

Measurements of ion concentrations in the D-region of the ionosphere with a Gerdien condenser rocket probe

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ABSTRACT

This report describes the development of a Gerdien condenser rocket system for measurements of ion concentrations in the ionospheric D-region. The Gerdien condenser and the instrumentation connected to it is separated from the rocket close to the top of the rocket trajectory, and the measurements are done during the descent with the instrumentation hanging under an inflatable parachute. Data from the first launchings at White Sands Missile Range indicate that the concentration of positive ions is of the order of 10^4 cm^{-3} and the concentration of negative ions is of the order 10^5 cm^{-3} in the height range 50–70 km. This indicates that heavy negative ions, which cannot be collected by the Gerdien condenser, most probably are present in the same height range. Heavy negative ions may be formed in chemical reactions or in clustering processes. Recombination to dust seems to be important below 50 km. This may be due to high dust concentrations above the launch site or dust layers from volcano eruptions observed at the time of the rocket firings.

List of symbols

Gerdien condenser symbols

$E(r)$ = Electric field at radius r
 r_o = Radius of outer cylinder
 r_i = Radius of inner cylinder
 l = Length of cylinder
 c = Capacity between inner and outer cylinder
 x = Direction of axis of condenser
 $v_x(r)$ = Air stream velocity at radius r
 v_r = Radial drift velocity in electric field
 i_o = Ion saturation current
 V_o = Voltage when ion current saturates

Concentrations

N^+ = Positive ions
 N^- = Small negative ions (O_2^-)
 N = Electrons
 N_M = Dust particles
 σN_M = Negatively charged dust particles
 N_x^- = Heavy negative molecules
 n = Neutral molecules
 n_1 = Small molecules to which electrons attach (O_2)
 N_i = Ion concentration (independent of ion polarity)
 λ = N^-/N .

Ionization and recombination

q = Ion production function
 α_d = Ion-electron dissociative recombination coefficient
 α_i = Ion-ion mutual recombination coefficient
 η = Coefficient for attachment of electrons to O_2
 ρ = Photodetachment coefficient
 κ = Collisional detachment coefficient
 β_o = Combination coefficient, ion-dust particle
 β_+ = Combination coefficient, attracted ion-charged dust particle
 β_- = Combination coefficient, repelled ion-charged dust particle
 β_e = Combination coefficient, electron-dust particle
 β_{e-} = Combination coefficient, electron-negatively charged dust particle
 β_x = Mutual recombination coefficient between heavy negative ions and positive ions
 γ_{nx} = Rate of attachment of small negative ions (O_2^-) to unknown molecules of concentration n_x
 e = $1.6 \cdot 10^{-19} \text{ A sec}$
 ϵ = $8.85 \cdot 10^{-12} \text{ F}$
 D = Coefficient of ion diffusion

v_D	= Ion diffusion velocity
d	= Debye length
Φ	= Dust particle surface potential
k_+	= Mobility of small positive ions
k_-	= Mobility of small negative ions
k	= Ion mobility (independent of ion polarity)
L	= Mean free path for collisions between small ions and gas molecules
L_M	= Mean free path for collisions between dust particles and ions
$\langle v^2 \rangle$	= Root mean square velocity of gas molecules
$\langle v_i^2 \rangle$	= Same for small ions
$\langle v \rangle$	= Average molecular velocity
$\langle v_i \rangle$	= Same for small ions
m	= Ion mass
M	= Gas molecule mass
k_B	= Boltzmann's constant
T	= Absolute temperature °K
p	= Atmospheric pressure
ρ_M	= Atmospheric density
ν	= Collision frequency for ions and gas molecules
τ	= Average time between collisions for ions and gas molecules
R	= Radius of molecule (dust particle)
R_i	= Radius of ion
Re	= Reynolds number
S	= Dynamic viscosity
v	= Relative velocity between probe and surrounding air
v_e	= Payload expulsion velocity
Q	= Air flow rate through Gerdien condenser
φ	= Payload angle off vertical direction
c_D	= Parachute drag coefficient
P	= Parachute opening projected area
χ	= Solar zenith angle.

Introduction

Our knowledge about the formation of the ionospheric D-region is rather limited dependent on the complexity of the ionization and recombination processes taking place in this height range. Solar radiation is the main source of ionization in the quiet ionosphere during daytime. Cosmic rays add to this ionization in the lower part of the D-region. In order to understand the formation of the quiet D-region it is necessary to have relevant solar spectral intensities above the atmosphere and knowledge about the absorption of this radiation at D-region heights, including cross-sections and

reaction rate coefficients for all the processes involved. The layer formation depends on a balance between ionization and loss processes. Electrons and ions are lost in recombination processes, mixing and diffusion. Electrons are also lost in negative ion formation by electron attachment to molecules. This is a very important process, which to a large extent controls the balance in the D-region.

