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COMA - A HIGH RESOLUTION TIME-OF-FLIGHT SECONDARY ION MASS SPECTROMETER (TOF-SIMS) FOR IN SITU ANALYSIS OF COMETARY MATTER

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A lot of clues concerning the origin of the solar system can be found by sending an exploring spacecraft to a rendezvous with a comet. Here we describe the space experiment CoMA, which will measure the elemental, isotopic and molecular composition of cometary dust grains. It will be flown on NASA's mission CRAF.

The motivation to build a sophisticated space probe experiment

One way to achieve a more profound understanding of the origin and the formation of the solar system is to have a close look at the refrigerated messengers from those times - the comets. Too small to undergo geological processing and too cold to be subject to major chemical changes, cometary nuclei consist of pristine material. Only their surface may have been processed by cosmic rays and electromagnetic radiation to higher complex (e. g. polymerized) molecules /1/.

This is one of the main motivations of NASA's cometary rendezvous and asteroid flyby mission (CRAF). Lasting about nine years, it is to perform a detailed in situ analysis of a comet and its surroundings. On the way out it also will examine an asteroid during flyby.

One of the experiments on board - contributed by the Federal Republic of Germany - is the cometary matter analyzer (CoMA). This is a time-of-flight secondary ion mass spectrometer. CoMA will shed some light on the elemental, isotopic and molecular composition of solid and gaseous cometary matter. It will give information about the organic inventory /2/, the gas-dust-interaction and the activity of the nucleus in different parts of the cometary orbit. All this will be achieved by examining dust grains and gas originating from a comet, probably p/Kopff.

A peek at the principles of time-of-flight secondary ion mass spectrometry

Primary ions impinging on a target surface produce - besides sputtered neutral target atoms and molecules - positively and negatively charged secondary ions. Those can be mass analyzed. In case of a time-of-flight mass spectrometer they are extracted with a fixed initial kinetic energy (keV-range) and fed into a drift space. Different ion masses translate into different times of flight to the detector which is located at the end of the drift space. A clock is set running when the primary ions impinge on the target surface and the secondary ions leave. To precisely pin down the starting moment, a primary ion pulse which is as short as possible must be used. But it still has to contain enough ions to sputter a sufficient number of secondary particles.

The goals of the cometary matter analyzer

CoMA will perform the analysis of cometary samples with a mass resolution unprecedented by a space instrument.

It will yield the abundances of all elements, except U and the noble gases. Thus it will be possible to better characterize their role in solar system chemistry.

Furthermore it will be able to separate the isotopes of a number of light elements (C, N, O, Mg). Due to the high mass resolution, interferences by isobaric molecules are reduced. For example, distinguishing between ^{12}CH and ^{13}C gives access to the presolar records of possibly stellar condensates. Determination of the isotopy of above mentioned key elements will set stringent constraints on the boundary conditions of models describing origin and evolution of comets.

In its extended operation mode CoMA will comprise a mass range up to 3000 da. This enables a detailed analysis of organic cometary constituents and will probably give insight into their formation processes. Perhaps even some questions concerning the origin of life on Earth will be answered.

The three parts of sophistication - CoMA's subunits

The cometary matter analyzer consists of three basic units: the dust collector subsystem, the primary ion gun and the time-of-flight mass spectrometer. CoMA's mass will be about 16 kg and the power consumption will be around 22 W.

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First part - the dust collector subsystem

Task of this subsystem is to handle the targets which collect cometary dust particles.

It accommodates around 100 targets located in a target wheel. They are individually selectable to meet the demands of the differing features of the particles to be collected. The system mechanically moves the targets from the store- to the collect-, clean- and analyze-positions. It also adds a mechanical scan capability (about 1 cm^2) and exact positioning to the electric scan capability of the primary ion beam.

The targets are optimized to softly collect cometary dust grains of different sizes and velocities or to adsorb cometary gases effectively. Foils coated with highly porous metal blacks are the best choice for this. For high velocity particles (> 100 m/s), platinum black structures will be used. Fluffy-brittle particles of low velocity (< 100 m/s) will be collected by ruthenium black covered targets. Palladium black is suited best for collecting compact, low velocity grains.

Each target has markers on it. Thus a reference system is established and collected particles can be found repeatedly.

