

# Mass Spectrograph for Imaging low energy neutral atoms

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## ABSTRACT

We describe an instrument concept for measuring low energy neutral H and O atoms with kinetic energies ranging from about 10 eV to several 100 eV. The instrument makes use of a low work function surface to convert neutral atoms to negative ions. These ions are then accelerated away from the surface and brought to an intermediate focus by a large aperture lens. After deflection in a spherical electrostatic analyzer, the ions are post accelerated to ~25 keV final energy into a time-of-flight mass analyzer. The latter consists of a thin carbon foil at the entrance that provides the secondary electrons for the start signal, a drift space, and a stop microchannel plate that detects the primary particles. Mass resolution is adequate for resolving H, He, and O, and the isotopes D and <sup>3</sup>He. The image created by the spherical electrostatic analyzer is arc shaped with initial incident direction dispersed in azimuth and energy dispersed radially. Energy and azimuth information are obtained by position imaging the secondary electrons produced at the foil. A large geometric factor combined with simultaneous angle-energy-mass imaging that eliminates the need for duty cycles provide the necessary high sensitivity. From a spinning spacecraft this instrument is capable of producing a two - dimensional map of low energy neutral atom fluxes.

## 1. INTRODUCTION

The objective of the inner magnetospheric imager mission presently under consideration by NASA is to obtain a global map of the distributions of plasmas in the earth's ionosphere and magnetosphere. Fast neutral particles which are created from ions that charge exchange when colliding with the neutral atoms of the upper ionosphere and geocorona offer the potential for imaging the original charged particle distributions. These neutrals are in principle well suited for remote sensing since they are unaffected by the magnetic field and thus follow ballistic paths. Neutral atom imaging is a relatively new technique<sup>1</sup>, that requires significant improvements in detector and analyzer methods to make it suitable for sensing the relatively low fluxes of neutral atoms. The High-Latitude Ion Transport and Energetics (HI-LITE) explorer<sup>2</sup> proposed to investigate the global ion outflow from the high-latitude terrestrial ionosphere includes such a novel neutral atom imaging instrument.

Conventional techniques for measuring neutral particle fluxes rely either on direct detection via the energy deposition in solid state detectors, or on ionization and subsequent analysis in charged particle instruments. The former technique has been successfully applied for imaging energetic (> 20 keV) atoms originating in the terrestrial ring current.<sup>3</sup> However, these techniques cannot efficiently be applied to much lower energies. Since low energy neutral atom fluxes in the planetary ionospheres and magnetospheres, and in interplanetary space are generally many orders of magnitude lower than charged particle fluxes<sup>1</sup>, a highly efficient ionization process is called for. Neither electron ionization with its low overall yield, nor photon ionization with its impractical demands on spacecraft resources (size, weight and power) meet these requirements.

Transmission ionization employing thin C-foils provides reasonably high yields ( $\sim 10\%$ ) down to energies as low as 1 keV/nucleon.<sup>4,5</sup> Using ultra-thin C-foils in combination with highly sensitive analyzers McComas et al.<sup>6</sup> have reported good efficiencies for negative O production at energies as low as 1keV. However, at still lower energies transmission and secondary electron yields decrease rapidly. As a result, the very low energy regime of neutral particle fluxes has thus far remained largely inaccessible to in situ measurements from spacecraft.

In recent years, new surface ionization techniques have been developed for laboratory applications that are capable of providing high ionization yields at energies below 1 keV.<sup>7,8,9</sup> These techniques make use of low work function surfaces for converting neutral particles to ions during surface impact and reflection. Surface ionization introduces additional design constraints which differ from conventional space flight instruments and require the development of new analyzer elements with matched ion optical properties.