The disturbed D-region is characterized by extraordinary ionization during a SID, a Polar Blackout, or a Polar Cap Absorption. In the case of a SID, solar X-rays will cause the extra ionization, and in the case of a Polar Blackout, energetic electrons and bremsstrahlung from these electrons will penetrate into the D-region. Energetic solar protons cause the extra ionization in the D-region during a Polar Cap Absorption.

Some principal features of the D-region have been obtained by groundbased radio observations and theoretical D-region model calculations and recently by rocket observations. Radio methods have been used to a large extent in the D-region studies. The groundbased observations have been done with riometers and instrumentations for measurement of cross-modulation and partial reflections. A large variety of radio methods have been used in rocket instrumentations for D-region measurements, some of them are the Seddon-Doppler principle, Faraday-rotation measurements, and differential absorption measurements.

The radio methods used till now can only give information about the electron concentration and electron collision frequency with neutral molecules. Some of the methods have limitations in that they can only be used during disturbed conditions, when the electron concentration is high enough to give reliable measurements.

With the present knowledge of observation techniques, it seems that rocket probe measurements represent the only possibility of observing ion concentrations in the D-region. However, on the basis of electron density observations and theoretical D-region model calculations, some conclusions can be drawn considering ions in the D-region. It is fairly well established that the principal positive ions are O_2^+ and N_2^+ . NO^+ may also be one of the dominating positive ions, NICOLET & AIKIN, 1960. As for the negative ions, the situation is much more complica-

ted. Observations during Polar Blackouts show that electrons must be attached to some molecule or atom during nighttime, and detachment by solar radiation during daytime increases the electron concentration, BAILEY, 1959. The negative ions are believed to be O_2^- and O^- as these molecules and atoms form stable negative ions. Solar radiation in the whole visible spectrum has sufficient energy for the detachment reaction. REID, 1963, has argued that both NO_2^- and O_3^- are possible candidates for the position as dominating negative ion in the D-region.

BOURDEAU, WHIPPLE & CLARK, 1959, have pointed out that dust can be of importance as recombination surfaces in the D-region, and in this way influence the ionization recombination balance in the D-region.

It can be concluded that there is a need for more reliable information about type of ions and ion concentrations in order to understand the processes in the D-region. The Gerdien condenser is considered as one of the possible instrumentations for this purpose. A simple Gerdien condenser system can provide information about ion concentrations and conductivities. Further development of the system to a mobility spectrometer is possible.

1. The Gerdien condenser

1.1. DEVELOPMENT OF THE GERDIEN CONDENSER

The investigation of ion conductivities and mobilities in air at ground level has been practiced within the field of atmospheric electricity for many years, and considerable experience has been accumulated in theory and observation techniques. The Gerdien condenser has its name from one of the first constructors of ion collector instruments, GERDIEN, 1905. The air, which includes the ions to be observed, is aspirated through a cylindrical condenser. A radial electric field in the cylindrical condenser attracts one sign of ions to the collector, which can be either the central electrode or the cylinder. Information about the ion conductivities and mobilities can be obtained from the current-voltage characteristics of the condenser.

Many authors have reported on further development of the Gerdien condenser system for special applications, ISRAEL, 1929, SCHOLZ, 1931, and SIKSNA, 1952. It will, however, be outside

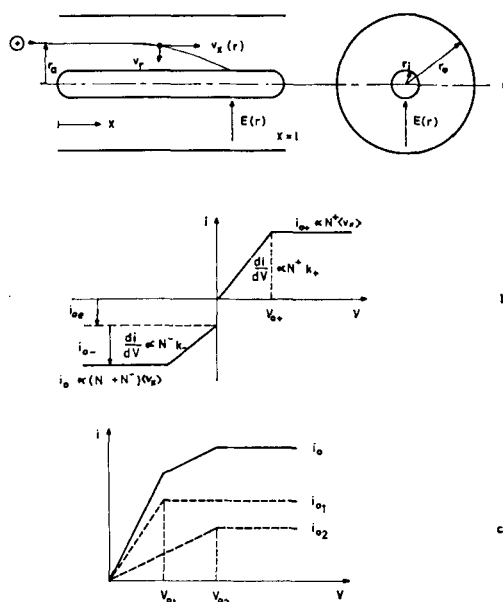


FIG. 1.2.1. Current-voltage characteristics of the Gerdien condenser.

$$E(r) = -\frac{V}{r} \frac{1}{\ln r_0/r_1}$$

V = voltage between electrodes

Air stream velocity, $v_x = v_x(r)$

Radial drift velocity,

$$v_r = k_+ E(r) = -k_+ \frac{V}{r} \frac{1}{\ln r_0/r_1}$$

k_+ = mobility of positive ions in air.

the scope of this paper to try to give a survey of this subject.

