A DOUBLE FOCUSSING MASS-SPECTROMETER FOR SIMULTANEOUS ION MEASUREMENTS IN THE STRATOSPHERE

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ABSTRACT

The identification of less abundant stratospheric ions requires an improvement of mass resolution and sensitivity of the instruments in use. A modified Mattauch-Herzog analyzer was developed for positive ion measurements in the mass range 12 to 500 u and will be upgraded for negative ions. The main characteristics, design parameters and first laboratory test results obtained with it are described here. The ions are mass- separated in combined toroidal electrostatic and constant magnetic fields. The simultaneous measurement of a spectrum part is achieved with the use of two detectors. They consist of a 1-inch microchannel plate, an attached phosphor screen, a fiberoptic seal and a linear position sensitive light detector. Ambient atmospheric ions are sampled through a small orifice. The atmospheric air density is reduced in the inlet region of the instrument with a liquid helium cryopump. An octopole HF-field was integrated into the ion optics in order to reduce the ion loss.

KEYWORDS: Mass spectrometers, electro-optical devices, atmospheric density, stratosphere.

1. INTRODUCTION

The nature and abundance of positive and negative ion species in the stratosphere and mesosphere can only be determined by means of in situ mass spectrometer measurements. In the mesosphere ions were measured with a detection limit of 1-10 cm^{-3} by Narcisi et al. (1965), Krankowsky et al. (1972) and Zbinden et al. (1975), by using cryogenic pumping. Although the very first mass spectrometric measurements of positive ions in the stratosphere were performed with rocket borne instruments by Arnold et al. (1977), the use of balloons turned out to be a much more appropriate means for stratospheric ion sampling. Balloon-borne instruments for stratospheric ion measurements were developed and successfully flown by Arijs et al. (1978) and Arnold et al. (1978). The knowledge of the nature and abundance profiles of mesospheric and stratospheric ions is essential for the understanding of atmospheric electricity, in particular the formation and loss mechanisms of free electrons and positive and negative ion clusters. All these parameters strongly depend on the ion composition. Stratospheric ion measurements by Arnold et al. (1980), Arijs et al. (1983a, b) and Viggiano and Arnold (1983) revealed the possibility to detect trace gases with very low concentrations. Ions of the middle atmosphere may also play an important role in the formation of aerosols and they can provide additional support for the laboratory investigation of thermochemical and kinetic ion-molecule reaction constants (see e.g. Arnold et. al., 1981).

So far only quadrupole mass filters have been used successfully for stratospheric ion measurements [for description and performance of instruments see Nevejans et al. (1985) and references therein]. Although such insturments have provided a wealth of data on the major positive and negative ions in the altitude range 20 to 45 km and gave a rather consistent insight into the major stratospheric ion chemistry [for recent references see reviews by Arnold (1982), Arijs (1983), Arijs et al. (1984) and Arijs and Brasseur (1986)] there still remain some questions about the less abundant positive and negative ions in the stratosphere. A lowering of the ion detection limit, an increase of the mass resolution, and the decrease of the integration time to build up ion spectra during a balloon flight are necessary to allow detailed investigations of small-scale structures in the ion composition. Such structures may originate from dynamical and electrodynamical variations or from rapid fluctuations of neutral minor constituents and the aerosol formation. Furthermore, an improvement of sensitivity and mass resolution is needed to extend the number of trace gas species which can be inferred from ion composition measurements.

With these objections in mind we aimed to develop a new balloon-borne mass analyzer with a mass range of 12-500 u, a mass resolution $M/\Delta M$ = 250 at the 1% level, a sensitivity of 10^{-1} cm^{-3} with 100 s integration time and an altitude resolution of 100 m. The instrument should also allow us to measure minor ion species because of the enhanced dynamic range 1:10^5 (100 s integration).