In this report we describe the concepts for an instrument capable of imaging low energy neutral H and O and to a lesser degree He atoms. Such an instrument would be suitable for imaging neutral atom fluxes from such diverse source regions as the cleft ion fountain and the interstellar neutral wind. An instrument based on the principles described here was proposed for flight on a NASA small explorer mission to image the charge-exchanged H and O neutrals from the high latitude terrestrial ionosphere. Alternate concepts that combine conversion ionization techniques with a spectrograph have been described by Herrero and Smith<sup>10</sup> and Gruntman.<sup>11</sup>

## 2. INSTRUMENT DESCRIPTION

### 2.1 Overview

The imaging low energy neutral analyzer (ILENA) proposed here combines state of the art laboratory technology with flight proven space plasma analyzer technology. A schematic cross section of the sensor in a plane containing the axis of symmetry

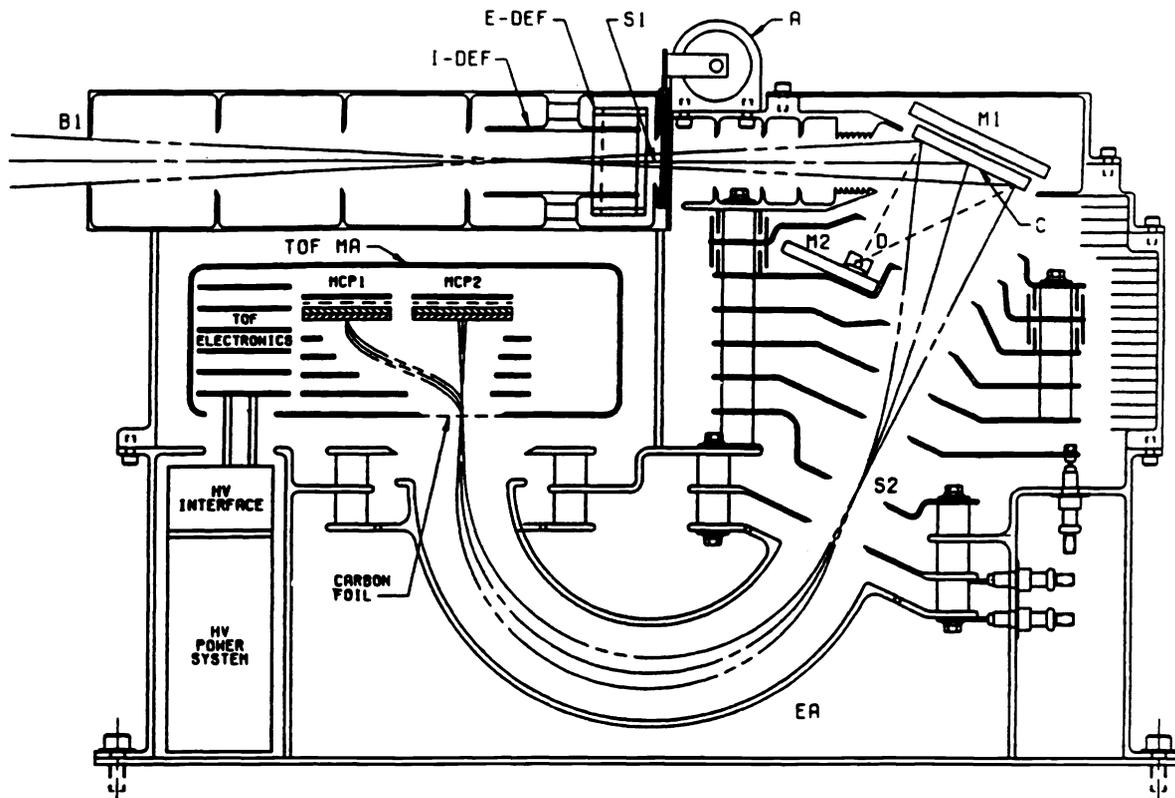


Figure 1. Schematic drawing of the ILENA instrument with principal components. The entrance collimation system with elevation angle acceptance slits B1 and S1, and ion and electron deflectors I-DEF and E-DEF, conversion surface C, cesium dispenser D, secondary electron guiding magnets M1 and M2, extraction lens L, energy limiting slit S2, spherical electrostatic analyzer EA, and the time-of-flight mass analyzer MA.