Some of the main difficulties with the Gerdien condenser are the effects of stray fields at the condenser opening and turbulence in the air stream through the condenser when doing the measurements at atmospheric pressure. BECKER, 1909, and SCHOLZ, 1931, have discussed some of these problems.

1.2. THE CURRENT-VOLTAGE CHARACTERISTIC OF A GERDIEN CONDENSER

The Gerdien condenser consists of two concentric cylinders of radii r_0 and r_1 , respectively, Fig. 1.2.1a. An electric field $E(r)$ is set up between the two cylinders. The direction of this field is such that the ions, which shall be measured, are drifting towards the central

electrode, which is the collector in this electrode arrangement. In order to calculate the current-voltage characteristics of a Gerdien condenser, the trajectory of a positive ion in an air stream through the condenser will be considered. The positive ion enters the condenser at a radius r_a and follows the air stream through the condenser, at the same time drifting in the radial electric field $E(r)$ inside the cylinder.

The volume of air flowing per second through the cross-section $\pi(r_a^2 - r^2)$ is,

$$\Phi_r^a = \int_r^{r_a} v_x(r) \cdot 2\pi r dr \quad (1.2.1)$$

$$dt = \frac{dr}{v_r} = \frac{dx}{v_x(r)}$$

$$dx = \frac{v_x(r)}{v_r} dr = - \frac{\ln r_0/r_i}{k_+ V} v_x(r) r dr.$$

$$x = - \frac{\ln r_0/r_i}{k_+ V} \int_{r_a}^r v_x(r) r dr. \quad (1.2.2)$$

Combining equations (1.2.1) and (1.2.2)

$$x = \frac{1}{2\pi} \frac{\ln r_0/r_i}{k_+ V} \Phi_r^a. \quad (1.2.3)$$

The (x, r) coordinates of the positive ion are determined by the voltage V and the total flow of air through the cross-section $\pi r_a^2 - \pi r^2$. This is valid for all velocity distributions $v_x(r)$.

If we consider a positive ion entering the condenser at a radius r_{a1} , a voltage V_1 is necessary to obtain $x=l$, when $r=r_i$, i.e. the ion is caught by the end of the central electrode.

$$\Phi_{r_i}^{a1} = \frac{2\pi l}{\ln r_0/r_i} k_+ V_1 = \frac{c}{\epsilon} k_+ V_1 \quad (1.2.4)$$

where $c = 2\pi\epsilon l / (\ln r_0/r_i)$ is the capacity of the condenser.

All positive ions entering the condenser with r_a values less than r_{a1} will go to the central electrode resulting in a current,

$$i_1 = N^+ e \Phi_{r_i}^{a1} = N^+ e \frac{c}{\epsilon} k_+ V_1 \quad (1.2.5)$$

N^+ = concentration of positive ions.

This means that before saturation the current

is proportional to the voltage V_1 , the current-voltage gradient is proportional to the conductivity of positive ions, $N^+ e k_+$. The saturation current is obtained for a voltage V_0 ,

$$i_0 = N^+ e \Phi_{r_i}^{r_0} = N^+ e \frac{c}{\epsilon} k_+ V_0$$

$$V_0 = \frac{\epsilon \Phi_{r_i}^{r_0}}{c k_+} \approx \frac{\epsilon \pi r_0^2}{c} \frac{\langle v_x(r) \rangle}{k_+} \quad (1.2.6)$$

πr_0^2 is the total cross-section for air flow through the condenser. The equations for current-voltage characteristics of the Gerdien condenser above are independent of the velocity distribution of air flow, $v_x(r)$ and vary only with the integrated flow $\Phi_{r_i}^{r_0}$.

The current-voltage characteristics will not be changed if we turn the electric field the opposite way and use the outer cylinder as a collector.

The equations above have been deduced for positive ions in the Gerdien condenser. All equations are, however, valid for negative ions if N^- and k_- are used instead of N^+ and k_+ .

The current-voltage characteristics of a Gerdien condenser is shown in Fig. 1.2.1b. One type of positive ion and one type of negative ion and electrons are thought to be present in the air flowing through the condenser. The current-voltage derivative is proportional to the conductivity, $N^\pm e k_\pm$ for $V < V_0$. The saturation current i_{0+} is proportional to $\langle v_x \rangle N^+$, where $\langle v_x \rangle$ is the mean velocity of air flow. The saturation current i_{0-} is proportional to $\langle v_x \rangle (N^- + N)$ where N is the electron concentration. Electrons having a high mobility will be picked up by the collector for a very small electric field in the condenser. We assume that no extra electrons are caught or repelled by the stray field at the condenser opening.

