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Surveys of Soviet-Bloc Scientific and Technical Literature

RADIO-FREQUENCY MASS SPECTROMETRY

Comprehensive Report

**AID Work Assignment No. 43
(Report No. 10 in this series)**

The publication of this report does not constitute approval by any U. S. Government organization of the inferences, findings, and conclusions contained herein. It is published solely for the exchange and stimulation of ideas.

Erratum

AID Report P-64-39 should be designated on the cover and title page "Task 10" instead of "(Report No. 10 in this series)".

FOREWORD

The following comprehensive report has been prepared in response to AID WA 43 Task 10. It is based on materials available to the Aerospace Information Division at the time this report was written.

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RADIO-FREQUENCY MASS SPECTROMETRY

I. INSTRUMENTS

This introductory chapter presents descriptions and specification data of Soviet r-f mass spectrometers in the approximate chronological order of their introduction or of publications in which such information appears. The principal agencies conducting research in this field appear to be the Institute of Applied Geophysics of the Academy of Sciences USSR in Novosibirsk*, the State All-Union Design Bureau of Analytical Instrumentation**, and the Committee for Radio Electronics under the Council of Ministers, USSR***. The personalities engaged in the field include, among others, such researchers as Vorsin, Doylnitsyn, Mikhnevich, Mirtov, Istomin, Pavlenko, Pokhunkov. Some of the devices described were not initially designed for upper atmosphere investigations, but were included as necessary links in the course of development of types adapted specifically for use in high-altitude research.

THE RMS-M

The RMS-M radio-frequency mass spectrometer can be considered one of the initial achievements of a group of scientists headed by Vorsin and associated with the Geology and Geophysics Institute of the Siberian Section of the Academy of Sciences USSR. The main goals were miniaturization and simplicity of operation. The instrument is 100 mm high and 23 mm in diameter, it operates on relatively poor vacuum of 10^{-3} mm Hg, and its resolving power varies between 10 and 16 atomic mass units. **** A general view of the device is shown in Fig. 1 [1]. (See Appendix for all Figs.)

*(Institut prikladnoy geofiziki)

**(Gosudarstvennoye sovuznoye konstruktorskoye byuro analiticheskogo priborostroyeniya)

*** (Gosudarstvennyy komitet no radioelektronika pri Sovete Ministrov)

****The specifications of all instruments described here are given in a table in the Appendix.

THE DOYL'NITSYN PATENT

According to an announcement published in the *Byulleten' izobreteniy* (Bulletin of Inventions) no. 13, 1960, Ye. F. Doyl'nitsyn was issued Author's Certificate no. 129868 for an r-f mass spectrometer in December 1958. The instrument, which is equipped with two arms operating under different conditions, is designed to analyze ions from a single source. It could be used, for example, for the simultaneous study of the composition of reacting materials and of the reaction products, or for measuring the ratio of two isotopes of widely differing mass [2].

THE RMS-1

This appears to be the first Soviet r-f mass spectrometer extensively used in upper atmosphere research. The RMS-1 has been actually used, according to Istomin [9], in 1957-1958 launchings and also [6] during the International Geophysical Year, being carried in high-altitude geophysical rockets and Sputnik III [7]. The instrument was described in great detail by Istomin in 1959 [6].

The RMS-1 consists of three parts: the analyzer and preamplifier, the electronics unit, and the power supply (Fig. 2a). The instrument carried by Sputnik III, however, had a somewhat different appearance (Fig. 2b) [18, pp. 166-212].

1. The analyzer of the RMS-1

The design of the 7/5 cycle analyzer was developed according to Istomin's specifications by a team under Z. G. Petrenko in "one of the enterprises" of the Government Committee for Radioelectronics under the Council of Ministers USSR. The basic design was Bennett's, with modifications introduced by Vorsin and others. The principal feature of this analyzer was a series of single-row grids (as opposed to Bennett's wire mesh). This system of grids was first described by Istomin in 1958 [5]. These grids in the RMS-1 were made by winding 20-micron tungsten wire on a frame to which polished Kovar rings were attached. The windings were retained in position by a spot-welded annular Kovar plate 0.1 mm thick. The grids have a working diameter of 30 mm, with a winding pitch of 0.5 mm, and a transparency of 96 per cent. Each grid with its windings is mounted to form a 120° angle with the preceding grid. Since the analyzer contains 15 grids, the total transparency becomes a major consideration with respect to the collector

current. In general, these grids are considered much simpler and cheaper than wire mesh grids and can be produced without any loss of efficiency [6]. The resolving power of the RMS-1 equipped with Istomin grids was the same as that of the Townsend spectrometer described in *Rev. Scient. Instrum.*, 1952, v. 23, no. 10, p. 538. In his initial description of 1958, referred to above, Istomin related that according to tests carried out in the Institute of Applied Geophysics in 1957 [5], the single-row grids showed 25 per cent better resolving power than the prototype tubes with conventional grids.

The diagrammatic layout of the RMS-1 analyzer grids is shown in Fig. 3.

The large drift-space gaps (A and B in Fig. 3) are maintained by copper cylinders which also serve as drift-space electrodes. The packet of grids and metal-glass ring spacers is assembled on three polished ceramic rods 4 mm in diameter. Collector and grid connections pass through Kovar seals. The stainless steel body of the analyzer tube has a flange for mounting it on the ion source, or the rocket, or sputnik. A tube with the ion source attached appears in Fig. 4.

The ion source is used primarily for laboratory adjustments and calibration and for checking the condition of the device in later tests [20].

The spectrometer tube with its ion source attached is thoroughly degassed by heating to 400° C for several hours, then filled with an argon-neon mixture of a pressure of about 3×10^{-5} mm Hg and sealed off from the vacuum system. Two to three hours after sealing, the tube is tested for leaks, after which a getter is vaporized in the tube. Experience has shown that the tube maintains this vacuum for months of operation [6].

2. The electronics unit of the RMS-1

The electronics unit consists of a d-c amplifier, an r-f generator, rectifiers for "shift" and "stop" voltages, a sawtooth voltage generator, a 600-volt d-c transformer, a commutator system for output telemetry, and a relay system.

The 4-stage d-c amplifier, which Istomin described in considerable detail by means of circuit diagrams, is based on an amplifier recommended in a thesis presented by L. S. Tsvang at the Institute of Applied Geophysics, Academy of Sciences SSSR in 1956 [30]. Cer-

tain features which might be of some interest will be related here. The first stage is a conventional electrometer arrangement operating on a 6Zh1Zh tube with an input resistance of 10^{10} ohms. Both tube and resistor were removed from the electronics unit and placed in the preamplifier unit which is mounted in the collector end of the spectrometer tube. The preamplifier is connected to the electronics unit by a multistrand shielded cable and RK-19 coaxial cable with corresponding plugs at the ends. The length of the cables is somewhat greater than one meter. The remaining tubes of the amplifier are of subminiature type. The second stage 6Zh1B tube operates in the so-called "microcurrent" mode with an anode load of 10^6 ohms and is characterized by a high amplification factor with negligible anode current. The third stage uses the same type of tube and operates as an ordinary triode. The first three stages are supplied with a 100 per cent negative voltage feedback, which produces an amplification factor equal to unity, thus reducing the time constant and improving the stability of the amplifier. The time constant, evaluated from oscillograms of the voltage drop at the amplifier output with stepwise change of voltage at the input, is shown not to exceed 5×10^{-3} sec with a pulse duration of the ion current of 3 to 5×10^{-2} sec under operating conditions. The last stage is a cathode follower that uses a 6S7B tube to match the output to the telemetering system. The coupling between all stages is galvanic. All batteries are composed of miniature OR-1K mercury oxide cells and are installed with the amplifier [6].

The cathode follower output is linear up to the input voltage value (about 5.5 volts), with an amplification factor of about 0.8. The low-sensitivity output of the amplifier is linear up to an input voltage of about 110 volts with a voltage amplification factor of 0.05 [6].

The filament circuits are fed by silver-zinc storage batteries, those of the anode by mercury-oxide cells installed in the power supply unit. In order to achieve increased stability of the spectrometer, the filament, anode, and grid of the electrometer stage are supplied by separate batteries [6].

The power supply circuitry of the RMS-1 analyzer tube was based on Townsend's work (*Rev. Scient. Instrum.*, v. 23, no. 10, 1952, 538). The quartz-stabilized r-f generator was derived from Pierce and uses a 6P9 tube. The supply system differs from that of the Townsend design in that high voltage is applied to the tube through

a capacitive divider formed by a condenser and the capacitance of grids 4, 7, and 10 of the analyzer. This change considerably decreases the power requirement of the generator. The high-voltage amplitude is controlled by the grid voltage of the 6P9 tube through a resistor. The decelerating ("shift" and "stop") voltages are obtained by rectification and doubling of the high voltage by two 6D6A tubes. Such circuitry ensures stable operation of the tube, because the "shift" and "stop" voltages change proportionately. A small portion of the r-f voltage rectified by the 6D6A tube serves to control the operation of the generator. "Shift" and "stop" voltages are regulated by two potentiometers. Two SG-1P voltage regulators are used to stabilize the anode voltage of the r-f generator [6].

The sawtooth voltage is supplied by a thyatron circuit that used a TG-1B tube with a linearizing 6Zh1B pentode [6].

The anode circuit of the thyatron includes a relay coil. Sweep reversal pulses activate the relay and this, in turn, operates the Sh1-11 step commutator. Thus, the contacts of the step commutator, which are normally closed, open during sweep reversal and preclude uncontrolled discharge of the thyatron [6].

The electronics unit of the RMS-1 contains a semiconductor transformer for high-voltage supply of about 600 volts at 50 microamperes to grid 15 of the analyzer; this results in an 8-milliampere drain from the 6.3 volt filament battery. A part of the transformer voltage (about 1 volt) is used to control its operation by feeding it to the even segments of section III of the step commutator. Odd segments of the same section carry control voltage of the r-f generator and the filament voltage of the first amplifier tube. Thus, three control parameters are switched by the step commutator at the sweep frequency and transmitted to one telemetering channel. This serves to reduce the number of telemetering channels. In addition, the "stop" voltage and part of the sawtooth voltage are telemetered. The step commutator also transmits the outputs of the d-c amplifier, which permits the operation of device by only one multiplex channel, if necessary. If more channels are available, the output connections bypassing the step commutator are used, providing independent transmission of both high- and low-mass channels. Sections IV of the step commutator can be used in various ways, depending on the particular application of the device [6].

3. The power supply unit of the RMS-1

The power supply unit feeds the electronics unit and grids 1 and 2 of the analyzer. Silver-zinc storage batteries and mercury oxide cell batteries are used for this purpose [6].

THE MKh-6401

This 5-stage r-f mass spectrometer was developed by the West Siberian Section of the Academy of Sciences and The State Special Design Bureau of Analytical Instrumentation some time in 1958 or earlier. It was described briefly in a review of Soviet industrial spectrometers by Pavlenko and others in mid-1958 [19], who presented a block diagram of the device and some specification data (see table). The instrument is designed for studying the molecular chemical composition of gases in the 2 to 60 mass number range. No reference is made by this author to its application in upper atmosphere research.

A further step in the development of r-f mass spectrometers was carried out by The Special Design Bureau of Analytical Instrumentation in 1959 or earlier. An instrument was designed especially for investigation of the ionic as well as the molecular composition of the atmosphere. It was described by Pavlenko, Rafal'son and others at the end of 1960, but no designation is given in this text [20]. A modification of the device was described briefly in 1961 by Pokhunkov in an article dealing with mass spectrometric investigation of the composition of the atmosphere by means of a rocket launched in July 1959. No designation was given, but the specifications which were mentioned indicate that the instrument belongs to the MKh-6401 series. A general view of the device appears in Fig. 5 [23].