is shown in Fig. 1. The principal elements of the ILENA are an entrance collimation system, a conversion unit, an extraction lens, an electrostatic analyzer, and a TOF mass analyzer with position sensing. Neutral and charged particles enter the sensor via the external aperture B1 and are collimated in angle and area by the S1 entrance slit. An electrostatic deflector removes all ions with energies  $< 100$  keV, while a broom magnet deflects all electrons with energies  $< 200$  keV. The remaining neutral particles proceed to the conversion plate (C) where they impact at an oblique angle. There, some of the neutrals undergo charge exchange and become negative ions. These ions are accelerated away from the converter surface and focused by a wide aperture low aberration lens (L) in the S2 slit plane. The conical slit S2 is set to transmit ions with initial energies within a passband of  $\sim 10 < E < 300$  eV. Transmitted ions are subsequently imaged by a spherical electrostatic analyzer (EA) geometrically configured to be focusing in elevation angle in the image plane of the carbon foil. Before entering the TOF section ions are post-accelerated to about 25 keV. Upon striking the carbon foil placed in the focal plane of the EA, the negative ions produce secondary electrons which provide the start pulse as well as the azimuth-radial position information. The transmitted particles (ions and neutrals) proceed to the stop MCP.

The entire instrument is rotationally symmetric about a vertical axis collocated with the S1 entrance slit. Ions that enter the analyzer through the S1 slit maintain their initial velocity direction except for non-specular reflection at the conversion surface. These effects are minimized through special ion optics design of the acceleration lens system. As a result an azimuth direction - position correlation is achieved in the plane of the carbon foil which enables one to deduce the original velocity direction of the neutral atom. In a similar manner energy information is extracted from the radial impact position.

## 2.2 Collimator

All particles enter the instrument through aperture B1 and pass through a baffle system that prevents forward scattering of photons and particles through the use of serrated blackened (CuS) surfaces. A pair of horizontal deflection plates sweep out charged particles with energies per charge less than  $\sim 100$  keV/e from the converter surface, and a small broom magnet deflects electrons with energies  $< 200$  keV. The collimator is fan shaped to provide the desired wide azimuth acceptance, while the elevation angle acceptance is defined by the heights of the B1 and S1 slits. A gas tight shutter located behind S1 can be closed on command to protect the converter surface during launch and during the perigee portion of a low earth orbit. An additional port with a shutter provides for added venting to accommodate the higher outgassing rates during surface conditioning.

## 2.3 Conversion

As discussed above, fluxes of neutral atoms with energies  $< \sim 100$  eV are typically low. In the case of the cleft ion fountain for example, the expected peak fluxes are of the order  $10^5 / (\text{cm}^2\text{-sr-s})$  at a distance of several 1000 km.<sup>12</sup> To be able to obtain images of this source region on reasonably short time scales requires a highly efficient ionization mechanism. The approach taken here is to use a low work function converter surface for converting fast atoms with positive electron affinity to negative ions. This type of charge exchange process works well for H and O atoms which have high electron affinities (0.75 eV and 1.46 eV). Particularly low work functions are obtained with monocrystalline tungsten W(110) substrates coated with a thin ( $< 1$  monolayer) layer of cesium.<sup>13</sup> The cesium layer acts to lower the work function (to  $\sim 1.5$  eV) and facilitates the electron transfer to the reflected particle.<sup>9</sup> This conversion process is well understood and produces under ideal laboratory conditions negative ion yields of up to 67%.<sup>8</sup> However, since optimal control of the cesiated layer is probably more difficult to achieve in flight than on ground, we prudently assume a somewhat lower conversion efficiency of  $\sim 10\%$ .<sup>14</sup>

To achieve near specular reflection and high conversion efficiencies it is best to orient the target relative to the neutral beam at near grazing incidence. The impact angle of  $\sim 65^\circ$  from the surface normal selected here represents a compromise between the need for high efficiency and specular reflection, and small converter and extraction optics size. The entire conversion unit consists of individual azimuthal facets each aligned on a conical surface centered about the axis of rotational symmetry. The width of each facet is primarily driven by the azimuth angle resolution requirements. For the HI-LITE instrument<sup>2</sup>, nine facets each spanning  $10^\circ$  in azimuth were considered.