In front of the entrance aperture a concentrator is located. It increases the effective aperture and so the number of collected particles will be higher by an order of magnitude.

Second part - the primary ion gun

Instead of using one of the widespread electron impact ion sources, a liquid metal ion source (LMIS) has been chosen for CoMA. Its mechanical setup is much simpler. Basically it consists of a heatable reservoir containing the metal, a needle which is wetted by the molten metal and an extraction electrode. The ion beam is emitted from a liquid metal protrusion near the needle tip/3/. This kind of source doesn't need any voluminous gas containers and sophisticated valves. Liquid metal ion sources also feature a high brightness.

Because of the small ion emission volume, those sources are well suited for microfocus applications. As a metal, isotopically pure ^{115}In is used. So there is no need for mass separation of the primary ion beam. Indium is advantageous to Gallium, because under normal conditions it is solid. The divergent 10 keV ion beam (some uA) is transformed to a parallel beam with an extraction lens. Afterwards it is scanned across an aperture. This results in a 100 ns pulse, which is subsequently further compressed to less than 2 ns by a bunching sequence. Latter has to time focus ions with different starting times and also different starting energies (energy spread of ion source). The ion pulse is forwarded through a focusing lens into a 40 um spot (high resolution mode)on the sample. Inside the acceptance area of the spectrometer's extraction lens (+ - 0.2 mm) electrical scanning can be performed. For erosion and cleaning purposes a DC-mode is implemented also.

The operation time of the gun will be at least 5000 h /4/.

The attached electronics mainly consists of a timing controller for the various voltage pulses.

Third part - the time of flight mass spectrometer

Secondary ions starting from the analyzed spot first are accelerated into the extraction lens and then move through the flight tube into the reflector /5, 6/. It sends them back to the additional ion mirror located on the baseplate. This unit mirrors them into the reflector, where they turn around once more. Finally they are sensed from a detector also sitting on the baseplate.

The asymmetric extraction lens features a wide acceptance angle at low chromatic and spherical aberration at a great focal length.

Using a two stage reflector high mass resolution as well as second order energy compensation are achieved. The two areas of different electric fields inside the stack of equipotential rings are separated by meshes of high transmission. This improves the spectrometer's acceptance.

Mechanical changes (i.e. due to temperature variations) can be made up for in wide ranges by adjusting the reflector voltages.

The additional ion mirror doubles ion flight times at constant geometric dimensions by folding once the flight path (3 m) of the ion beam.

Secondary ions are detected by a two stage channelplate with integrated nonlinear preamplifier.

Overall transmission will be 0.35, mass resolution about 13000. Both positive and negative ions can be analyzed.

Instrument electronics consists of three parts. The fast data acquisition system has a measuring range of about 400 us with an accuracy of 1 ns. Data preprocessing will allow to set time windows within the measuring range as well as the variation of time resolution. The spectrum data accumulation will perform a summation of spectrum events.

Putting the parts together - the setup as a whole

The dust collector subsystem is connected to the baseplate of the time-of-flight mass spectrometer. On this baseplate the secondary ion extraction lens, the hard mirror and the detector assembly are mounted. To the other side follows the flight tube and a second plate. This one connects the tube to the reflector.
Between both plates there is space for the primary ion gun and electronic boards (FIGURE 1). The remainder of the electronics is housed in an electronic box.
The CoMA instrument is managed by a processor system.