Only a much later (1963) source by Pavlenko and others definitely identified this spectrometer as the MKh-6401 [21]. A photograph showing a general view of the device, however, displays some details in which it differs from the one described here (see Fig. 6). The analyzer arrangement is shown in Fig. 7.

In this arrangement, the maximum energy boost is experienced by the "synchronized" ions which pass the first grid at 46° of the high-frequency phase and the second grid at the instant the field drops to zero. The positive delay voltage (Fig. 7) insures that only the synchronized ions reach the collector. An increase in resolving power,

as well as suppression of "harmonic" masses, was achieved by placing the successive three-grid stages at distances of 5, 9, 4, 7 high-frequency periods from one another. An example of the spectrum obtained from a mixture of 5% Ar, 35% He, 25% Ne, and 35% H₂ at a residual pressure of 1×10^{-6} mm Hg and an inlet pressure of 1×10^{-5} mm Hg is shown in Fig. 8 [20].

Other details of the MKh-6401 that were described in article [20] are the ion current amplifier, the high-frequency generator, the sawtooth voltage generator, and the d-c transformer. The device feeds the following information into the telemetry system: 1) the voltages of the outputs of the ion current amplifier (mass spectrum), 2) the r-f voltage, 3) the cathode emission of the ion source (in molecular analysis), and 4) the power supply voltage. A ground control unit is included which is used for setting and measuring the operational data of the spectrometer, monitoring mass spectra on the screen of an electron-beam tube, or for recording them by a loop oscillograph. The specification data are included in the table (Appendix). Light weight, small size, low power consumption, and long periods of operation (hundreds of hours) without need for recalibration are properties which are said to make the RMS-Pavienko (MKh-6401) particularly suitable for upper atmosphere investigations in addition to other applications. At the time of publication, the device was said to have successfully passed the laboratory tests and to have taken ion and molecular composition measurements from rockets, without there being any mention, however, of specific experiments or results [20].

In this connection, it appears that one should mention the launching of 15 June 1960 which was described by Istomin in late 1961 in an article dealing with ions of extraterrestrial origin in the ionosphere [10]. In this article, Istomin referred to both the RMS-1 [6] and the MKh-6401 [20], as the instruments used in the investigation of his problem. However, he did give a very general description of the spectrometer actually used in the launching of 15 June 1960, referring to it as "one of the latest models of a mass spectrometer" but designating it later in the text as MKh-6403 (see Fig. 9). It is said to be of increased sensitivity [10]. It appears, therefore, that the "15 June" or MKh-6403 (as it is once more referred to by Istomin in [9]) spectrometer was a new development superseding the RMS-1 as well as the MKh-6401.

THE MS-"POKHUNKOV"

A 5-stage r-f mass spectrometer, referred to as an improved version of the MKh-6401 is briefly described by Pokhunkov in an article published in 1962 dealing with measurements of the molecular weight of night air in a launching of 23 September 1960 [24]. The improvements were made to overcome difficulties experienced during earlier upper atmosphere investigations and arising from changes in the composition and the relative amounts of the analyzed mixture of gases during the measuring process, mainly due to recombination and reflection phenomena on the intake and the analyzer surfaces. To minimize these effects, the intake was shortened to a minimum and its diameter substantially enlarged. The diagrammatic arrangement of the improved A2 analyzer is shown in Fig. 10.

A known mixture of H₂, He, Ne, and Ar sealed in the analyzer at a pressure of 1×10^{-5} mm Hg prior to launching was used for control calibration of measurements. Specification data of the spectrometer appear in the table presented in the Appendix.

THE MKh-6403 AND THE MKh-6405

A further developmental step in the direction of automation and miniaturization is represented by two closely related types, the MKh-6403 and the MKh-6405 described by Pavlenko and others in September 1963 [21]. The MKh-6403, the basic type for the MKh-6405, permits automatic change from ionic to molecular analysis, either by advance programming or by command from the ground. A general view of the MKh-6403 is shown in Fig. 12 and its measurement unit in Fig. 13a. The specifications are given in the table. One of the distinct features of the MKh-6403, as compared with the MKh-6401, is the improved transparency of the ion source which makes it possible to analyze ionized gases of the atmosphere without removing the ion source. The analyzer and the ion collector form a single welded unit without seals, a feature which contributes to the reliability and improved performance of the instrument. The measurement unit of the MKh-6403 contains the following units: a) ion current amplifier, b) high-frequency generator, c) sawtooth voltage generator, d) mass range commutator, e) power supply and voltage regulator. The ion current amplifier has a 100 percent negative voltage feedback and it includes a correction system which reduces the time constant to 0.002 sec. It has three stages of sensitivity. The high-frequency generator has a voltage regulator which compensates for substantial

changes in ambient temperatures and detuning of circuits within 0.1 to 0.05 percent. The sawtooth generator is based on an arrangement of capacitors charged through a pentode which yields good sweep linearity. The commutator accomplishes the switching of high-frequency ranges, sweep voltages, and amplifier output stages. The power supply is a push-pull relaxation vibrator operating on two semiconductor triodes [21].

The MKh-6405 is a modification of the MKh-6403 specifically designed for studies of the composition of the upper layers of the atmosphere. This instrument permits one to analyze the composition of both ionized and neutral gases, with automatic switching from one type of analysis to another. The MKh-6405 has better sensitivity than the MKh-6403. More detailed specifications of the MKh-6405 appear in the table. The spectrometers are said to work normally under fluctuations in ambient temperatures from -40 to $+40^{\circ}\text{C}$, also under increased humidity and considerable mechanical stresses. The life of the instruments is measured in hundreds of hours at a minimum noise level and stable zero point, as shown by actual test results [21].

A further modification of one or the other of the above instruments is briefly characterized by Pokhunkov in a 1963 report on the results of the 15 November 1961 launching [26]. Some specification data mentioned in the article are included in the table. The sensitivity of this instrument is stated to have been increased tenfold, without clearly referring, however, to a comparable type of spectrometer. In the ion source, the metallic electron focusing screen around the filament that prevents the direct passage of particles from the atmosphere into the ionization region was replaced by a mesh grid permitting free (without collision with the walls of the analyzer) passage of atmospheric particles into the ionizing region [26].

Because the cathode screen was negatively charged and the grids forming the source region were at the body potential of the rocket, the possibility of atmospheric ions passing into the ionizing region was not entirely excluded, especially at high (with respect to the thermal velocity) speeds and with sharp angles between the analyzer axis and the velocity vector, also with negative body potential [26].

II. STUDIES OF THE COMPOSITION OF THE ATMOSPHERE

The most important, certainly the most widely publicized application of the r-f mass spectrometer in the USSR has been upper atmosphere and space research. There are belated indications that rocket experiments of some kind have been conducted since 1954 [11], but the initial indication that Soviet scientists were interested in this field was expressed in an article by Mirtov in 1957 on the general subject of rocket investigations of the composition of the atmosphere at high altitudes [16]. The same issue of the periodical, *Uspekhi fizicheskikh nauk*, contains an article by Mirtov and Istomin which describes the operating principle of the Bennett r-f mass spectrometer and refers to it as an instrument that should enable scientists to obtain rocket data on the composition of the upper atmosphere [17]. All the references of this article are Western, and as it is frequently referred to by later articles, it can be considered one of the initial definite proposals to use the Bennett mass spectroscope in Soviet geophysical rocket and satellite research. A proposal to develop satellite-borne experiments using the r-f mass spectrometer was advanced. A 7/5-cycle, 3-stage system was favored in this article. This system was later developed by Istomin, the most prolific Soviet researcher in the field, to become the device known as the RMS-1 [17]. Soviet experimental work began in 1957 with this experiment. The chief personalities associated with upper atmosphere experimental studies are Istomin and Pokhunkov, the first concentrating on the investigation of ionized components, the second dealing mostly with neutral components. Theoretical treatment is carried on intensively by Danilin of the Institute of Applied Physics (Institut prikladnoy fiziki), Academy of Sciences USSR.

1. STUDIES OF THE IONIZED COMPONENTS OF THE UPPER ATMOSPHERE

a. The Rocket Experiments of 1957-1959

From 1957 to 1959, four experiments were conducted in the Soviet Union to determine the mass spectra of positive ions at altitudes ranging from 90 to 210 km by means of r-f mass spectrometers. Istomin presented a report on the activities of this period in 1961 [8]. The launchings required for the rocket experiments took place on 9 September 1957; 2 and 13 August 1958; and 22 July 1959 [8].

In each experiment, the mass spectrometer was installed in a cylindrical container which was separated from the rocket during the ascent phase, thus insuring the maximum possible freedom from contamination of the experiment by the rocket. Mass spectra and some control parameters were transmitted to the earth by a multichannel, high-precision radio telemetry system. The container was not oriented in any particular direction during flight. The launchings took place in the "middle latitudes of the European part of the Soviet Union."

The three experiments in 1957-1958 used a 7/5-cycle r-f mass spectrometer of the RMS-1 (Bennett) type, which was tuned in the laboratory to a resolving power of about 20 for neon isotope peaks at mass numbers 20 and 22. The isotopes were sealed in the analyzer tube for purposes of calibration [8].

Istomin considered the data obtained from the evening launching of 9 September 1957 to be of little value because of the high noise level and the small number of spectra obtained. Therefore, these data were not sufficient to establish the nature of the difference between day and evening conditions in the ionosphere [34].

In the launching of 1959, an MKh-6401 type mass spectrometer was used, with the same calibration procedure as in the preceding three launchings. The mass numbers were determined from ion current graphs obtained during flight by means of comparisons with calibration graphs of a known gas mixture sealed in the analyzer. The final calibration and checking procedures were carried out in flight, before the separation of the ion source and opening the tube intake at about 90 km altitude for admission of atmospheric gases [8, 10].

In all experiments of this period, the mass spectrometer analyzer was installed in a recess in the cylindrical surface of the container in such a manner that the first grid of the device was positioned approxi-

mately at the surface. This grid was kept at a negative attracting potential of -50 volts in the RMS-1 and at -43 volts in the MKh-6401. The attracting potential was applied in order to increase the sensitivity of the spectrometer and also to prevent possible closing of the device if the container picked up a positive charge. Under the conditions of the rocket experiment, differences in the sensitivity of the device to ions of various masses could not be significant. As the velocity of the container was on the order of one kilometer per second, the energy of ions with mass numbers 16 and 30 was about 0.08 and 0.16 electron volts, respectively. The thermal energy of the ions at a temperature of approximately 1000° K was also on the order of 0.1 electron volts [8].

Under these conditions, the relatively strong attracting field controlled ions of various masses in approximately the same way, without introducing any strong discrimination. This reasoning was supported by the data obtained [8].

Although all four experiments were conducted at different times, under different circumstances, and with mass spectrometers differing in some details, they still yielded identical conclusions in regard to the composition of the ionosphere. At altitudes of 100 to 200 km, the three main components were found to be positive ions with mass numbers 30, 32, and 16, which were associated with nitrogen oxide (NO^+), molecular oxygen (O_2^+), and atomic oxygen (O^+). In addition to these main components, the altitude variation of which further confirms their identification, ions with other mass numbers were also registered which were associated with such atmospheric components as ions with mass number 28 (molecular nitrogen N_2^+), and mass number 14 (atomic nitrogen N^+), as well as the mass number 18 of water (H_2O^+). The last was not positively identified. Identification of these ions as true atmospheric components was not fully proved, especially in the case of H_2O^+ . No hydrogen and helium ions were observed at altitudes of 100 to 200 km [8].

Peaks with mass numbers 47, 45, 31, and 19 made up a third group obtained chiefly during the descending phase of the trajectory of the container. These ions were identified as impurities introduced by the rocket.

b. The Experiments with Sputnik III

In the meantime, the third Soviet Sputnik was launched in May 1958. Istomin, who was awarded a Doctor's degree in 1961 for his r-f spectrometer studies of the ionosphere, reported the results obtained by Sputnik III in 1960 [7]. This satellite carried a RMS-1 type r-f mass spectrometer.