The converter unit includes a Cesium dispenser (D) and a heater for baking the surface to remove undesired adsorbate contaminations. This allows for periodically reconditioning the converter surface during flight when needed. As discussed above, the ideal Cs-layer thickness is somewhat less than a monolayer. To verify the condition of the surface it is first necessary to measure its work function. This is accomplished by sequentially illuminating individual azimuth segments with light from several (3) laser diodes at different wavelengths. Photo electrons emitted from the converter surface are then collected on a positively biased anode with the aid of a guiding magnet (M2). This current provides a measure for the

conversion efficiency since the photon and negative ion production rates are both governed by the work function of the surface. During this operation the entrance slit shutter is closed to prevent interference by external EUV light.

The required regeneration frequency will depend on the rate of deterioration of the surface. Special care must be taken to prevent contamination of the converter surface at launch and from low altitude exospheric gases. Generally, if the gas load to the converter surface is kept to less than one monolayer  $10^{15}$  atoms  $\text{cm}^2$  the effects on conversion efficiency are expected to be small. For example, at altitudes of  $\sim 1 R_e$  the expected average ram flux of hydrogen, the dominant constituent, is  $< 10^8$  atoms/ $(\text{cm}^2\text{-s})$ , thus requiring more than 100 days for a monolayer of H to form (assuming perfect sticking). To protect the surface during launch and in the low altitude portion of a satellite orbit the entrance slit shutter will be closed. In the case of the proposed HI-LITE mission we conservatively estimate that regeneration of the surface will not be necessary more frequently than every 10 days for a one year mission. A similar system that relies on in flight conversion surface regeneration is presently in operation on the Ulysses solar probe<sup>15</sup>.

Standard space instrument techniques for maintaining a high degree of chemical cleanliness and low residual gas pressure within the sensor will be used. In addition, the entire instrument will be baked in vacuum after assembly and subsequently dry- $\text{N}_2$  purged until launch. The converter surface itself will be subjected to a separate high temperature bake-out before assembly into the sensor.

## 2.4 Extraction optics

After acquiring a charge, the negative ions are accelerated away from the surface by a wide aperture lens system (L). The potential distribution of the lens (Fig. 2) was designed to efficiently collect the ions produced on C and to focus them in the plane of the S2 slit. Equipotentials are parabolically shaped over much of the interior region to minimize spherical aberrations. Fig. 3 illustrates the achromatic focusing properties of the acceleration lens; specularly reflected ions are focused toward larger radii with increasing energy. Angle scattering about the specular reflection direction at the converter tends to broaden the focal spot. Since this effect is smaller than the energy dispersion, it is in principle feasible to extract some energy information from the radial position.

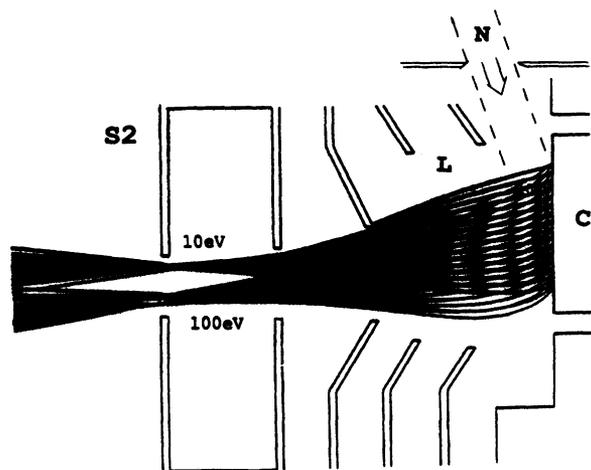


Figure 3. Trajectories of ions originating at the converter surface with energies of 10 eV and 100 eV respectively. Reflection angles are  $\pm 10^\circ$  from the specular direction ( $65^\circ$ ). Total acceleration potential to S2 is 8 kV.