We have investigated three basic types of instrument, the time of flight (TOFS), quadrupole mass filter (QMFS) and the double focussing magnetic mass spectrometer (DFMS). All three instrument types have been used in aeronomic measurements in

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the Earth's atmosphere and in that of other planets (cf. Nier and Hayden, 1971; von Zahn and Mauersberger, 1978). The general requirements for the instrument improvement can be best fulfilled by the DFMS instrument which is capable of performing a simultaneous measurement of ions within a selected mass range. This feature is not available in QMFS instruments. The latter devide the mass range in small domains which are measured separately (scanning).

The TOFS instrument would allow much larger ion inlet apertures than QMFS or DFMS, but the improvements in ion transmission probability are lost because this instrument is working in a pulse mode. Incoming ions are only analyzed during a small fraction of the time.

The selected instrument type is a modified Mattauch-Herzog geometry (Mattauch and Herzog, 1934), a combination of a radial electrostatic field and a homogeneous magnetic sector field. In order to improve the ion transmission a toroidal field is used. This field configuration allows also axial focussing (β-plane). The imaging plane has been chosen slightly (at least one gap) away from the permanent magnet. By consequence, angles of the ion beam at the entrance of the magnetic field and the imaging plane are non-standard.

2. INSTRUMENT DESCRIPTION

The instrument from which the vacuum part is shown in detail in Figure 1 uses the liquid helium-cooled cryopump from BISA described by Ingels et al. (1978) and Nevejans et al. (1985). The inlet plate, which is insulated from the pump, has a typical sampling hole of 0.2 mm diameter. The opening device is activated as soon as the balloon reaches the desired altitude.

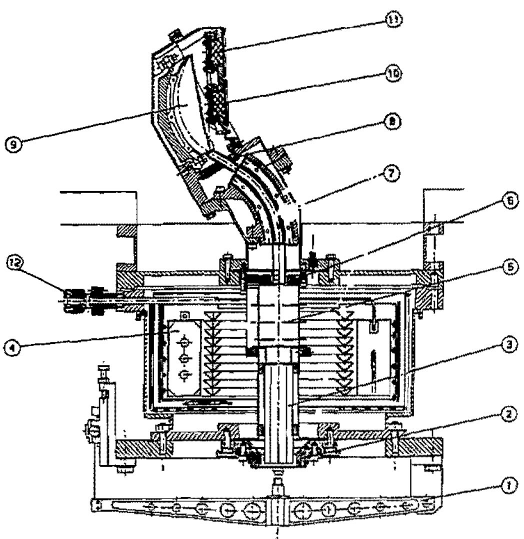

Figure 1 Cross section of high vacuum part of the mass spectrometer. 1) spring-loaded opening device; 2) ion inlet plate; 3) octopole ion transfer; 4) liquid helium container; 5) ion lense system; 6) Ion inlet slit; 7) toroidal electrostatic deflector; 8) ion guard; 9) permanent magnet; 10) micro channel plate; 11) fiberoptics; 12) liquid helium filling part.

Ions entering the inlet opening are guided through an octopole RF-field and are focussed and accelerated by a lense system on the inlet slit of the mass analyzer. The central ion beam passes the toroidal condensor at a radius of 10.51 cm and an angle of 59.4°. The tube between electrostatic and magnetic field keeps the region field free. Ions of different mass to charge ratio are deflected between a minimum radius of 2.80 cm and a maximum radius of 8.39 cm by means of a permanent magnet and are focussed on the imaging plane. In case the total length of 9.7 cm of the imaging plane could be used as detector, the mass range of 12-500 u could be covered with two different settings of the ion acceleration voltage. The magnetic deflection angle of the rare earth cobalt magnet (Recoma 28 from Ugimag) is 96.6°, its gap is 7.0 mm and the field strength in the center is 0.64 T. A contour plot of the magnetic field in the plane of the ion trajectory is shown in Figure 2. At the border of the magnet the field has decreased by about 10% and drops to