The device operated from May 15 to May 25 1958, during which time about 15,000 mass spectra were obtained at altitudes ranging from 225 to 980 km. Measurements were conducted only in the northern hemisphere, within a range of 27 to 65° north latitude and only during the day, mainly between 7 and 11 a. m. Moscow time.

Mass spectra obtained by the device showed harmonic false peaks as well as true mass peaks, thus adding to the difficulty of identification of components. These harmonic peaks were present because the effective decelerating potential of the spectrometer was reduced greatly for two reasons. First, all atmospheric ions had a directed velocity equal to the velocity of the satellite in addition to their thermal velocity. Due to this factor, the decelerating potential of the instrument was lowered by different values for ions of different masses, the difference being equal to energies expressed in electron volts. In addition, an analysis of the spectra showed that the Sputnik had a negative potential of several volts, which likewise led to additional lowering of the effective decelerating potential by a value that was equal for all atmospheric ions [7].

The effective decelerating potential, which was lowered for these two reasons, increased the sensitivity of the spectrometer severalfold, more for heavy ions than for light ions. However, mass resolution was correspondingly degraded to about one-half the performance shown by the device during calibration in the laboratory. The mass numbers of all peaks in the spectra were shifted on the main scale of the device toward light masses due to the velocity of the Sputnik and to its negative charge, as was expected [17].

Separation of the main and harmonic peaks in the spectra was accomplished by comparison of their amplitudes and by the nature of their variation with altitude and orientation of the satellite. The positions of the harmonics in the spectra of the device were determined previously in laboratory experiments. An additional criterion which indicated that the main harmonic peaks had been identified correctly was the fact that the relative widths of harmonics were less than those of the main peaks. This was also borne out in laboratory experiments [7].

After a correction for the velocity of the Sputnik was introduced, the mass numbers of those peaks taken to be the "true" peaks differed from their integral values by a fraction of an atomic mass unit. This difference was associated with the negative charge of the Sputnik. Thus, for instance, for two days, 22 and 24 May, the difference was 0.3 and

0.5 mass units, respectively. Taking account of the 7.2 v/amu constant of the device, the negative potential of the Sputnik was -2.2 and -3.6 volts according to these data [7].

All spectra contained a very large peak, the mass number of which, after correcting for the Sputnik's velocity, came close to 16. For this reason, the peak was identified as due to atomic oxygen O^+ [7].

The peak which was second in intensity, was that noted at mass number 14. It was considered most likely that this peak was associated with atomic nitrogen N^+ . Peaks with mass numbers 12 and 10.5 were identified as harmonics corresponding to peaks 16 and 14 [7].

Next to peak 16 in the direction of increasing mass there was a very weak but clearly discernible peak in most spectra at mass number 18. This peak was not a harmonic of any of the present main peaks, and its appearance could be explained only by the presence of the corresponding ionized molecules or atoms in the atmosphere. These ions were tentatively identified as either water ions (H_2O^+), or ammonium (NH_4^+). The presence of these ions was considered to be an indirect indication of considerable quantities of neutral or ionized hydrogen in the upper atmosphere. However, it was held even more likely that the peak at mass 18 could be attributed to an isotope of oxygen (atomic mass number 18), the relative content of which was 0.2 percent [7].

In addition to the group of peaks at mass numbers 18, 16, and 14, there was a distinct group of peaks at mass numbers 32, 30, and 28 which were also identified as true peaks. Most intense among these was a peak at mass number 30, which was identified as due to nitrogen oxide (NO^+) [7].

Peaks at mass numbers 32 and 28 were attributed to molecular oxygen (O_2^+) and molecular nitrogen (N_2^+). In spite of the fact that these peaks were not fully resolved and the extreme peaks, especially those at mass number 32, were often fused with the middle peak at 30, their presence in the spectra was beyond doubt. All other peaks in the spectra were identified as harmonic false peaks. Thus, a group of three peaks, among which the most intense was the peak at mass number 22.5, was determined to be composed of harmonics of peaks at 32, 30, and 28. Peaks at mass numbers 40 and 43 were determined to be harmonics of peaks at 28 and 30 [7].

Determining relative concentrations of ions from the peaks of the mass spectrum was quite difficult due to a number of circumstances, one of which was the separation of ions of different masses in the field of

the Sputnik itself, which occurred when the body of the satellite was not at the same potential as unperturbed plasma. The presence of an attracting field created by the first grids of the mass spectrometer tube led to additional ion separation. Finally, ions of different masses were in different states in the analyzer itself due to the varying initial energy with which they entered the analyzer. These differences varied by a factor of two for ions with mass numbers 16 and 30. Therefore, the deceleration of these ions was also different and the ratio of peak intensities was not equal to the ratio of concentrations of corresponding ions at the input to the analyzer. However, this mass separation, whatever its cause, was great for only those ions whose masses differed significantly from each other, and was small for ions of similar mass. Thus, some quantitative conclusions could be reached [7].

Absolute as well as relative intensities of mass peaks in the spectra showed considerable variation in time. As conditions in the device were controlled and remained unchanged throughout the experiment, variations in the spectra were attributed to such factors as: a) changes in the orientation of the input orifice of the analyzer with respect to the direction of flight of the rotating Sputnik, b) variations of the coordinates of the Sputnik's position, that is, the altitude, geographic latitude, and longitude, and c) variations of external conditions influencing ionization of the atmosphere [7].

The results of measurements obtained at altitudes from 225 to 980 km confirmed the predominance of O^+ in this region. At the same time, the relative (with respect to O^+ ions) content of heavy molecular ions NO^+ , O_2^+ , and N_2^+ decreased and that of the light ion N^+ increased with altitude [4, 7]. Unlike the altitude dependence of composition (which could not be established with the desired degree of reliability due to simultaneous change of latitude), the variation of composition with latitude could be determined with some certainty. The relative content of atomic nitrogen ions at altitudes of 225 to 350 km increased considerably in passing from the region of 30—50° north latitude to that of 55—65°. Although in much less pronounced form, the same thing appeared to be the case at altitudes of 450 to 980 km. The relative content of molecular nitrogen ions, molecular oxygen ions, and nitrogen oxide ions is also considerably greater in the 55—65° north latitude region than at lower latitudes [7].

c. The Rocket Experiment of 15 and 16 June 1960

An additional experiment to determine the ionic composition of the atmosphere was carried out (as described by Istomin in 1961 [9, 10]) on 15 June 1960 by a rocket which carried for the first time an improved r-f

mass spectrometer of the MKh-6403 type. This device differed from the former instruments in its greater sensitivity and somewhat smaller dimensions and weight (see Fig. 9, Devices) [10]. The launching took place during the morning hours (the solar elevation at launching time was 15°) in the middle latitudes of the European part of the USSR.

The great sensitivity of the MKh-6403 permitted registration of ionic components present in comparatively small concentrations in addition to registration of the main components of the ionosphere, that is, NO^+ , O_2^+ and O^+ . Istomin determined some of those ions to be of extraterrestrial origin [12, 10].

The launching of 15 June 1960 also registered ions with mass numbers 11 (B^+) and 12 (C^+). At an altitude of 200 km, their concentrations were about 3×10^3 and 3×10^2 per cubic centimeter. Ions with these mass numbers had not been found previously in the atmosphere. The nature of the variations in amplitude of the mass peaks of these ions shows that they could not be attributed to impurities introduced by the rocket, nor could they be attributed to impurities introduced by the container [9].

Ions with mass number 18 (H_2O^+) were recorded during this flight as in the previous 1959 flight, thus confirming the tentative conclusion that these ions were indeed H_2O^+ ions. Their origin, however, remained unclear as they could not be positively identified as atmospheric components [9].

The launching of 15 June 1960 also registered magnesium ions (Mg^+) [10]. This observation, together with some others referred to above, led Istomin to assume extraterrestrial origin of some of the observed components discussed in an article published in 1961 [10].

Over 100 spectra, five of which contained peaks with mass numbers 24 and 26, were obtained at altitudes of 92 to 206 kilometers. Three of those five spectra were obtained in the ascending phase of the trajectory and two during the descending phase. These peaks, the maximum amplitudes of which were registered at 103.5 and 105 kilometers during the ascending and descending phases, respectively, were identified as caused by magnesium 24 and magnesium 26 isotopes. Comparison of the altitudes of the two peaks yields a ratio of intensities equal to 9.3, which is close to the theoretical value of 7 based on the distribution of these two isotopes in nature. On the basis of electron concentration data and mass spectrometer data, the absolute concentration of Mg^+ was determined to be $1.36 \times 10^4 \text{ cm}^{-3}$ at altitudes of 103 to 105 km [10].

One of the spectra obtained during the ascending phase at an altitude of 103.5 km shows an ion peak at mass number 40, identified as due to the presence of Ca^+ . This is confirmed by the presence of ionized calcium lines in the luminescence of the evening sky [10].

Another observation in this connection is discussed by Istomin. At least two spectra obtained in the ascending as well as descending phase at altitudes corresponding to those at which the magnesium ions appeared showed extraordinarily high peaks at mass number 56. Although the mass number 56 was the limit of the spectrometer range, and an ion current peak at this point was a known characteristic of the instrument, the magnitude of the observed peaks left no doubt that it was associated with some atmospheric component. This component was identified as Fe^+ [36]. A careful check with earlier data revealed that, for instance, similar (mass number 56) peaks were recorded previously in the 2 August 1958 launching, in that case by means of a spectrometer with a range up to mass number 62. Using the results of electron concentration measurements of the same launching, researchers calculated the concentration of Fe^+ ions to be $1.2 \times 10^4 \text{ cm}^{-3}$. One of the spectra obtained during the 15 June launching showed a peak at mass number 28 at an altitude of 100 kilometers. A similar peak was discovered on reexamination of the 2 August 1958 launching. The maximum concentration of these ions was estimated at $7.5 \times 10^3 \text{ cm}^{-3}$. They were tentatively identified as Si^+ ions, which is consistent with the discovery of magnesium, calcium, and iron ions in the same altitude range. The presence of these ions at such altitudes is attributed to stony meteorites. It is concluded from this that meteorites play a significant part in the ionization of the E region of the atmosphere [9].

The information concerning the genuinely atmospheric components collected during the 15 June 1960 launching and that of the year before (22 July 1959) served Istomin as a basis for a method of determining the absolute ion concentrations from the data on relative concentrations, using the electron concentration data collected simultaneously with ionic data during the same launchings [34]. It should be noted here that measurements of electron concentration are considered by Istomin as an advantage of most of the Soviet launchings over the analogous American experiments [9]. A formula is given for these calculations which is correct under the following assumptions: 1) the sum of positive ion concentrations is equal to the electron concentration; 2) the sum of the ion peak amplitudes is proportional to the total concentration of positive ions; 3) the ratio of ion peak amplitudes in the spectrum is equal to the corresponding ion concentrations. The absolute concentration data thus derived from both launchings are given in two tables [9].

d. The Rocket Experiment of 15 November 1961

This was the first experiment arranged for simultaneously measuring both the ionized and the neutral components of the atmosphere and it was also the first to extend the altitudes beyond those of previous rocket experiments. The site was the "middle latitudes of the Soviet Union" and the time — 1600 hours local time [26]. The experiment of 15 November was also the first to yield direct measurements of light gases (i to 4 amu) at altitudes exceeding 210 km [26, 27].

A large geophysical rocket which reached an altitude of 430 km carried an r-f spectrometer of the same general type as that used in the 1959 experiments [20, 4], but with considerably increased sensitivity (tenfold) and a change in the design of the ion source aimed at better transparency for incoming neutral particles. The characteristics pertaining to the ion source of the device appear, however, to have more in common with those of the MKh-6403 and MKh-6405 types as described in the section on devices [20, 21].