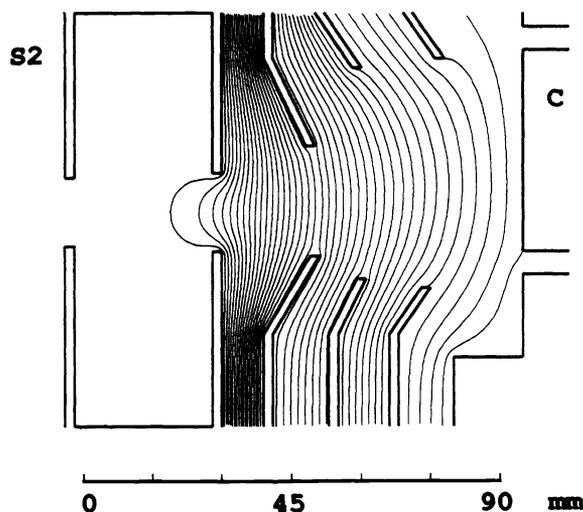


Figure 2. Equipotential lines in extraction lens between converter surface C and exit slit S2.

To minimize the effects of non-specular reflection on azimuth resolution (out of plane of Fig. 1), it is necessary to apply a high extraction field near the surface and to have a high ratio of final to initial energy. A lens extraction voltage of about 8 kV represents a good compromise between the requirements for energy dispersion and azimuth angle resolution. With this voltage, beam spread in the azimuthal direction is sufficiently small to permit for  $\sim 5^\circ$  azimuth resolution.

## 2.5 Energy analyzer

The spherical analyzer (EA) efficiently transmits all ions that passed through the collimating slit S2 to the TOF mass analyzer. It is geometrically configured to image the object slit S2 onto the carbon foil. Since its magnification is near unity (-1), the more energetic ions are mapped to smaller radii. These elevation angle focusing and radial dispersion properties are illustrated in Fig. 4. To achieve the desired wide energy transmission passband from 10 to 300 eV requires an unusually wide plate separation for the spherical analyzer. While this condition does not significantly affect the imaging properties of the analyzer, it does lead to high plate to plate voltages. However, since these voltages need not be scanned they can be directly derived via voltage dividers from the static TOF acceleration voltage. The analyzer further provides for the desired additional UV-light filtering by introducing multiple surface reflections and solid angle attenuation.

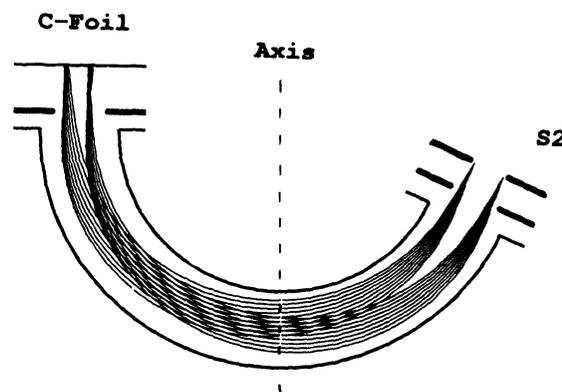


Figure 4. Ray-tracing of ions in the spherical electrostatic analyzer originating at the object slit S2 with angle and energy dispersion defined by the extraction lens. Geometric parameters are center radius 62 mm, sector angle 155°, plate separation 24 mm.

