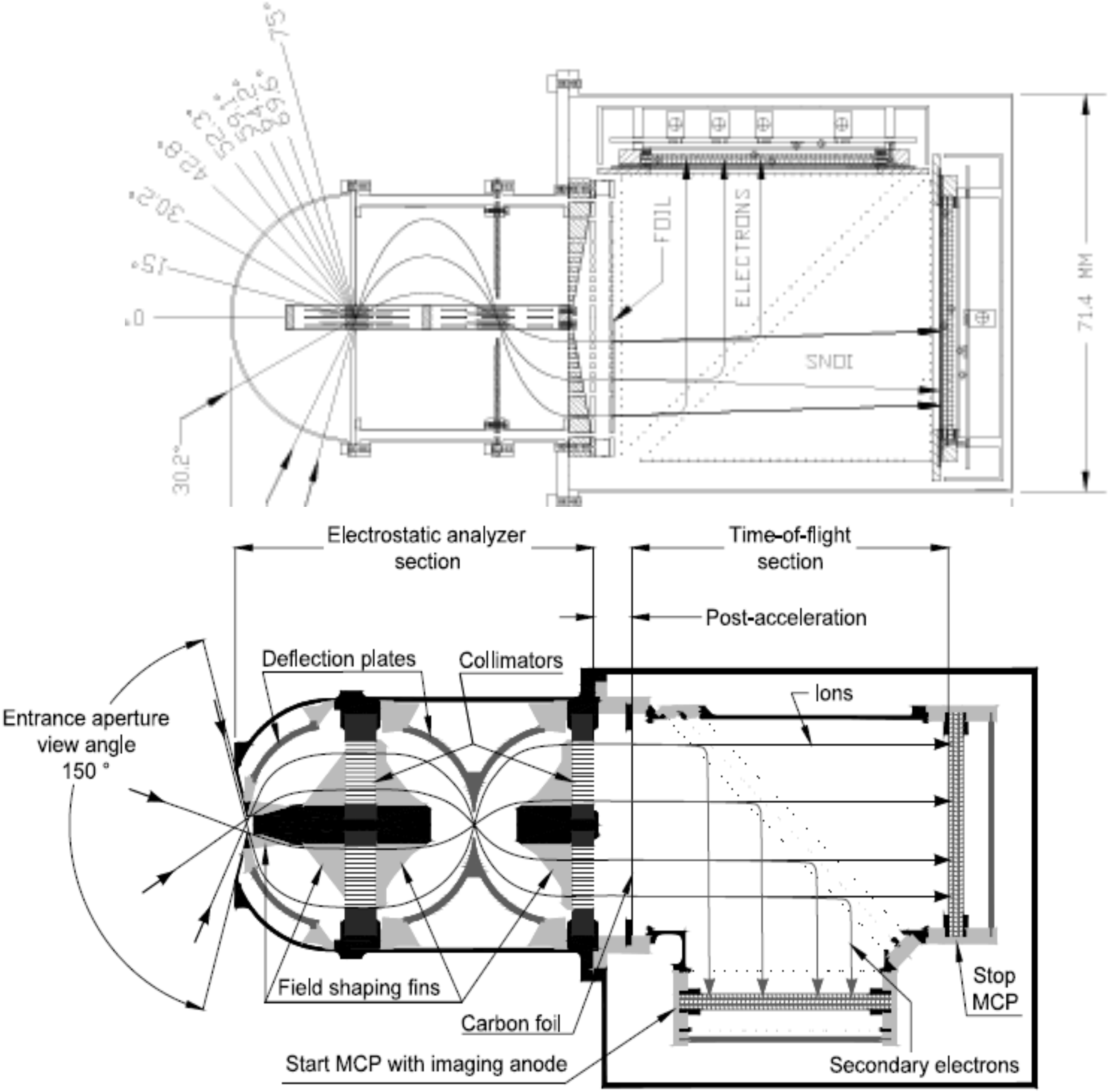

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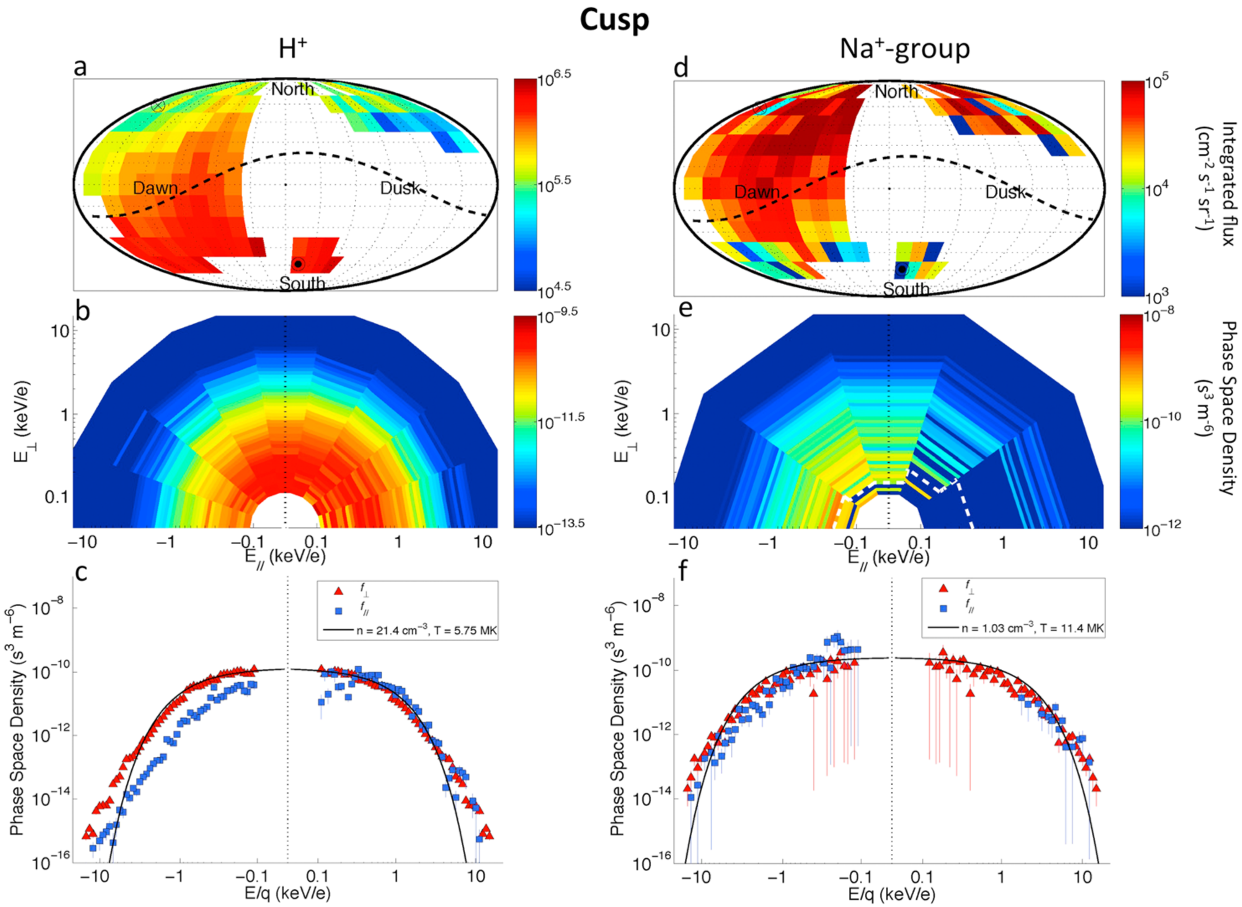

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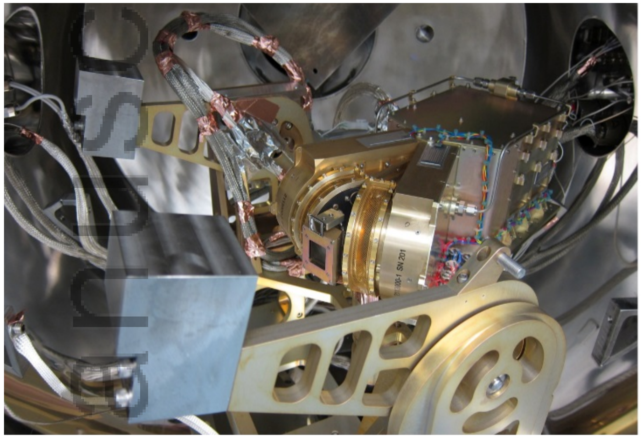