In the experiment described, the analyzer of the mass spectrometer was installed in the body of the rocket, under the protective cone and parallel to the axis of the rocket. The protective cone was ejected at an altitude of about 100 km on command of a programming device. At this time, the glass bulb was separated from the metallic inlet tube by means of a flexible cable attached to the protective nose cone, thus opening the analyzer. Mass spectrograms of gases were transmitted to the earth by means of a telemetering system [26].

During the ascending and descending phases of the trajectory, the axis of the spectrometer was held almost strictly parallel to the velocity vector. On one hand, this condition simplified calculations of the concentrations of atmospheric particles when translational motions of the analyzer in the ascending phase were taken into account; on the other hand, it did not allow data to be obtained on the spectra of atmospheric gases in the molecular shadow in the descending phase when the container moved at velocities exceeding the thermal velocity of atmospheric particles [26].

In the launching of 15 November, 85 spectra of ionized as well as neutral gases of the atmosphere were recorded. All spectra up to the 400 km altitude were obtained with constant (zero angle of attack) orientation of the analyzer intake.

The results in respect to the neutral components were discussed in more detail by Pokhunkov in [26], and are treated separately in the corresponding section of this report. In this section, only the ionized components within the 130—430 kilometer altitude range are discussed.

The identification of peaks caused by atmospheric components, as opposed to those due to gases liberated from the surface of the rocket, was based on the fact that the concentration of the latter is a function of time only, but the concentration of atmospheric gases depends on altitude. The separation of ionic peaks from those of neutral gases was accomplished through utilizing peculiarities of the altitude distribution of each type of particle and peak splitting at the same mass. The latter was ascribed to the presence of a certain negative potential of the rocket body which conveyed additional energy to outside ions, as opposed to originally neutral particles that became ionized in the ion source. This splitting of peaks reached a magnitude of 0.5 amu, corresponding to a potential of the rocket body of about -3.5 volts [27, 26].

Analysis of the obtained data isolated N^+ , O^+ , NO^+ , and O_2^+ ions as the main components of the atmosphere, thus confirming the results of earlier work. However, the behavior of O_2^+ with respect to quantity and to altitude dependence proved difficult to identify owing to the presence of neutral O_2 . The separation of N_2^+ was impossible due to the presence of the heavy background of the same ions created in the ion source. The results are presented in the graph of Fig. 13b.

The absolute concentrations of individual species of ions at various altitudes were obtained by comparing the total ion current from all ions with the absolute concentration of electrons (as given by Gdalevich and others [3] for the same experiment). The results are compiled in the table below [27]:

h, km	170	190	210	210	270	300	310	370	400	430
$n_e, 10^4 cm^{-3}$	7.2	17	40	68	57	42	25	19	14	10.8
$[He^+], 10^4 cm^{-3}$	—	—	—	—	—	—	—	0.17	0.3	0.7
$[N^+], 10^4 cm^{-3}$	—	—	—	0.3	0.5	0.7	0.7	0.63	0.6	0.6
$[O^+], 10^4 cm^{-3}$	1.7	6.8	26.6	58	51	40.7	21.3	18.2	13.1	9.5
$[NO^+], 10^4 cm^{-3}$	4.2	6.8	6.3	5.8	2.2	0.6	—	—	—	—
$[O_2^+], 10^4 cm^{-3}$	1.3	3.4	5.1	3.9	3.3	—	—	—	—	—

e. The Rocket Experiment of 18 October 1962

This experiment, according to Istomin [13], was carried out with a geophysical rocket in daytime with a sun elevation of 30° at the moment of launching. The locality of the launch was not identified. The MKh-6403 type mass spectrometer was contained in a spherical container of the "high-altitude automatic station" designated as VGAS. The spectrometer is said to have been mounted in a "pole" of the sphere. The altitude range covered was from 150 to 508 km, in both ascending and descending phases. The container was oriented so that the analyzer intake had a zero angle of attack during the ascending phase of the trajectory. During the descending phase, the intake was in the region of molecular shadow, where the number of particles taken in depends on the ratio of the container velocity and the particle thermal velocity. The ratio of ion currents noted at the same altitude of ascending and descending phases may serve as a basis for determining particle velocities and the temperatures of ionic components. The author presented an example of a possible analysis of this problem, leaning on Whipple (J. Proc. I. R. E., 47, no. 11, 1959, 2023) and applying the theory to the data obtained in the experiment. Ion current peaks corresponding to mass numbers 16, 18, 30, and 32, identified as those of O^+ , H_2O^+ , NO^+ , and O_2^+ , respectively, were recorded during both ascending and descending phases. The character of the recordings can be briefly described as follows [13].

H_2O^+ peaks were observed throughout flight. Their amplitude, in general, decreased monotonically, but showed weak maxima at the beginning and at the end of the record, at approximately the same altitude (200 to 250 km) and corresponding in time to the maxima of O^+ peaks. These peaks were ascribed to the desorption of water from the container surface and subsequent ionization in charge exchange with atmospheric ions of atomic oxygen [13].

The O_2^+ peaks appearing at the very beginning of the spectrometer record (altitude 150 km) decreased monotonically up to 300-km altitude, after which the record became irregular. This was ascribed to ionization of molecular oxygen liberated by the rocket in charge exchange with atmospheric O^+ ions [13].

NO^+ peaks were recorded clearly in the ascending phase (altitudes 150 to 300 km), they were definitely missing at higher altitudes, then appeared again in the descending phase below 250-km altitude, with much weaker peaks. The ion current ratio at the 160-km altitude was 15, which agrees fairly well with ideas concerning the temperature of

NO^+ ions at that altitude (1000 to 1500° K) [13].

The O^+ ions, unlike those of NO^+ , were recorded with nearly equal intensity during both ascending and descending phases of the trajectory, which means that the effect of the molecular shadow was relatively weak in this case. The ratio of ion currents in the ascending and descending phases varied between 1.6 and 2. In view of the container velocity of 2.25×10^5 cm/sec, the thermal velocities of O^+ , or their temperatures, must have been of a high order [13].

However, the considerable difference noted in O^+ and NO^+ peak amplitudes in the ascending and descending phases can hardly be explained by the rather slight difference in their thermal velocities (1.2×10^5 and 0.9×10^5 cm/sec, respectively). The phenomenon may be caused by factors not accounted for in the analysis, such as: 1) deviation of the container potential from zero, 2) the negative potential of 45 volts applied to the first grid of the analyzer, and 3) failure of a number of ions to reach the collector after passing the first grid.

In conclusion, Istomin questions the general assumption of existence of thermodynamic equilibrium in the atmosphere, that is, Maxwellian distribution of particle velocities or the temperature equality of all components. Ionization mechanisms may convey different energies to resulting ions. The effect of photoionization, however, is considered negligible, since the energy produced is carried away chiefly by electrons. In view of the results of this and other experiments, the existence in the atmosphere of O^+ ions with energies exceeding the thermal, appears to be an established fact [13].

2. STUDIES OF THE NEUTRAL COMPONENTS OF THE UPPER ATMOSPHERE

According to Pokhunkov, experiments for determining the neutral composition of the atmosphere above 100 km altitude have been carried on in the USSR since 1958 [22, 23]. This applies to mass-spectrometric investigations by rockets and satellites; balloons and probes are known to have been used much earlier in studies of lower altitudes. The initial rocket and satellite launchings in 1958 involved use of the early RMS-1 Bennett-type r-f mass spectrometer and the more significant developments began only with the launchings of July 1959 in which the improved MKK-6401 type spectrometer (see Fig. 5) [23] was used.

a. The July 1959 Experiments

Two rocket launchings took place in July 1959, the first occurring at 2¹/₂ hours after sunrise and the second at sunrise. On each occasion, the recoverable container with the mass spectrometer was separated from the rocket at a high altitude, so that the measurements were made at a distance of several hundreds of meters from the rocket. The analyzer was installed in a recess perpendicular to the cylindrical surface of the container [23].

The ion source of the spectrometer was supplied with an ionizing voltage of 36 volts from the electronics unit. The grid of the ion source was covered on the input side by an opaque metallic screen which aided in the formation of a space charge and in focusing the electron current. The input tube was sealed into a glass bulb containing an atomized getter layer on the inside. The spectrometer was launched with a sealed analyzer filled to a pressure of 1×10^{-5} mm Hg by a known mixture of gases. These gases (H₂, He, Ne, Ar) served to control the operation of the device and to facilitate calibration of mass spectra [23].

After the container was separated from the rocket, the ion source was turned on by a programming signal, and control spectra were registered. Then the analyzer was opened by a device which broke the bulb. In 1 to 1¹/₂ seconds the gases initially in the analyzer were, for all intents and purposes, fully replaced and the mass spectrometer began analyzing atmospheric gases [23].

During free flight of the container, data on mass spectra were transmitted to the earth by means of a telemetry system. In the first experiment, this system was double-checked by recording with a loop oscillograph. When the loop oscillograph was used for recording, the

sensitivity of the spectrometer was several times greater than in telemetric recording, which in part led to the discovery of a weak peak due to H_2^+ that was not detected in the telemetric recording [23].

Several tens of spectra were obtained in the ascending and descending phases of both experiments, within altitude ranges from 98 to 203 kilometers for the first launching and 94 to 211 kilometers for the second launching [23].

The first experiment registered the following mass numbers: 1, 2, 14, 16, 17, 18, 28, 32, 40, 44. These were identified as H_1 , H_2 , N_1 , O_1 , OH, H_2O , N_2 , O_2 , Ar, CO_2 and N_2O , respectively. CO_2 and N_2O were registered, in accordance with their common mass number, at the same peak.

In the second experiment, the efficiency of the ion source was much lower (1/6 to 1/8), and the device was correspondingly less sensitive. This experiment registered mass peaks at the following mass numbers: 14, 16, 18, 28, 32, 40, and 44. The identification procedure was analogous to that employed in the first experiment. The nature of the variation of ion currents with time made it possible to divide the gases registered in both experiments into two groups, each of which contained gases of similar nature. In the group that included H_2O , OH, H_2 , and H_1 in the first experiment and H_2O in the second, the variation in ion currents with time showed a monotonic decrease. The group including N_1 , O_1 , N_2 , O_2 , Ar, CO_2 , and N_2O in both experiments was characterized by variations of ion currents showing a decrease with altitude and periodicity with time [23].

Pokhunkov proceeded further with a rather detailed description of the results by analyzing the character of altitude and time dependences of both groups of components. Without delving into the detailed data here, two results may be mentioned which may serve to clarify certain more obscure problems. First, the presence of neutral helium within the investigated altitude range was not confirmed, at least not within the limits of sensitivity of the instruments (1×10^6 particles/cm³) [23]. Second, the gravitational separation of Ar and N_2 , as interpreted from the ratio of their ion currents, which decreases monotonically with altitude, appears to take place at altitudes above 100 km, the level of separation remaining uncertain due to the scarcity of measurements near the 100 km altitude [23]. Third, these experiments failed to yield reliable data for determining the concentration of atomic oxygen and, therefore, the mean molecular weight of the air within the altitude range covered. This problem was attacked more than a year later, in September of 1960.

b. The 23 September 1960 Experiment

The launching took place at 0056 hours local time in the "middle latitudes of the USSR." Both the methodology and the mass spectrometer used were improved [24, 25]. The mass spectrometer was a "version of the MKh-6401," identified in a later article [29] as the MKh-6403, a later variant of the MKh-6401. The analyzer of the mass spectrometer was redesigned to minimize decreases in the concentration of atomic oxygen due to recombination at the input of the ion source. This was accomplished by reducing the length of the input manifold as much as possible and increasing its diameter (see Fig. 10) [24].

The mass spectrometer was installed in the container in such a manner that it could swing out at a 45° angle to the body of the container. Spectra from the calibration mixture were recorded for 20 seconds prior to opening of the analyzer [24].

In this launching 50 mass spectra were obtained during the ascent and 51 during the descent of the container, over an altitude range of 100 to 210 km. The data obtained were used to calculate relative concentrations of the main components of the atmosphere and their variation with altitude, the mean molecular weight of the atmosphere, the gravitational separation of gases, and the kinds and amounts of impurities [24].