## 2.6 Time-of-flight mass analyzer

Following deflection in the EA, the ions are post-accelerated to a carbon foil (C-foil) at a potential of +25 kV. The TOF analyzer used here is similar to the CODIF and TEAMS spectrometer designs<sup>16</sup> for the CLUSTER and FAST missions. Its principal components are the C-foil, a drift path for the ion and neutral particles, a secondary electron extraction optics, and two MCP detector units. Secondary electrons produced on the back side of the C-foils are accelerated and focused onto MCP1 producing both the start pulse for the TOF and providing radial and/or position information. The signal produced at MCP2 by the primary particle provides the stop pulse. The azimuthal position can be provided from either MCP1 or MCP2. Both the start and stop signals are obtained from low (50%) transmission grids placed behind the respective MCP's. The anode behind the MCP1 grid is divided into ~5 radial segments providing moderate energy resolution. Similarly, the anode behind the MCP2 grid is divided into 9 sectors providing 10° azimuth angle resolution. The position and TOF electronics are contained within the high voltage bubble. The encoded information is transmitted across the HV interface via fiber optics. Since this instrument is primarily sensitive to atoms with positive electron affinities, the TOF mass analyzer needs only to be able to separate H, O, and He. The requirements for mass resolution ( $m/\Delta m \sim 4$ ) are thus rather modest when compared with proven designs presently under development for space flight.<sup>16</sup>

## 3. DISCUSSION

Early space flight instruments performed differential measurements of ion distributions and required scanning in multidimensional parameter space for obtaining distribution functions. While most newer instruments are imaging spectrographs<sup>6,16,17</sup>, they still rely on energy scans for covering the energy range. In the ILENA instrument we have carried the development a step further by simultaneously imaging over the three parameters azimuth angle, energy, and mass. This triple spectrographic imaging eliminates the need for a duty cycle thus increasing sensitivity by the ratio of cycle period to accumulation time per cycle step. Compared with conventional energy scanning analyzers (16 energy steps), the ILENA design provides an ~20 times higher sensitivity. The lack of a need for fast high voltage scanning provides the added benefit of simplified, and lighter HV supply design.

The rotational symmetry of this design makes it possible to obtain a wide field-of-view in azimuth direction coupled with simultaneous imaging of the incident azimuth angles. Although the azimuth acceptance of the present optics is geometrically limited to  $\sim 160^\circ$  due to the flat field-of-view, such an instrument would nevertheless be able to cover more than 90% of the full 4-pi solid angle from a spinning spacecraft. Using a conical entrance field-of-view would permit coverage twice per spin. For source regions of spatially limited extent, such as the auroral acceleration region, a 2-pi instantaneous field-of-view provides no further benefits in geometric factor. The azimuth resolution that can be achieved with this type of instrument is intrinsically limited by the width of the entrance slit S1, the radius of the conversion surface, and the magnitude of the lens extraction voltage. For a  $1 \text{ cm}^2$  entrance slit area and a 10 cm radius, a resolution of  $\sim 5^\circ$  is feasible in principle.

The ability to detect very low fluxes of neutral atoms relies on a low background from all sources. Although the TOF coincidence technique used here is inherently less sensitive to background, the large fluxes of EUV photons from the sun, geocorona and the earth's limb would cause a serious background problem if not suppressed. In the proposed design, the required attenuation is achieved by a combination of efficient light traps<sup>10</sup>, multiple and diffuse surface reflections, and low reflectivity "black" surface coatings<sup>18</sup> at critical places. Besides the photon background, the two other major potential sources of background are photoelectrons from the converter surface and negative ions produced by dissociative attachment of photo electrons to residual gas molecules. Due to the low work function of the converter surface photo electrons will be produced in great quantities. These electrons would produce unacceptably high chance coincidence rates if allowed to reach the TOF system, even though individually they could be discriminated against due to their short flight times. To divert and trap these electrons a weak magnetic field is applied between the pole faces of M1 and M2 (Fig. 1). As discussed in section 2.3, this same trap serves as a collector for the photo electrons during converter surface regeneration. The ion background is minimized by maintaining a low residual gas pressure within the instrument. A low outgassing rate of all internal surfaces coupled with a high conduction pumping port to outer space insure that a low internal pressure is maintained throughout the operational phase of the orbit. Furthermore, by quickly accelerating the photo electrons away from the sensitive region the electron attachment probability is further reduced. Any negative ions produced by electron attachment from the residual gas proceed along somewhat different trajectories and are collimated by the S2 slit.