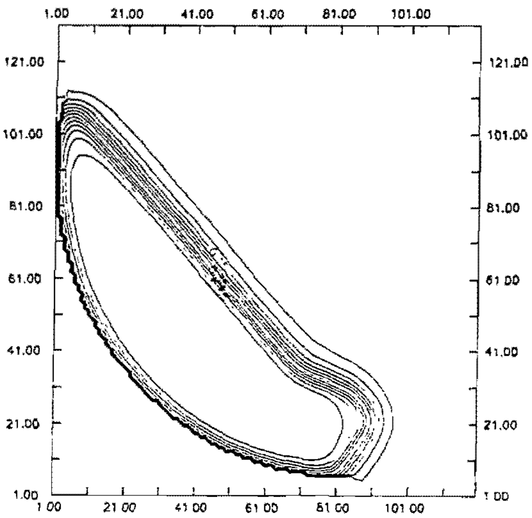

Figure 2 Contour plot of the magnetic field B. The central field is 0.64 T. Contours are separated by 0.05 T. X/Y-scales are given in mm.

about 20% within one gap distance away from the magnet. In our configuration two 1-inch electro-optical ion detectors are used. Each of the two assemblies consists of a) a multichannel plate (MCP), b) a phosphor screen deposited on the vacuum side of a vacuum sealed fiberoptic rod bundle and, c) a 1-inch 512-pixel linear photodiode array (LPDA). The LPDA is placed outside the vacuum system at the end of the fiberoptic rod bundle and stores the optical signals in an analogous way. The active area of each pixel is 35 um × 2.5 mm with a pixel separation of 50 µm. The large pixel size guarantees high pixel saturation charge levels. The use of two detector systems with one inch width requires four different settings of the ion acceleration voltage to cover the mass range of 12-500 u as shown in Table 1.

Similar instruments based on the Mattauch-Herzog geometry which are operating with linear array detectors for simultaneous detection of a mass spectrum have been developed and investigated by Giffin et al. (1974), Murphy and Mauersberger (1985), Krankowsky et al. (1986) and other authors cited in their references.

Table 1 Mass ranges of the two detectors for different ion acceleration voltage (IAV)

Det. A (u)	Det. B (u)	IAV (V)
12 - 28	63 - 95	1340
28 - 65	147 - 221	576
42 - 98	221 - 334	382
64 - 148	333 - 504	253

3. DETECTOR

A schematic view of the electron optical ion detector is shown in Figure 3. The ions leaving the magnetic field are accelerated towards the entrance of the two MCPs. In this experiment C-type MCPs with 25 µm curved channels (Galileo Electro-Optics) are used. The details of the performance of MCPs can be found in the papers by Wiza (1979) and Timothy (1981). An ion striking the front of the MCP causes an electron pulse of the order of 10^6 electrons leaving the MCP. These electrons are accelerated towards a conductive P20 phosphor layer (AEG Telefunken) which is deposited on the front surface of a fiberoptic rod bundle (Galileo Electro Optics). The fiberoptic rod bundle has fibers of 6 µm diameter and an overall maximum diameter of 35 mm at its reverse side. Two solid state optical image detectors, each consisting of a 512 pixel self-scanned linear photodiode array (Hamamatsu S 2304-512F) fitted to a fiber optic rod bundle are used for the recording of mass spectra. The two LPDA-arrays are read out simultaneously in 54 ms and their serial analog video output signals are digitized by an ADC having a 12 bit resolution.

Prior to the use of a new MCP in the detector at least a three day period of extensive heat treatment in vacuum at 300°C was applied. After the heat treatment the MCPs were burnt in with a low intensity ion beam for about 10 hours, using 1000 V as the MCP-voltage at room temperature. Our MCPs were at pressures below 2×10^{-6} mbar and at a nominal supply voltage of 1.6 kV.

We have tested the ion optical detector configuration in a homogeneous ion beam with constant ion energy, different intensities and uniform mass to charge ratio. Figure 4 shows a linearity plot for N_2^+ ions with a nominal impact angle of 50°. The plot is an average of over 100 read-outs taken from the 200 center pixels out of the 512. A value of 1550 V is used for the MCP voltage and 2200 V for the electron acceleration at the output of the MCP towards the phosphor screen. A current density of 8000 ions/mm^2 s resulted in 3323 ADC charge counts being accumulated from a single LPDA-pixel during an integration time of 54 ms. The results show that in this configuration one ion gave rise to an average number of 88 ADC-counts. The slight bending of the linearity plot is an artifact which originates from the beam measurements with a reference detection system.