Comparison of the results obtained in 1959 with those of this experiment shows that the relative concentration of atomic oxygen at all altitudes, as measured by the new analyzer, was approximately four times greater than the corresponding measurements obtained with the old analyzer. The difference in concentrations shown by the 1959 and 1960 data was considered to be due either to a difference in the efficiency of registration of the two analyzers or to seasonal variations, or, perhaps, to a combination of these two factors. Seasonal variation, however, was considered to be the smaller of the two factors. An empirical correction factor of 1.75 was obtained for conversion of the 1959 data to the 1960 data. This factor was used in calculating the concentration of atomic oxygen in the atmosphere [24].

On the basis of both the 1959 and 1960 experiments, the principal basic component of the atmosphere is molecular nitrogen up to the upper limit (210 km) of the altitude range covered.

The atomic nitrogen content in the atmosphere at these altitudes did not exceed 2 percent of the molecular nitrogen content, which confirmed previous spectrometric measurements. It was concluded that processes leading to accumulation of atomic nitrogen in notable concentrations do not play a significant role at the altitudes considered [33].

The relative concentration of atomic oxygen increased with altitude by a factor of 5, and at an altitude of 210 km reached about 65 percent of the concentration of molecular nitrogen [24].

The relative concentration of molecular oxygen, which at an altitude of 100 km is approximately equal to the concentration at the surface, decreases with increasing altitude by a factor of 2 and drops down to about 14 percent of the concentration of molecular nitrogen at an altitude of 210 km. The concentration of molecular oxygen was determined with recombination of atomic oxygen inside the analyzer taken into account and on the assumption that all atomic oxygen leaving ion currents set up by interaction with the analyzer surface is converted into molecular oxygen [24].

The data thus obtained were used to calculate the relative concentration of all three main atmospheric components, also the degree of dissociation of molecular oxygen at various altitudes was calculated. The results show that a considerable quantity of molecular oxygen still remains at an altitude of 210 km. This is considered to be evidence of the considerable effect of diffusion mixing at these altitudes [24].

Gravitational separation, the composition, and the structural parameters of the atmosphere at night at altitudes from 100 to 210 km, derived from the same 23 September 1960 launching, were considered by Pe'khunkov in a separate article [25]. The mass spectra were recorded by a loop oscillograph located in the sealed portion of the container. When this registration method was employed, the minimum detectable ion current at the collector of the analyzer (at an input resistance of 10^{11} ohms) was 4×10^{-15} amperes [25].

A notable feature of the spectra was a periodic modulation of the peak amplitudes due to rotation of the container. This phenomenon was utilized in data processing to separate peaks caused by gases liberated by the container.

Ion peaks with the following mass numbers were registered: 1, 2, 12, 14, 16, 17, 18, 28, 29, 30, 32, 34, 36, 40 and 44, which were

identified correspondingly as H_1 , H_2 , C, N_1 , O_1 , OH, H_2O , N_2 , N^{14} , N^{15} , NO, O_2 , O^{16} , O^{18} , Ar^{36} , Ar^{40} , CO_2 , and N_2O . In addition, gases with mass numbers 9, 10, and 42 were detected [25].

Study of the altitude variation of the ratio of Ar to N_2 shows an almost exponential decrease with altitude which indicates gravitational separation of Ar and N_2 . Comparisons of laboratory measurements of the ratio of ion currents due to Ar and N_2 near the surface with the content noted at high altitudes show that gravitational separation begins at altitudes of 105 to 110 km [25].

The main components of the atmosphere at altitudes from 100 to 210 km were shown to be N_2 , O_1 , and O_2 . In the altitude interval from 100 to 150 km, isotopes of N_2 (N^{14} , N^{15}) with a mass number of 29 were recorded, and at altitudes from 100 to 126 km, isotopes of O_2 (O^{16} , O^{18}) with mass number of 34. The relative concentrations of these isotopes at all observed altitudes were constant, being equal to about 7.6×10^{-3} for N_2 and about 4.1×10^{-3} for O_2 , which is in good agreement with the relative distribution of isotopes N^{14} , N^{15} (7.6×10^{-3}) and isotopes O^{16} , O^{18} (4.0×10^{-3}) [25].

Traces of H_2O , OH, H_1 , and H_2 were detected in the range of altitudes studied. The quantity of H_2O registered was considerably less than that obtained in the 1959 experiments [22, 23], and the nature of the variation of the ion current was likewise different. Modulation of the ion current by H_2O is quite weak compared to the ion current due to N_2 , caused by the rotation of the container. This shows that the H_2O registered by the spectrometer consists only of molecules on the surface of the container carried into the upper layers of the atmosphere. Generally, only that part of the ion current which is modulated by variations in the orientation of the input orifice is due to H_2O originating in the upper atmosphere [25].

It is, however, also possible that modulation was caused by molecules reflected from the incoming beam within the analyzer. The maximum value of the partial pressure of H_2O at an altitude of 115 km, evaluated on the basis of modulation of the ion current, does not exceed 3×10^{-7} mm Hg, which is approximately 0.6 per cent of the total atmospheric pressure at this altitude. It was decided that this value constitutes the upper limit of H_2O in the night atmosphere at altitudes of above 100 km. When H_2O is dissociated in the ion source, hydroxyl ions and atomic hydrogen H_1 are formed which are then ionized and create currents at the collector. The presence of hydroxyl ions detected by the mass spectrometer can be explained fully by dissociation of H_2O in the

ion source. Assuming the instrumental error to be equal to the upper limit of the OH content in the atmosphere, Soviet workers have shown that the relative hydroxyl content in the night atmosphere above 100 km does not exceed 6×10^{-5} percent of all gases [25].

The behavior of ion current due to H_1 is similar to that caused by H_2O and OH, which indicates a dissociative connection between H_1 and H_2O . However, beginning with an altitude of 145 to 150 km, the ion currents due to H_1 decreased more slowly than is necessary to satisfy the ratio of ion currents observed under laboratory conditions of H_2O dissociation. The excess of H_1 ion current indicates a particle concentration of 10^8 particles/cm³. This could be atmospheric hydrogen, but the results are not conclusive [25].

The variations in the H_2 ion currents discovered at altitudes up to 130 km during the ascent phase correlated with variations in the H_1 ion current. It is concluded from this that the recorded molecular hydrogen originates in recombination of atomic hydrogen inside the spectrometer analyzer. The absence of H_2 in spectra at altitudes above 130 km indicates that its concentration does not exceed the sensitivity threshold of the instrument, that is, 3×10^7 particles/cm³. The recombination rate of atomic hydrogen in the analyzer was determined by the ratio of H_1 and H_2 currents, with effective resolution of light masses taken into account. It was shown that when this type of mass spectrometer was used, not more than 3 to 4 percent of H_1 was subject to recombination. According to Pokhunkov (contrary to Istomin's view [11]), this supports the feasibility of using the available model of mass spectrometer for quantitative measurements of the concentration of atomic hydrogen [25].

As in previous experiments, atmospheric helium was not detected in any quantity above the sensitivity threshold of the instrument (in this case 6×10^7 particles/cm³) [25].

No definite conclusions were reached concerning the CO_2 and N_2O content of the atmosphere because the container liberates considerable amounts of CO_2 . Variations in the ion current due to CO_2 and N_2O showed a monotonic decrease with altitude and weak modulation by rotation of the container. The same method of calculation that was used to evaluate the upper limit of the H_2O content was also applied to determining the CO_2 and N_2O content. At an altitude of 120 km, the maximum concentration of the mixture of these two gases was 1 percent which approximately coincided with the results of the 1959 experiment [22, 23]. A part of this mixture could be the CO_2 formed in the reaction of atomic

and molecular oxygen of the atmosphere with the oxide-thorium cathode of the ion source [25].

The presence of a peak at mass number 12 was attributed to carbon formed during dissociation of CO_2 in the ion source, as suggested by the fact that the ratio of ion currents due to gases with mass numbers 12 and 44 was independent of altitude [25].

A small quantity of gas with mass number 30 and identified as NO was registered at altitudes from 130 to 180 km during ascent and descent. The concentration of NO was about 0.1 percent of that of N_2 . Apparently, a considerable part of the registered NO was formed inside the analyzer due to charge-transfer reactions of the $\text{O}^+ + \text{N}_2 = \text{NO}^+ + \text{N}$ type, as seen from the correlation between the altitude variation of the concentration ratio NO/N_2 and the variation of the O_1/N_2 ratio. Therefore, the indicated percentage should be interpreted as its upper limit within the 130- to 180-km altitude range [25].

At altitudes from 100 to 125 km, gases with mass numbers 9, 10, and 42 that are not characteristic of the lower layers of the atmosphere were recorded during both the ascending and descending phases. The first two were not identified, although it was suggested that beryllium and boron 10 isotopes may be responsible for these peaks. This means, however, that the origin of these elements in the upper atmosphere and the absence of the main isotope boron 11 in the spectrum will have to be explained [25].

Discovery of a gas with mass number 42 aroused considerable interest. This gas, registered within the altitude range between 103 and 116 km, was identified as an oxide of the magnesium isotope Mg^{24} . The other two Mg oxides with mass numbers 40 and 41 could not be resolved, owing to certain technical characteristics of the instrument. From the character of the altitude dependence of the $\text{Mg}^{24}/\text{N}_2$ ion current ratio, it was found that the absolute concentration of all three magnesium oxides could be about 10^9 particles/cm³ within the altitude range. The presence of this considerable quantity of MgO in the upper atmosphere indicates its extraterrestrial, most probably meteoritic origin. The maximum concentration of MgO relative to N_2 was registered at an altitude of about 117 to 118 km during both the ascending and descending phases. The occurrence of this maximum was related to gravitational separation at altitudes above 100 km and the presence of a layer of transition from turbulent mixing to one where

pure diffusion predominates; in such a layer the gravitational separation could be disturbed by currents from the lower layers. According to data, this gravitational separation begins to take place at altitudes of 105 and 110 km, but the transition layer reaches to an altitude of 117 to 118 km. Above this layer the relative concentration of $Mg^{26}O$ decreases again, but in agreement with the laws of gravitational separation of $Mg^{24}O$ and N_2 [25].

c. The Experiment of 15 November 1961

This experiment has been described previously in connection with investigation of ionized components of the atmosphere [27]. The results of this launching in respect to neutral components were reported by Pokhunkov in July-August, 1963 in an article "On the Distribution of Helium, Nitrogen, and Argon in the Earth's Atmosphere up to an Altitude of 430 Kilometers" [26].

In this experiment, the gases liberated from the rocket contained mainly H_2O and CO_2 molecules. The liberation of N_2 molecules became notable at altitudes above 325 km [26]. The identification of liberated particles was made possible by comparing spectra of the ascending and descending phases of the trajectory as described in the section dealing with ionized components.

According to Pokhunkov, helium ions were detected at altitudes of 370 km and above, as described before in the section dealing with ionized components. This led the author to assume that neutral He does not occur in measurable quantities (1×10^8 particles/cm³) at altitudes below 370 km and down to 130 km [26]. This conclusion corresponds to Pokhunkov's earlier measurements of the composition of the neutral atmosphere at altitudes above 100 kilometers [22, 23, 24, 25].

The following gases were reliably detected at altitudes above 130 km: O_1 , N_2 , O_2 , and Ar. Due to the simultaneous recording of ions and neutral particles, the direct measurement of neutral O_1 became possible only in the 130 to 160 km range. As the concentration of atmospheric O^+ ions increased sharply at high altitudes, the mass spectrograms showed an ion peak at mass number 16, due chiefly to the atomic oxygen component [26].