Sputtered (negative) ions, originating from energetic ion bombardment on the converter surface also represent a potential source of contamination. Here surface adsorbed gases are of primary concern since W or Cs have very low transmission efficiencies in the TOF section and can easily be recognized by their unique heavy mass. Since energetic ions are abundant in earth orbit it is essential to reduce their fluxes. In the present ILENA design, ions with energies up to 100 keV are rejected by means of a conventional electrostatic deflector in the entrance collimation system. The required deflection plate voltages are  $\sim 5 \text{ kV}$ .

A critical element of the ILENA instrument concept is the neutral to ion conversion technique proposed here. As discussed in 2.3, the optimum conversion efficiency is attained with an  $\sim 0.5$  monolayer of cesium on a W(110) substrate. However, reasonably high efficiencies are also obtained with somewhat thicker layers. The problem of maintaining a near optimum layer thickness is facilitated by the fact that thicker layers tend to evaporate quickly due to the high vapor pressure of Cs at room temperature, leaving behind a stable monolayer. After reconditioning the surface for an estimated 10 to 100 times during a mission, the average contamination with Cs on internal surfaces of the sensor, other than the converter itself, is expected to be less than one monolayer. Since the vapor pressure of a Cs monolayer is very low, migration of Cs between different elements of the instrument is minimal. Nevertheless, special design precautions are taken to guard all internal high voltage insulators (e.g. individual guard baffles). No deterioration of the MCP detectors which are well shielded behind the carbon foils are expected at the estimated Cs evaporation levels.

While cesiated conversion surfaces have been thoroughly investigated in the laboratory environment, they have, to our knowledge, thus far not been applied to space plasma instrumentation. It is the goal of the ongoing research effort to develop this technology for use on spacecraft instrumentation. In parallel, other candidate conversion surfaces that provide low work functions and are chemically stable are presently being investigated for use on this type of instrument.<sup>14</sup>

#### 4. CONCLUSIONS

We have developed the concepts for a new type of mass spectrograph that is specifically designed for performing Low Energy Neutral Atom Imaging measurements on space platforms. The instrument covers the energy range from about 10 to 300 eV, and the mass range from 1 to 20 amu with mass resolution of about 4. This mass resolution is sufficient to separate the major masses of interest H, He, O and their isotopes D and <sup>3</sup>He. Its large geometric factor ( $0.2 \text{ cm}^2\text{-sr}$ ) for a  $90^\circ$  field-of-view combined with high conversion, transmission, and detection efficiencies (Table 1), and 100 % duty cycle give it the necessary

high sensitivity for imaging the low energy outflow from the high latitude ionospheric acceleration regions. Using the fluxes calculated by Hesse et al.<sup>12</sup> we estimate peak count rates from the ion fountain source region of  $\sim 100$  Hz per  $10^\circ$  azimuth pixel for a HI-LITE orbit, thus providing a reasonably well defined image within  $< 5$  minutes.

Table : ILENA Instrument Summary for HI-LITE mission.

Energy Range	: 10 eV to $\sim 300$ eV
Resolution	: $\sim 5$ steps
Mass Range	: H, O, He
Field of View	
Azimuth	: $8^\circ$
Elevation	: $90^\circ$
Angle Resolution	
Azimuth	: $10^\circ$
Elevation	: $10^\circ$
Conversion Efficiency	: 0.1
TOF efficiency	$(\epsilon_e \cdot \epsilon_B^2 \cdot T_C^3)$ : 0.4
Geometric Factor	: $2 \times 10^{-1} \text{ cm}^2\text{-sr}$