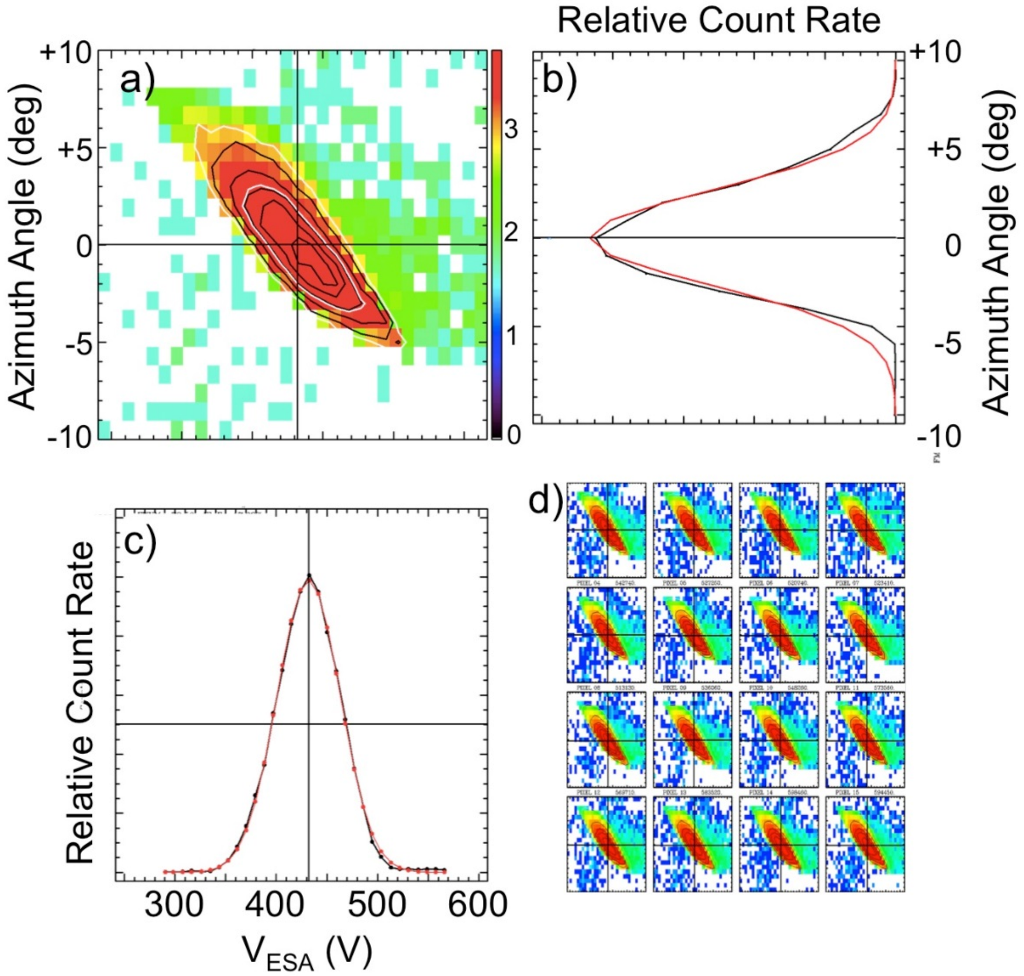

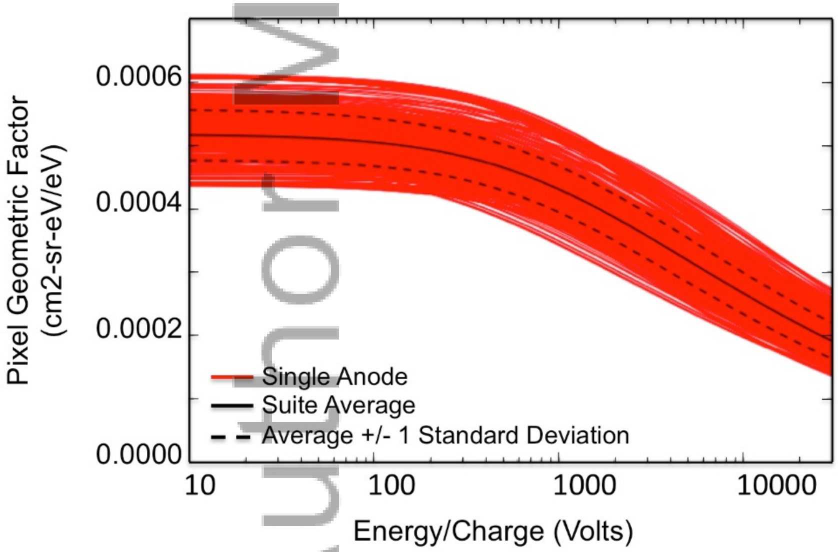

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