By comparing the ion currents of O_1 and N_2 , one can obtain the value of the relative concentration of O_1 with respect to N_2 , if he takes account of such factors as discrimination of light gases and possible recombination of atoms on the inner surface of the analyzer, which are

characteristic for each type of instrument. Using this method for comparing the data from this experiment with those of 1960 [24, 25], Soviet scientists found the concentration of O_1 particles at 160 km to be less than 35 percent of the N_2 concentration at that altitude [26].

It has become possible to trace the distribution of neutral molecular O_2 to an altitude of about 200 km; however, the quantitative data obtained are not very reliable due to the unaccounted for contribution of O_2 resulting from recombination of O_1 atoms inside the analyzer. Nonetheless, one can conclude with a large degree of certainty that molecular oxygen exists at altitudes of 130 to 200 km in at least those quantities required to maintain its gravitational equilibrium with molecular nitrogen. This consideration indicates the dominating role of diffusion in reestablishing the temperature equilibrium disturbed by photochemical processes [26].

The distribution of molecular nitrogen up to a maximum altitude of 430 km is of considerable interest. When the distribution of N_2 is not distorted by background gas liberated from the rocket, it can be traced to an altitude of 300 km. At higher altitudes, the distribution of N_2 was obtained by subtracting the background of gas liberated measured in the descending phase of the trajectory (during molecular shadow). Since the magnitude of the ion current at the collector is directly proportional to the pressure (or concentration) of the corresponding component, this operation was conducted with primary data, disregarding the nearly negligible effect of atmospheric N_2^+ ions (see Fig. 14) [26].

By analyzing the curve of Fig. 14 with the aid of formulas of molecular kinetic theory, one can obtain the absolute concentration of N_2 molecules at various altitudes, and also calculate the temperature distribution of the atmosphere. The analytically deduced formulas were used to determine the temperature, concentration, density, and pressure distribution in the atmosphere at altitudes ranging from 130 to 325 km, and an approximate method was used for higher altitudes. The results were compiled in a table [26] which is presented below.

$h, \text{ km}$	$T_a^\circ \text{ K}$	$n(\text{N}_2), \text{ cm}^{-3}$	$\rho(\text{N}_2), \text{ g/cm}^3$	$P_n(\text{N}_2), \text{ ALM Hg}$
130	425±50	$(13.5 \pm 1.4) \cdot 10^{10}$	$6.3 \cdot 10^{-12}$	$6.1 \cdot 10^{-6}$
140	480±50	6.6 ± 0.6	3.1	3.4
150	600±60	3.3 ± 0.3	1.5	2.0
160	770±80	1.8 ± 0.2	$8.4 \cdot 10^{-13}$	1.5
170	1000±105	1.2 ± 0.1	5.6	1.3
180	1070±110	$(9.0 \pm 0.9) \cdot 10^9$	4.2	1.0
190	1150±115	6.6 ± 0.6	3.1	$8.15 \cdot 10^{-7}$
200	1200±120	5.1 ± 0.5	2.4	6.6
220	1260±125	2.9 ± 0.3	1.4	4.0
240	1300±130	1.8 ± 0.2	$8.4 \cdot 10^{-14}$	2.5
260	1360±140	1.1 ± 0.1	5.15	1.6
280	1410±145	$(7.0 \pm 0.7) \cdot 10^8$	$3.2 \cdot 10^{-14}$	1.0
300	1440±150	4.55 ± 0.5	2.1	$7.1 \cdot 10^{-8}$
325	1470±150	2.65 ± 0.26	1.2	4.2
350	1470±150	1.0 ± 0.15	$7.5 \cdot 10^{-15}$	2.6
375	1470±150	$9.4 \pm 1.5 \cdot 10^7$	4.4	1.4
400	1470±150	5.5 ± 1.8	2.6	$8.7 \cdot 10^{-9}$
425	1470±150	3.3 ± 3.0	1.5	5.2
430	1470±150	3.0 ± 6	1.4	4.7
		-3		

If one compares the density of N_2 obtained in this way with the density of the atmosphere calculated from its retarding effect on artificial earth satellites (for instance, from the data of Martin and Priester (COSPAR Internat. Reference Atmosphere, 1961, p. 59), then it can be concluded that there are significant quantities of undissociated molecular nitrogen N_2 at high altitudes [26].

An important factor in determining the state of the atmosphere is the altitude dependence of relative concentrations of any two gases where these concentrations do not vary within the studied range of altitudes. Such gases are molecular nitrogen and argon. Changes in the relative concentrations of Ar and N_2 with altitude (see Fig. 15) indicate that there is a significant gravitational separation of these gases even at an altitude of 130 km.

APPENDIX

Classification of Production Model Mass Spectrometers in the USSR

Soviet mass spectrometers are designated by two capital letters followed by a four-digit number (e.g. MKh-6401). The letters indicate general groupings as follows:

- MKh - for chemical analysis
- MI - for isotopic analysis
- MV - high-resolution

The first digit of the number indicates the ion separation principle of the spectroscopy as follows:

- 1 - Uniform magnetic field
- 2 - Non-uniform magnetic field
- 3 - Reserve
- 4 - Magnetodynamic
- 5 - Time-of-flight
- 6 - Radio frequency

The second digit indicates the area of application as follows:

- 1 - Indicator
- 2 - Industrial control instrument
- 3 - Laboratory instrument
- 4 - Special-purpose instrument

The last two digits indicate the model number.

Thus, the MKh-6401 mass spectrometer, for instance, is a device for chemical analysis (MKh) which uses the r-f principle of ion separation (6), intended to be used under special circumstances (4), and is the first model (01) of the instrument [19].

It must be noted, however, that this classification system is not always used. Some devices were developed before the classification system, and even the later devices are not labeled consistently.

SOVIET R-T MASS SPECTROMETERS

Specification Data

Year, Author	Reference	Type of spectrometer	Mass Band, amu	Resolving Power, amu	Sensitivity (to argon), mm Hg	Sweep cycle, sec	Working Pressure, mm Hg	Power supply, Volta Watts	Weight, kg	Other information	Remarks
1958/1959 Doyl'init-syn	1	RMS-M		10-16			10^{-3}			Dimensions 100 x 23 μ mm, Frequency -10 Mc	
1958, Pavlenko and others	19	MKh-6401	2-60 2-8, 12-56	45	0.1 per cent		2×10^{-3}			Frequency - 5 and 15 Mc. Accelerating voltage 80 to 400 V. Relative error - ± 5 per cent	For industrial use
1960, Pavlenko and others	20	7 Referred to by Pavlenko 1963 as the MKh-6401.	1-4, 12-56 1-4, 12-60*	50	5×10^{-9}	3	10^{-4} - 10^{-6}	27.5 δ^*	2.1 δ^* +1.2 δ^*	M5.3 for ion analysis. Working temperature -40 to +40°C. Dimensions electronics unit 210 x 90 x 70 mm, analyzer - 270 x 30 μ mm, ion source - 140 x 50 μ mm	MAnalyser MxElectronics
1963, Pavlenko and others	21	MKh-6401	1-4, 12-56*	50	5×10^{-9}			δ^*	2.1 δ^* 1.2 δ^* 3.3 δ^* 1.2 δ^*		MAnalyser with ion source MxElectronics MxWithout power unit MxPower unit
1959, Istomin	6	RMS-1. Used in 1957-1959 launchings.	6-48	20*		1.7**				Input resistance - 10^{10} ohms Two output ranges - 0-5 δ^* x 10^{-3} A and 0-100 x 10^{-3} A	MWithin the 20 a.s.m. range
1963, Pavlenko and others	21	RMS-1	6-48	20				25	6 δ^* 10 δ^*		MWithout power unit MPower supply
1961, Mirtov	18	RMS-1 (7) Used in 1957-1959 launchings.	6-50	28		1.7**				Output resistance 10^{10} ohms	
1962, Pokhunkov	24		1-4, **, 12-60**	45**, δ^* 10**, δ^* in the 4 amu range	5×10^{-10} x	3		27.5 δ^* 27	2	Sensitivity recorded by loop oscillograph with minimum detectable ion current of 4×10^{11} A. Input resistance 10^{11} ohms.	
1961, Istomin	9 10	MKh-6403 Used in 1959 and later.	1-4, 10-56							Increased sensitivity, reduced dimensions and weight	
1963, Pavlenko and others	21	MKh-6403	1-4, 12-56	50	5×10^{-10} δ^*			4	2 δ^* 0.6 δ^*	Accelerating voltage - 70-380V Frequencies - 8.6 and 30 Mc. Time constant - 0.002 sec.	MWithout power unit MPower unit
	21	MKh-6405	1-2, 12-36	20	1×10^{-10} δ^*			4	2 δ^* 0.6 δ^*		

*. These data apply to an unidentified spectrometer described by Pokhunkov in 1961 in connection with the launching of July 1959 [23].

** According to Pokhunkov, these data apply to a modification of the MKh-6401 [26].

+. According to Pokhunkov these data apply to a modification of the MKh-6041 used in the 13 November 1959 launching [27].

++. The same data are given by Istomin in reference [10].

FIGURES

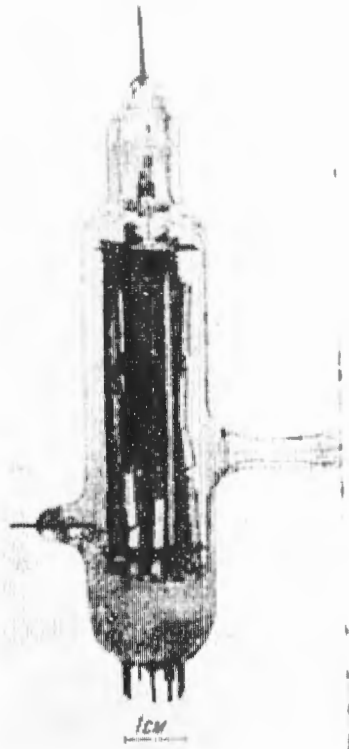


Fig. 1. A general view of the RMS-M

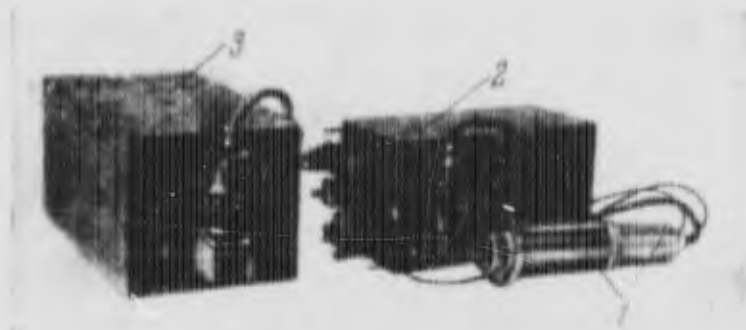


Fig. 2a. RMS-1 radio-frequency mass spectrometer

1 - Mass spectrometer tube with pre-amplifier; 2 - electronics unit; 3 - power supply unit (satellite variation).

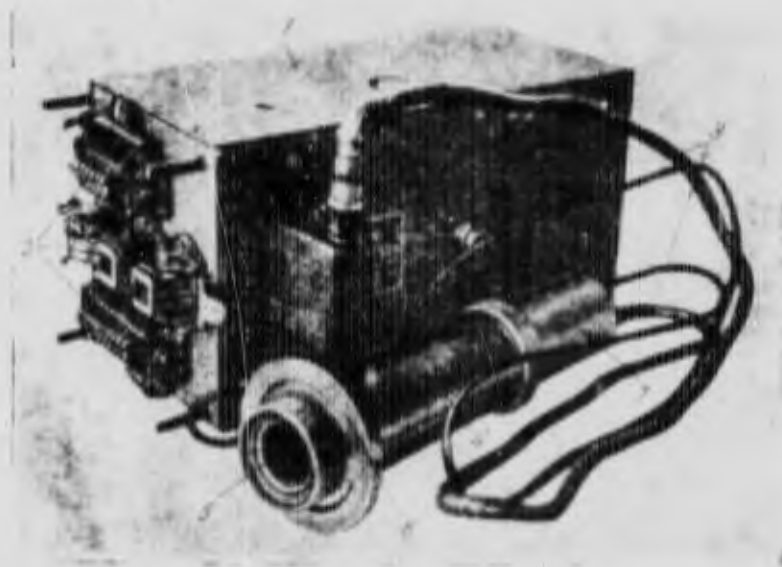


Fig. 2b. Radio-frequency mass spectrometer

1 - Electronics unit; 2 - plug-in connector; 3 - connecting cables; 4 - analyzer tube; 5 - analyzer tube intake; 6 - mounting flange; 7 - preamplifier.