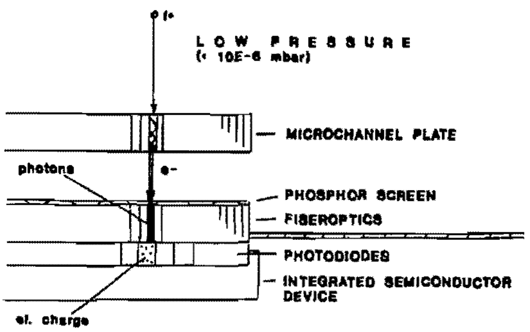

Figure 3 Elements of the linear electro-optical array detector. The fiberoptics separate the high vacuum part from the electronic part at atmospheric pressure.

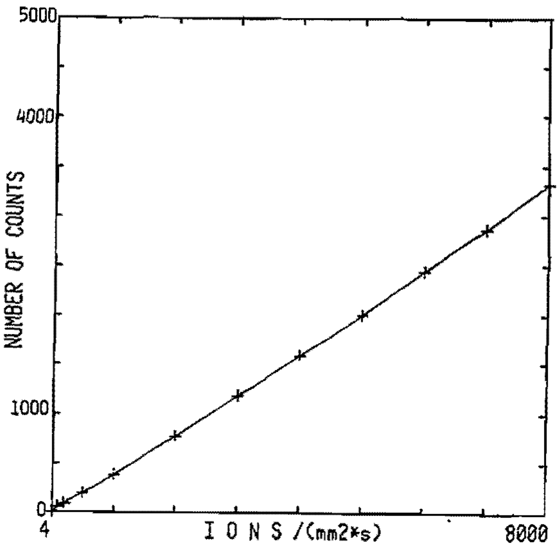

Figure 4 Linearity plot of the detector measured with N_2^+ ions with 2.5 kV energy, 1.55 kV MCP voltage. The scale of the LPDA read-out is given in units of 500 with maximum ADC counts of 3323 at 8000 ions/mm^2 s.

The 25 mm C-plate MCP (Galileo Electro Optics No. 1034-201-012) has been tested similarly for the investigation of the overall gain homogeneity. Again N_2^+ ions with an energy of 3000 eV and a current density of 2500 mm^{-2} s^{-1} have been used. Figure 5 displays the variability of ADC counts of the Hamamatsu LPDA against the local pixel position. The gain variability is for this

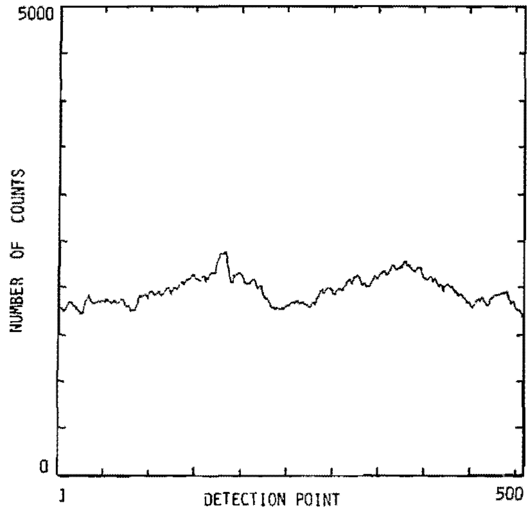

Figure 5 Variability of the MCP gain of a curved 1-inch C2 MCP. The measurement was made with N_2^+ ions at 3 kV energy and 1.6 kV MCP voltage. The maximum ADC count rate is 2378 on pixel 184 and the minimum 1716 on pixel 27.

case almost the same as observed in the original beam. The gain uniformity is well within 10% for this exceptionally good case. The pulse height spectrum of the MCP as recorded for Kr^+ ions of 800 eV energy with the same detector operation parameter settings is shown in Figure 6. The number of counts/ion is equivalent and linear to the detector gain which is normally used for such analyses. The maximum of the distribution is at 44 counts/ion and the distribution is within the specification, 90% at half of the maximum (fwhm ∿ 90%). In all measurements the number of ADC counts were corrected by a subtraction of the background spectrum recorded with the ion beam turned off.