## 5. ACKNOWLEDGMENTS

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## 6. REFERENCES

1. Hsieh, K.C., C.C. Curtis, C.Y. Fan, and M.A. Gruntman, "Techniques for remote sensing of space plasma in the heliosphere via energetic neutral atoms: A review", in "Remote Sensing of Plasmas", 357, 1992.
2. Smith M.F. et al., "Hi-latitude ion transport and energetic explorer (Hi-Lite): a mission to investigate ion outflow from the high-latitude ionosphere", SPIE Proceedings Vol 2008, 1993.
3. Roelof, E.C., "Energetic neutral atom image of a storm-time ring current", *Geophys. Res. Lett.*, 14, 652, 1987.
4. Gonin, M., "Interaction of low energy ions with thin carbon foils; Charge exchange, energy loss, and angular scattering", Masters Thesis, University of Bern, 1991.
5. Gonin M., A. Burgi, M. Oetliker, and P. Bochsler, "Interaction of solar wind ions with thin carbon foils - Calibration of time-of-flight spectrometers", *ESA SP-348*, 381, 1992.
6. McComas, D.J., B.L. Barraclough, R.C. Elphic, H.O. Funsten III, and M.F. Thomsen, "Magnetospheric imaging with low-energy neutral atoms", *Proc. Natl. Acad. Sci.*, 88, 9598, 1991
7. Van Wunnik J.N.M., J.J.C. Geerlings, E.H.A. Granneman, and J. Los, "The scattering of hydrogen atoms from a cesiated tungsten surface", *Surf. Sci.*, 131, 17, 1983.
8. Geerlings J.J.C., P.W. van Amersfoort, L.F.Tz. Kwakman, E.H.A. Granneman, J. Los, "H- formation in proton-metal collisions", *Surf. Sci.* 175, 151, 1985.
9. Los, J. and J.J.C. Geerlings, "Charge exchange in atom surface collisions", *Phys. Reports*, 190, 133, 1990.

10. Herrero, F.A., "Light trap cavity design using multiple reflections and solid angle attenuation: Applications to a spaceborne electron spectrometer", *Applied Optics*, Vol 31 , 5331, 1992.
11. Gruntman, M., A., "Hi situ measurements of the composition (H, D and O atoms) of interstellar gas", Report Np. 102 M, University of California L.A., 1991.
12. Hesse M., M.F. Smith, F.A. Herrero, A.G. Ghielmetti, E.G. Shelley, P. Wurz, P. Bochsler, D. Gallagher, T.E. Moore, T. Stephen, "Imaging ion outflow in the high-latitude magnetosphere using low-energy neutral atoms", *SPIE Proceedings Vol 2008*, 1993.
13. Desplat, J.L., and C.A. Papageorgopoulos, "Interaction of cesium and oxygen on W(110) I. Cesium adsorption on oxygenated and oxidized W(110)", *Surf. Sci.*, 92, 97, 1980.
14. Wurz P., P. Bochsler, A.G. Ghielmetti, E.G. Shelley, F. Herrero, and M.F. Smith, "Concept for the Hi-Lite neutral atom imaging instrument", in "Proceedings of the Symposium on Surface Science", ed: P. Varga and G. Betz, Austria, in press, 1993.
15. Rosenbauer H., H.J. Fahr, E. Keppler, M. Witte, P. Hemmerich, H. Lauche, A. Loidl, and R. Zwick, "The ISPM interstellar neutral gas experiment, ESA SP1050, 123, 1983.
16. Reme et. al., "The ion spectrometry experiment to measure the properties of the ionic plasma composition and distribution function at energies between ~0 and 40 keV/e", in "The Cluster Mission", ESA SP-1103, 65, 1988.
17. Shelley et al., "The toroidal imaging mass-angle spectrograph (TIMAS) for the polar mission, submitted to *Space Sci. Rev.*, 1993.
18. Balsiger H., P. Eberhardt, J. Geiss, A. Ghielmetti, H.P. Walker, and D.T. Young, "A satellite-borne ion mass spectrometer for the energy range 0 to 16 keV". *Space Sci. Instr.* 2, 499, 1976.