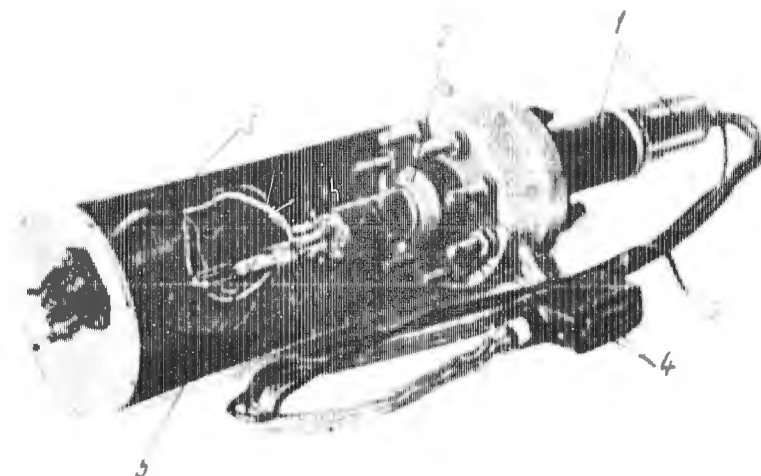


Fig. 4. Body of analyzer tube with ion source attached

1 - Analyzer with the preamplifier; 2 - ion source; 3 - protective casing; 4 - tie belts; 5 - nipple with getter.

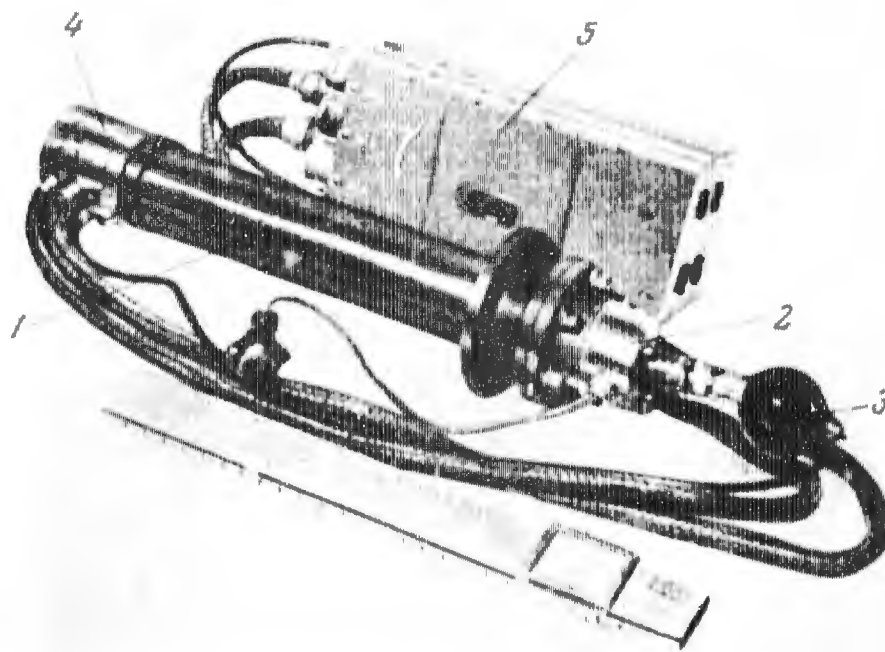


Fig. 5. General view of 5-stage mass spectrometer

1 - Analyzer; 2 - ion source; 3 - glass envelope with atomized getter; 4 - preamplifier; 5 - measuring unit.

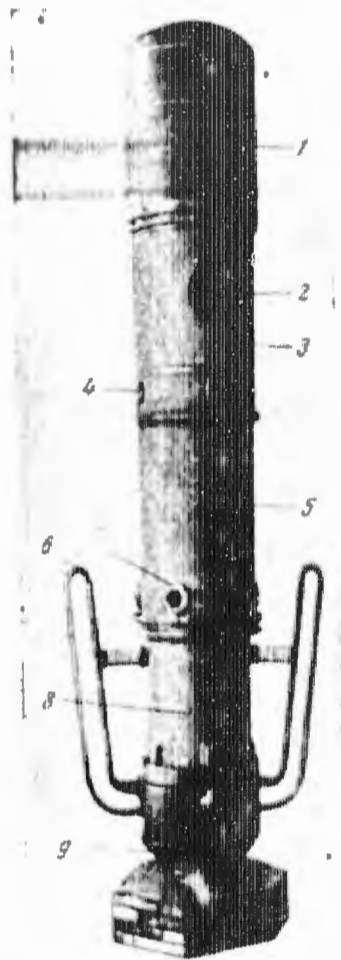


Fig. 6. The MKh-6401 spectrometer

1 - Parachute section (braking flaps removed); 2 - opening for the analyzer intake; 3 - airtight section containing the electronics; 4 - manometer windows; 5 - instrument section; 6 - radio transmitting antennas; 7 - windows of photo-cameras; 8 - power supply; 9 - shock absorber.

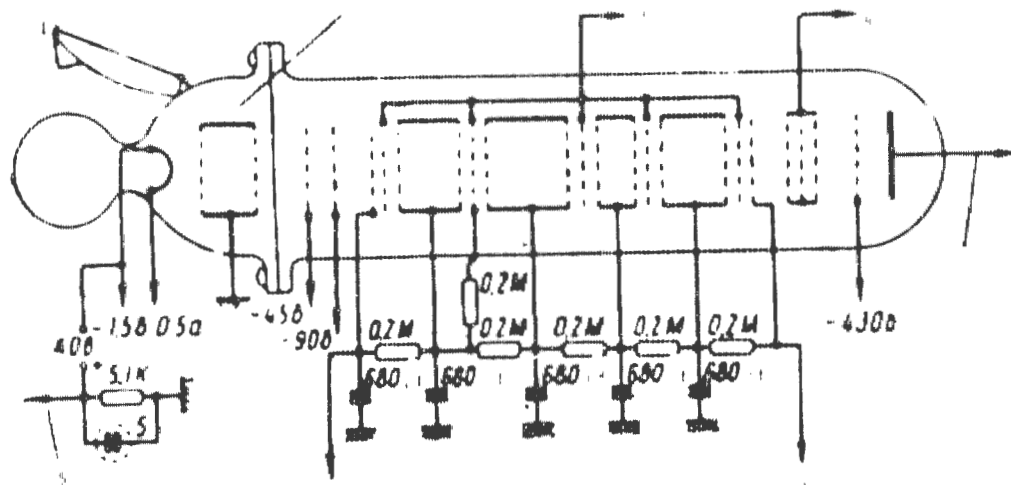


Fig. 7. Principal scheme of five-stage analyzer

- 1 - Knife for breaking the spectrometer bulb;
- 2 - detachable ion source; 3 - high frequency voltage;
- 4 - delay voltage; 5 - control of emission into telemetry system; 6 - sweep voltage; 7 - shift voltage;
- 8 - to ion current amplifier.

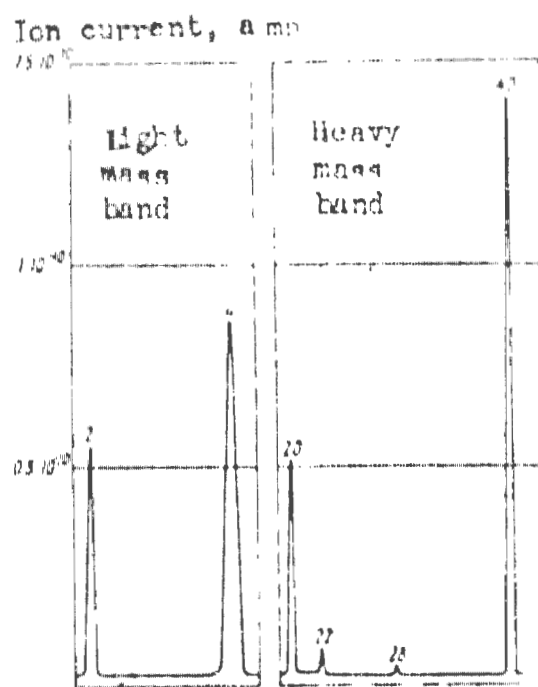


Fig. 8. Mass spectra of a gas mixture of 5% Ar, 35% He, 25% Ne, and 35% H₂; residual pressure, 10^{-6} mm Hg; working pressure 10^{-5} mm Hg

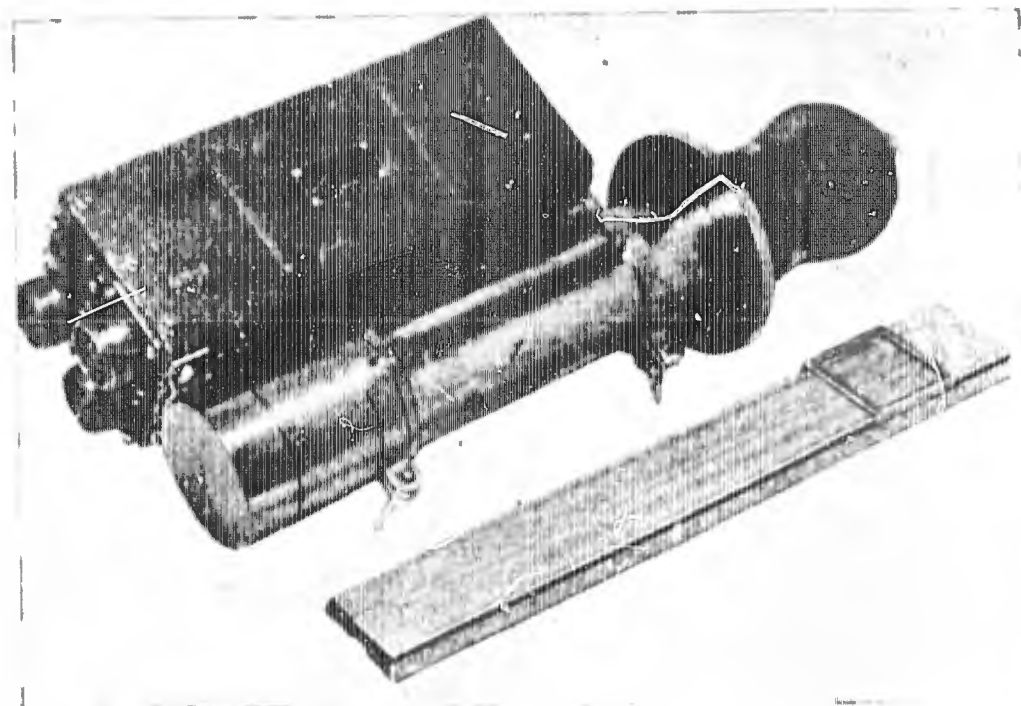


Fig. 9. External view of the radio-frequency mass spectrometer used in the rocket launching of 15 June 1960

1 - Analyzer; 2 - electronics unit.