The full detector operation is shown with the recording of a krypton spectrum in Figure 7. The krypton ions were formed in a plasma ion source and passed the magnet system with an energy of 900 eV. 100 spectra of 54 ms integration were averaged and corrected with the LPDA background. The main krypton peaks on masses 78, 80, 82, 83, 84, and 86 u are clearly visible. The peaks on masses 87, 85, 79, and 77 u are spurious ions created by the plasma ion source. Masses 87 and 85 can be identified as Rb isotopes. The mass resolution M/ΔM at the 1%-level calculated at 84 u is 120.

4. PIXEL PROCESSOR UNIT (T4)

The T4 unit is a data processing and experiment control unit, which has been developed for the SIDAMS sounding rocket version. In the balloon experiment the operation of the T4 unit is reduced to the read-out and digitizing of LPDA-data, subtraction of background signals, summation and averaging of a selected number of LPDA read-outs and the data transfer over serial

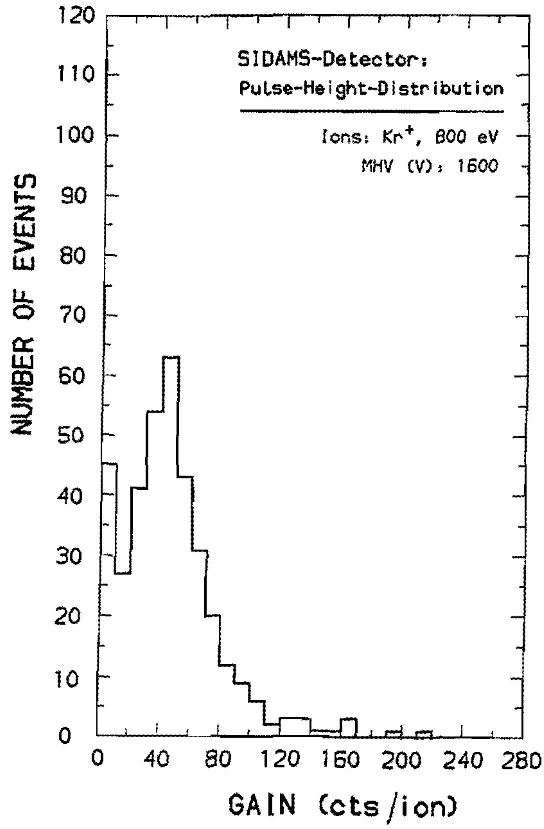

Figure 6 Pulse height distribution of Kr^+ ions at 800 eV energy measured with a curved 1-inch C2-type Galileo Optics MCP.

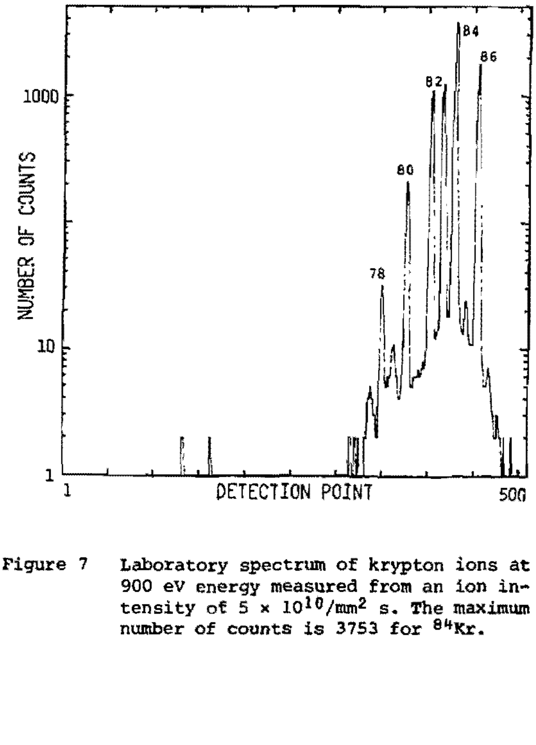

Figure 7 Laboratory spectrum of krypton ions at 900 eV energy measured from an ion intensity of $5 \times 10^{10}/mm^2$ s. The maximum number of counts is 3753 for ^{84}Kr.