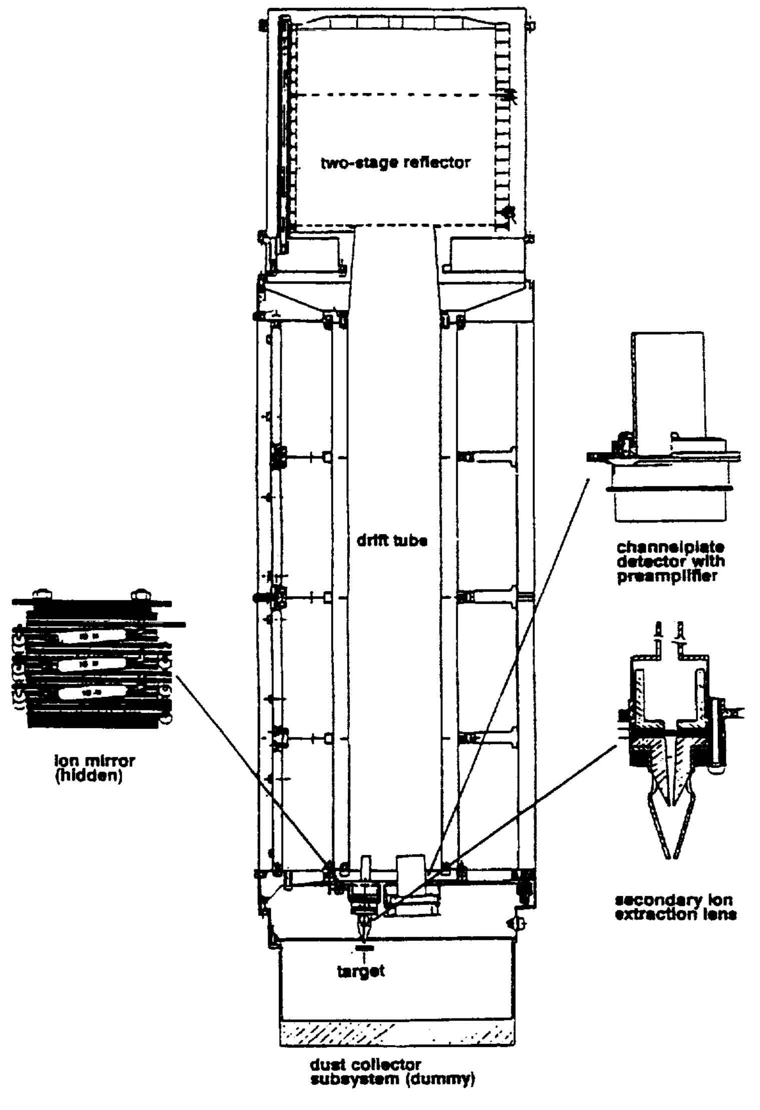

FIGURE 1
The present sophisticated setup of CoMA. Shown is a cut view of the hardware of the time-of-flight mass spectrometer. This mechanical design is very similar to the final space design. Some of the elements are additionally shown magnified.
Length is about 780mm, diameter about 170mm.

Present status of CoMA

The feasibility of the spectrometer design containing the additional ion mirror was verified. This first model utilized components of standard mechanical precision. A 3 ns pulse N_2-Laser generated the secondary ions from the target. The next step consisted of measurements with a more sophisticated model, which basically resembled the flight unit. In those successful measurements secondary ion extraction lens, additional ion mirror and detector could be externally adjusted. The channelplate detector had a fluorescent screen, so that position and shape of the secondary ion beam could be evaluated.

In all those measurements the mass resolution was limited by the duration of the secondary ion formation process and not yet by the spectrometer design.

With a similar model, vibration tests were undertaken.

The primary ion gun in its present state can deliver ion pulses of 2.8 ns duration. They are generated by a combination of scanning the DC-beam across an aperture and subsequently bunching the emerging pulses. Specially designed HV-switches produce voltage pulses of high amplitude (500 V) and short risetimes (some ns). The ion source is a commercial one. Its small reservoir is directly heated.

Development of an ion source containing about 5 g of ^{115}In in an indirectly heated ceramic reservoir is under way to meet the demand of an unusual long and reliable source operation.

Also progress is made with a detector for the secondary ions. It consists of a chevron type channelplate assembly with integrated amplifier and a limited planar resolution capability.

The fast data acquisition electronics can measure events in a range up to 400 us with an accuracy to 2 ns at present. The development evolves along two tracks. The first version, a digital solution, centers around a tapped transmission line. Main difficulty here is the number of logic elements needed. The second version is an analog one. It performs an analog interpolation by ramp time to analog converters.

Especially critical is the stability of the high voltages required. The design of extraordinarily stable high voltage converters has been finished, stabilities being in the 10 ppm range.

Outlook

The mechanical concept of the time-of-flight spectrometer seems basically sound, as thermal studies and mechanical tests up to now demonstrated. The primary ion gun has to be miniaturized and its fulfillment of the requirements must still be verified. The dust collector subsystem is at the beginning of its development. Electronics is well on its way, the concept being established, the problem being the adaption to space requirements. Also a lot of software still has to be developed.

So in the near future there will exist a sophisticated space experiment which will perform a lot of exciting analyses on cometary matter.

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