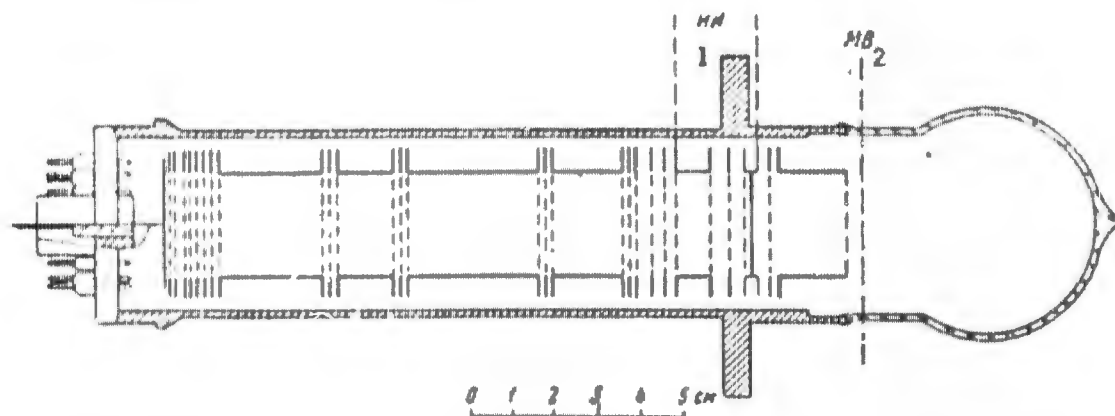


Fig. 10. Diagrammatic arrangement of the improved A2 analyzer

1 - Ion source; 2 - plane aperture of the analyzer.

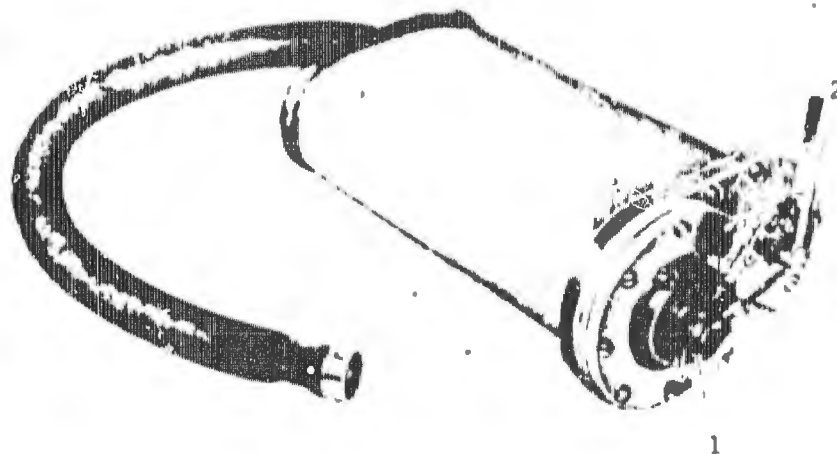


Fig. 11. General view of the small seated container and mass spectrometer (1) and the bulb device (2)

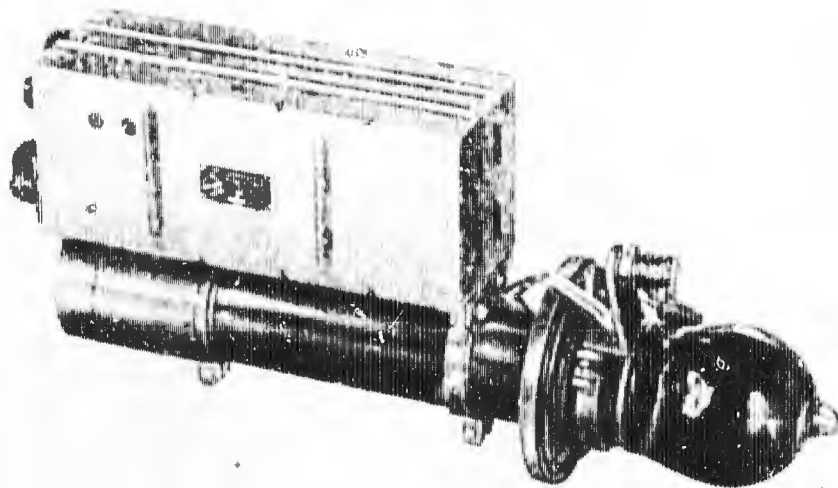


Fig. 12. General view of the MKh-6403

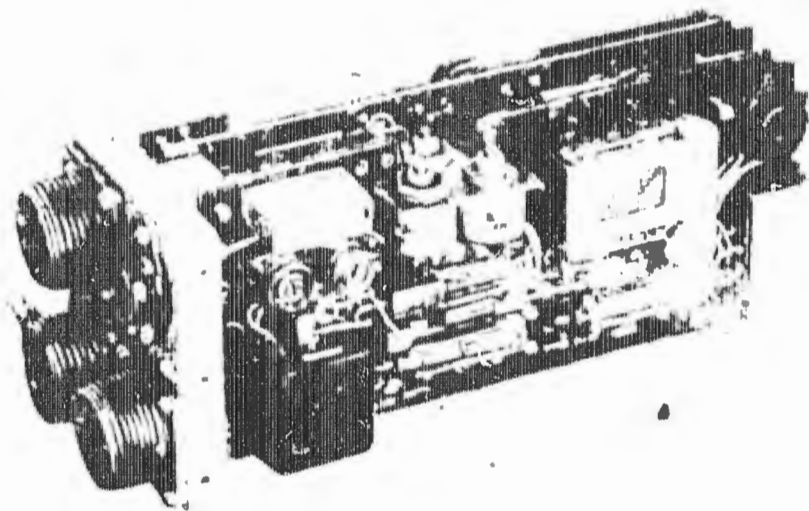


Fig. 13a. Exterior view of the measuring unit (without case)

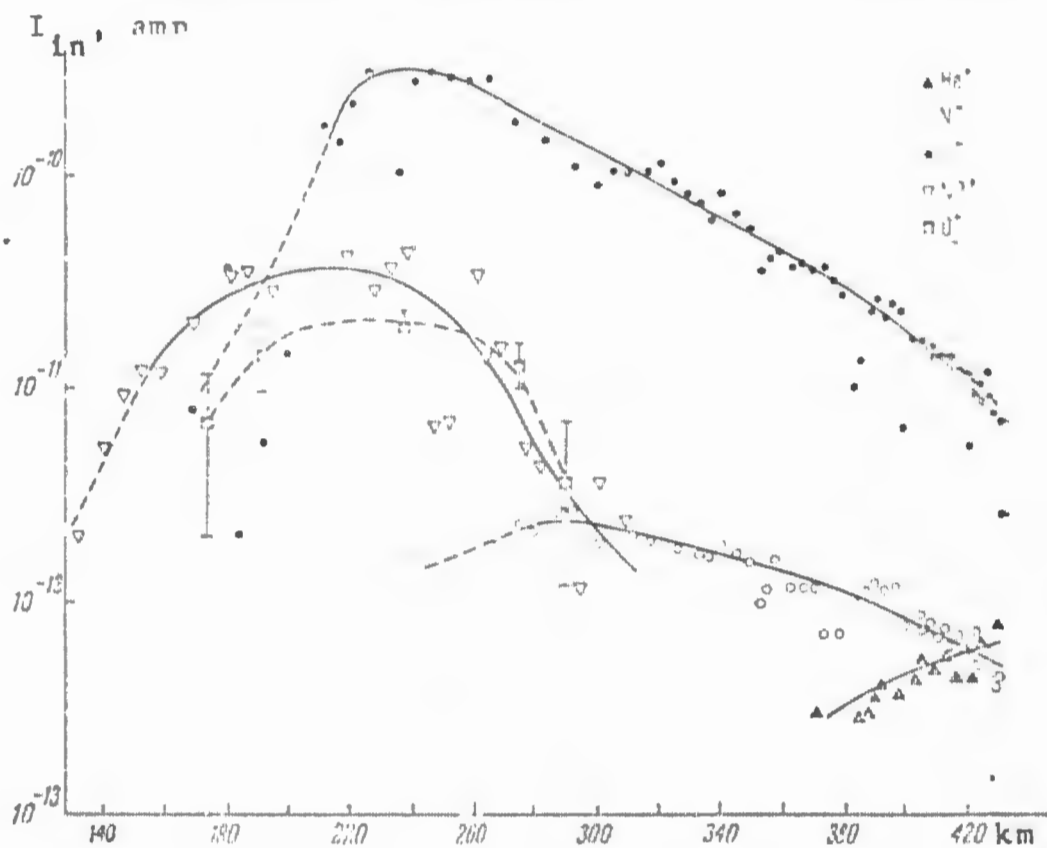


Fig. 13b. Distribution of He^+ , N^+ , O^+ , NO^+ , and O_2^+ ion currents as a function of altitude

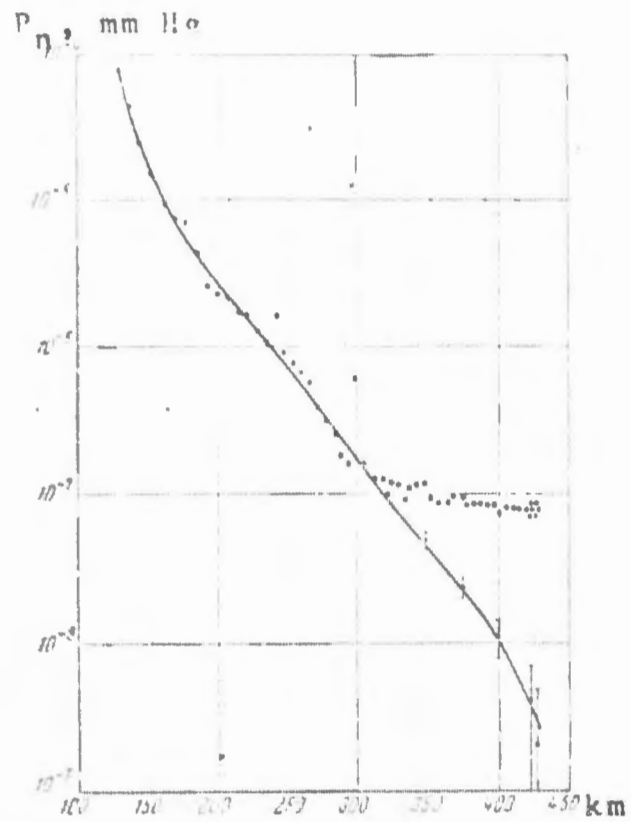


Fig. 14. Distribution of H₂ pressure inside the analyzer plotted as a function of altitude, with the liberated gas background subtracted for altitudes above 300 km (solid curve); the same without subtraction of the background (dots)

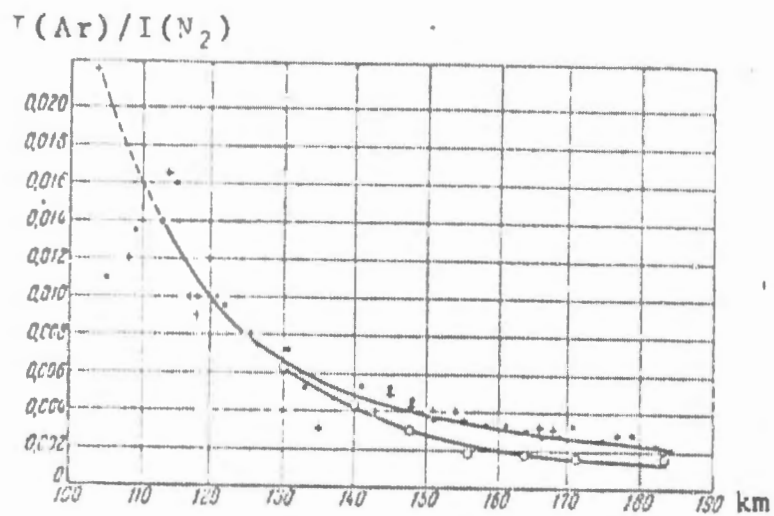


Fig. 15. Variation of Ar and N₂ ion current ratios in two experiments

23 September 1960 - ascending phase (dots), descending phase (crosses);
 15 November 1961 - ascending phase (circles).

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