Pickup Ion Mass Spectrometry for Surface Bounded Exospheres and Composition Mapping of Lunar and Planetary Surfaces.
J. W. Keller[1] and T.H Zurbuchen[2], R.A. Baragiola[4], T.A. Cassidy[4], D.J. Chornay[1], M.R. Collier[1], R.E. Hartle[1], R.E. Johnson[4] , R.M. Killen[3], P. Koehn[2], K.W. Ogilvie[1], S. Scherer[2], T. Stubbs[1], [1]NASA-Goddard Space Flight Center, Greenbelt MD, 20771, [2]University of Michigan, Ann Arbor, MI 48109, [3]University of Maryland, College Park, MD 20714, [4]Engineering Physics, University of Virginia, Charlottesville, VA 22904

Introduction: Many of the small to medium sized objects in the solar system can be characterized as having surface bounded exospheres, or atmospheres so tenuous that scale lengths for inter-particle collisions are much larger than the dimensions of the objects. The atmospheres of these objects are the product of their surfaces, both the surface composition and the interactions that occur on them and also their interiors when gases escape from there. Thus by studying surface bounded exospheres it is possible to develop insight into the composition and processes that are taking place on the surface and interiors of these objects. The Moon and Mercury are two examples of planetary bodies with surface bounded exospheres that have been studied through spectroscopic observations of sodium, potassium, and, on the moon, mass spectrometric measurements of lunar gases such as argon and helium.

The creation of these ions and the action of acceleration in the solar wind derived motional electric field (pickup ions) provides a highly sensitive method for studying these exospheric objects, both their surfaces and atmospheres through ion mass spectrometry. Because of the extreme sensitivity of ion mass spectrometry and the fact that the acceleration separates the ion population from background thermal ions, it is possible to characterize exospheric atmospheres to a level that cannot be achieved by other commonly used methods. For example we anticipate that measurements of the lunar atmosphere from an orbiting spacecraft will dramatically lower the threshold concentration by which water in the atmosphere can be detected.

We will discuss here how this measurement can be made, what sensitivity is required, how to relate the observation of atmospheric ions to the source of these ions and how an elemental map of the surface can be constructed using these data. Here we concentrate on the Earth's moon since it is largely unmagnetized resulting in relatively simple trajectories for the ions found there. Also, it is accessible, well studied, and finally, because the Moon is a focus of a renewed exploration initiative to the Moon and Mars. A pickup ion instrument on a spacecraft with a low lunar orbit will be capable of measurements of both the lunar atmosphere and surface.

The lunar atmosphere is constantly undergoing loss through Jeans escape (esp. H, He), radiation pressure (Na, K), and ionization followed by pickup by the passing solar wind. The latter is most important for atoms heavier than helium and provides the key toward a sensitive measurement of the lunar atmosphere. Ions created at or near the surface experience an acceleration due to the motional electric field derived from the streaming solar wind and the imbedded interplanetary magnetic field. This acceleration will deliver ions to an orbiting spacecraft where an ion mass spectrometer[1] can characterize the ion flux. With knowledge of the ion direction, energy and the local magnetic and electric fields measured either on the spacecraft or by upstream monitors, it will be possible to map the measured ion back to the source, and for sputtered ions, develop a map of the composition of the lunar surface.
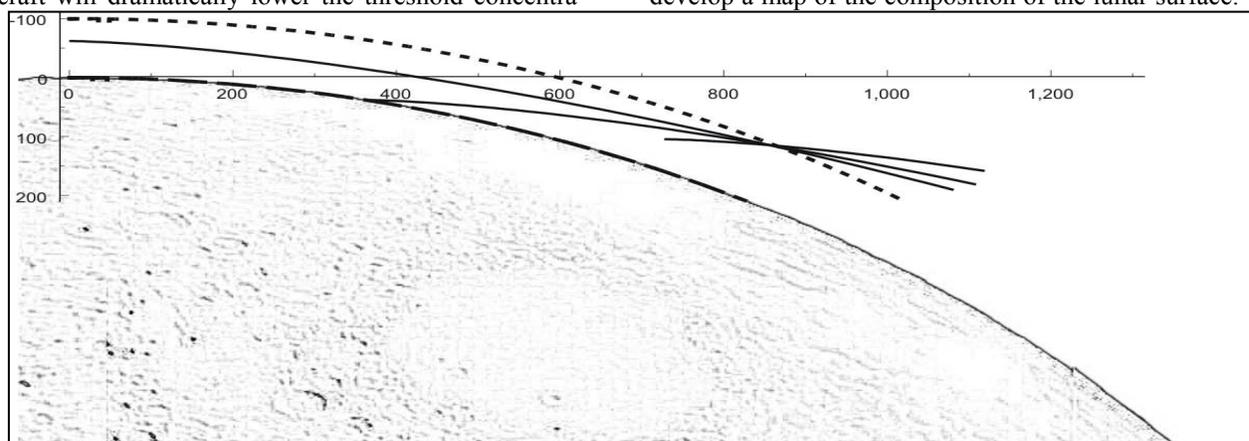

