Advances in Hypervelocity Sampling with Mass Spectrometers: From Earth to Deep Space

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Analysing the chemical composition of celestial objects is key for understanding the origin and evolution of the Solar System. Although Earth’s exosphere provides the simplest access compared to other deep space destinations, it is poorly understood. Last measurements were conducted in the 1980s. These measurements lead to some understanding of the scale heights of the major species. The evolution of Earth’s atmosphere was simulated from its initial composition, which was comparable to the composition of Venus and Mars. However, there remains a discrepancy between the model output and the currently observable chemical composition of Earth’s atmosphere. Moreover, the influence of the external drivers of the exosphere and the exospheric loss remains unclear. These drivers, such as, for example, Sun, Moon, night-side transport of species, etc. seem to influence both the temporal and spatial abundance of species considerably.

An analysis of Earth’s upper atmosphere with mass spectrometers will end this ongoing debate. Regions of interest are low flying satellites at altitudes well below 1,000 km. To study drivers, maintaining such orbits over months, if not years, is key requiring typical relative encounter velocities of about 7 to 8 km/s. Additional requirements are the high sensitivity for species, a high dynamic range and a mass range of about m/z 1 to 150 at an instant. Overcoming the space-time degeneracy necessitates at least two instruments measuring simultaneously, though, a network of several satellites is preferred for almost real-time analysis of the space weather.

For that purpose, we designed a mission concept complying with these requirements enabled by a novel mass spectrometer design. The goal of this Constellation of High-performance Exospheric Science Satellites (CHESS) mission is to provide an inventory of chemical species present in Earth’s exosphere and analyse both its dynamics in response to external drivers. The scientific payload of this mission are neutral gas and ion time-of-flight mass spectrometer in CubeSat format (1U) for chemical composition analysis and a new generation of dual-frequency global navigation satellite system (GNSS) instrument for analysis of the total electron content. A technical goal of this mission is to demonstrate the concept of the novel ion optical system that allows for direct measurements at high relative encounter velocities implying reliable measurements of complex molecules.

Speed limits of mass spectrometers constrain modern deep space mission designs. Fly-by mass spectrometer mostly have two operation modes. In open source mode, the mass spectrometer handles the rapidly incoming stream of gas by (electrostatic) deflection of the ionized species it into the mass analyser. This mode is limited to about 5 km/s. For higher relative encounter velocities, an antechamber is used to thermalise the species arriving at hypervelocities, where incoming species undergo many collisions with the chamber wall until they are thermalized. The collisions cause chemical alteration of complex molecules, and the reconstruction of these chemical reactions is very
challenging, if not impossible for heavier species. We designed a novel ion optical system to directly measure the incoming species without deflection or an antechamber at relative encounter velocities of up to 20 km/s while maintaining a mass range of about m/Δm 1,000 (full width half maximum). Other scientific parameters such as, for example, sensitivity and dynamic range are comparable to the Neutral and Ion Mass spectrometer (NIM) on board ESA’s L-class JUICE mission.

Thus, this next generation of mass spectrometers enables reliable, unambiguous measurements of complex (bio) molecules during hypervelocity fly-bys. Given its mass range of about m/z 1 to 1,000, an application to volcanic active objects such as, for example, Io or ocean worlds become feasible either as a major instrument on board a spacecraft or using the smaller version as a descent probe that is deployed during a fly-by. Such investigations will provide valuable data for understanding their status including their exosphere and possible plumes. In combination with the data collected from Earth’s exosphere, these measurements enable comparative planetology on composition level for objects with and without life.