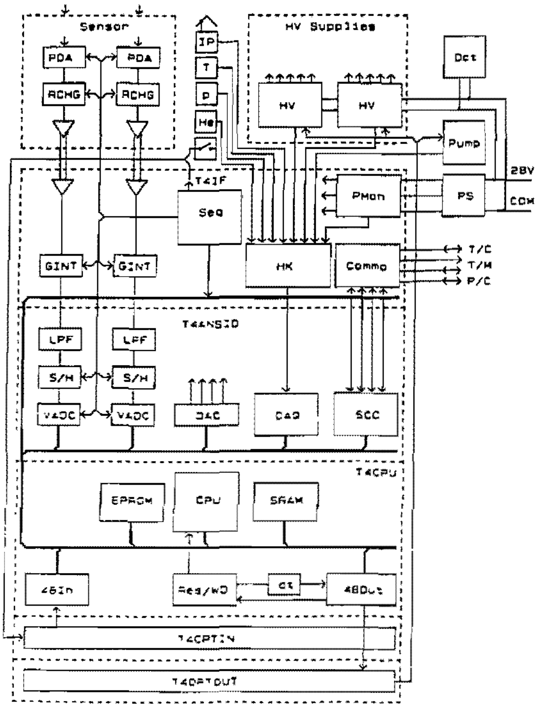

Figure 8

Block diagram of the SIDAMS T4 pixel processor unit. Explanation of abbreviations: PDA: Photo diode array; RCHG: Recharge of pixels; GINT: Gated integrator; LPF: Low pass filter; S/H: Sample and hold; VADC: Video analog-to-digital converter; Seq: Sequencer; HV: High voltage; PS: Power supply; Oct: Octopole power supply; T: Temperature sensor; p: Pressure sensor; He: He-level sensor; switch: Break wire monitor; $P_{\sim}$Mon: Power monitor; HK: Housekeeping unit; DAQ: Data acquisition system; Commo: Communications interface; SCC: Serial communications controller; DAC Digital-to-analog converter; CPU: Central processing unit; EPROM: Erasable programmable read only memory; SRAM: Static random access memory; 48 In/Out: 3 16-bit parallel input/output ports; Res/WD: Reset/Watchdog; dt: Delay for parallel output; Opt In/Out: Isolated input/output channels; T/C: Telecommand; T/M: Telemetry; P/C: Payload Console.

interfaces to telemetry. The T4 unit can also provide telecommand signals.

A schematic of the T4 unit is shown in Figure 8. The pixel processor unit contains five basic printed circuit boards, T4 IF, T4 ANSIO, T4 CPU, T4 OPT IN and T4 OPT OUT.

The T4 CPU is a CMOS single board computer, based on a 80C186 Intel microprocessor, a clock frequency of 8 MHz, 128 Kbyte EPROM and static RAM. The board has input and output registers and two DMA channels for LPDA and TM data. The T4 ANSIO is the analog input/output board for LPDA signals, equipped with a sample and hold unit, an ADC with 12 bit resolution and 12.5 us conversion time for both LPDA channels. The input and output operates under DMA or interrrupt control. On the T4 ANSIO board 16 channels can be used for the experiment housekeeping and four RS-232 interfaces with handshake provide the communication to the main experiment control, the test console and telemetry.

On the T4 IF interface board the Intel 87C196 CMOS microcontroller generates the clock frequency. This board delivers also the necessary control signals to the T4 ANSIO board.

The two T4 OPT IN/OUT boards are used for the optical isolation of input and output controls. 48 input and 48 output channels with 500 VAC isolation can be used at a maximum data rate of 300 kbit/s.

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