Figure 1 *Mass 16 ion trajectories for typical values of the field parameters. The upper dashed arc represents a 100 km circular spacecraft orbit. Solid lines represent trajectories of atmospheric photoions and sputtered surface ions. Note crossing of trajectories from sputtered and exospheric ions.*

Laboratory measurements of secondary ions sputtered from lunar simulants[2] indicate that ion fluxes from 10 to 10^4 cm^{-2} s^{-1} will be observed. Sputtered species above the 100 cm^{-2} s^{-1} level include potassium, sodium, calcium, magnesium, manganese, aluminum, titanium, chromium, iron, and silicon. This yield is sufficient to develop detailed maps of elemental abundances of the lunar surface with a lunar orbital mission in under one year. Because the pickup ions are accelerated in the motional electric field from a relatively low temperature and spatially narrow source they will arrive at an orbiting spacecraft with a beamlike distribution function. Under most observational conditions there will be limited *a priori* knowledge of the beam direction at the spacecraft. Thus an instrument with a wide field a view will be required.

Ion Trajectories: We confine ourselves to the simple physical picture where ions injected more than a few Debye lengths above the surface travel cyclodial paths defined by the crossed interplanetary magnetic field and the motional electric field.

The motional electric field in the solar wind **E** can be determined from the velocity of the solar wind, **V**, and the magnetic field, **B**, which will be measured by other instruments on the spacecraft or obtained by upstream monitors; $E = -VB\sin\varphi$, where φ is the angle
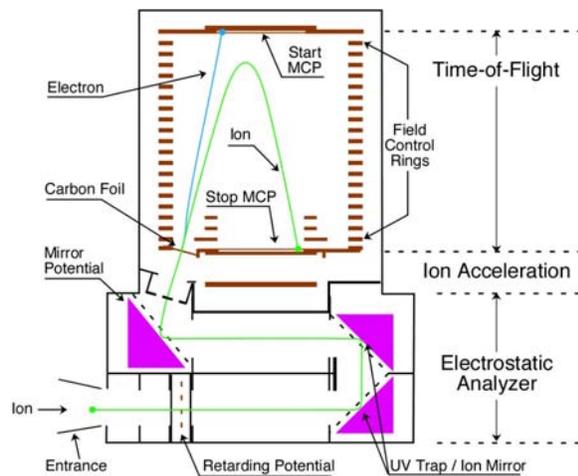
***Figure 2** Schematic design of a highly sensitive ion mass spectrometer. This sensor, based on previous pickup ion instruments, is optimized for measurements of surface-bounded exospheric atmospheres.*

between the velocity and magnetic field vectors. On average, **V** and **B** are in the ecliptic plane so that **E** points north or south.

Ideally the instrument will be on a spacecraft with near circular polar orbit of around 50 to 100 km alti-

tude. Thus, an ion coming from near the polar surface to the spacecraft will have an energy of about 150 eV, very large with respect to sputtered ion energies and the few volts the surface layer electric field will impart[3] on the dayside surface. Consequently, most sputtered ions are born with effectively zero velocity, which is also true for those ions born from the exosphere. Thus, to a good approximation, all ions will move in cycloidal orbits in a plane perpendicular to **B** that is also perpendicular to the **V** - **B** plane. The cusps of a cycloidal trajectory are the ion source points (where the particle velocity vanishes). The drift velocity, **E**x**B**/B^2, is always away from the Sun.

Examples of pickup trajectories for 16-amu ions are shown in Figure 1, where the typical field parameters above have been used. For simplicity, the orbital planes of the spacecraft and the ion trajectory are the same. Two ion classes are shown; i.e., those sputtered from the surface and those born in the exosphere.

Instrument Characteristics: Because of ion acceleration by the motional electric field, ions will arrive at the spacecraft with a narrow angular spread and an energy distribution characterized by the voltage drop from the source and the location of the spacecraft. For atmospheric photoions, we should observe a broad distribution of ion energies since all elevations below the spacecraft will be accessible for a nadir viewing instrument. The population of ions ejected from the surface will exhibit a sharp energy distribution which should serve to distinguish them from atmospheric photoions. The instrument (Figure 2) will require a wide field of view to maximize the probability of containing the ion beam. Based on measurements of ion sputtering of lunar soil simulants[2], a geometric factor of 10^{-4} cm^2 str eV/eV will assure counting rates greater than 1 Hz for Fe, K, Si, Na, Mg, Al and Ca for ions ejected from the surface and over time provide a map of the lunar surface as well as determine the atmospheric composition well beyond present knowledge.

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