The positive current-voltage characteristic for a Gerdien condenser when air with two types of positive ions of different concentrations and mobilities flows through the condenser is shown in Fig. 1.2.1c. In this example the saturation current i_0 is proportional to $(N_1^+ + N_2^+) \langle v_x \rangle$. The derivative of the current-voltage characteristic is proportional to $(N_1^+ k_{+1} + N_2^+ k_{+2})$ for $V < V_{01}$ and proportional to $N_2^+ k_{+2}$ for $V_{01} < V < V_{02}$.

From the foregoing discussion, it can be seen that the conductivity, $N^\pm e k_\pm$, of an ion can be

derived from the current-voltage gradient, and $N^\pm \langle v_x \rangle$ can be derived from the saturation current. In order to obtain information about $N^\pm$ either $k_\pm$ or $\langle v_x \rangle$ must be known. If both $k_\pm$ and $\langle v_x \rangle$ are known, the current-voltage characteristic gives a double check on $N^\pm$. When ions of different mobilities are present, they can be distinguished as demonstrated in Fig. 1.2.1c, when the mobilities of the two types of ions are far enough apart.

1.3. GERDIEN CONDENSERS IN UPPER ATMOSPHERIC RESEARCH

The Gerdien condenser has been used in numerous experiments with balloon-borne instrumentations. GISH & SHERMAN, 1936, WOESSNER, COBB & GUNN, 1958, STERGIS, CORONITI, NAZARECK, KOTAS, SEYMOUR & WERME, 1955, HATAKEYAMA, KOBAYASHI, KITAOKA & UCHIKAWA, 1958. Several measurements have also been done with Gerdien condensers mounted on aircrafts, SAGALYN, 1958, and KRAAKEVIK, 1958.

The balloon measurements will only give information about ion conductivity as it is difficult to determine the flow of air through a Gerdien condenser hanging under a balloon. The results of conductivity measurements from balloons and aircrafts are in good agreement with the conductivity to be expected from cosmic ray ionization. There are, however, indications in some of the measurements that the conductivity is below the expectation value at heights above 20 km, see for example GISH *et al.*, 1936. See also discussion of recombination to dust in Chapter 8.2.

BOURDEAU, WHIPPLE & CLARK, 1959, have reported the first rocket experiment using Gerdien condensers. In their experiment, which took place at White Sands 21 November 1959 at 10^h18^m MST, two Gerdien condensers were mounted at the nosetip of a Viking rocket, and measurements were done during the rocket ascent. The voltage to the central collector electrode was operated in steps to obtain a current-voltage characteristic. Their measurements show a reduction of the positive ion conductivity to values below the expectation value calculated from cosmic ray ionization above 50 km height. A similar reduction of negative ion conductivity is observed at 70 km. As one should expect that the ionization from solar radiation adds to the conductivity caused

by cosmic ray ionization at heights above 70 km, the authors conclude that this effect can be due to dust particles acting as recombination surfaces for ions and electrons. The authors at the same time point out the uncertainty in the measurement. The strong electric field in the condenser, which is necessary in order to collect ions from the high velocity air flow, will most probably change the mobility of both positive and negative ions, LOEB, 1955, and VARNEY, 1953. Shock waves may also disturb the air flow in the condensers as the rocket is moving at a speed equivalent to $M = 4$. The shock wave may also cause thermal ionization. WHIPPLE, 1960, has described a further development of the Gerdien condenser system mounted at the tip of a rocket nosecone. A detailed description of this system is given by COOPER, 1961, and some of the experimental results from Aerobee firings at Fort Churchill are given by WHIPPLE, 1964.

A very interesting and promising probe has been reported by SAGALYN and SMIDDY, 1963. They use a meshed sphere with a central electrode for ion collection. This probe is extended on a boom from the side of the rocket at about 50 km during the rocket ascent. The grid structure of the meshed sphere is made of thin metal threads allowing the air to pass through the sphere. The spherical electric field which is completely enclosed in the meshed sphere, will draw ions to the central collector. In principle the meshed spherical probe and the Gerdien condenser are similar as a saturation current is obtained in both probes. The current-voltage characteristics are, however, different. The advantage of the meshed sphere construction is that no stray fields outside the probe will influence the collection of ions. The disturbance of the central collector and the grid structure on the flow of air through the probe are under investigation in a wind tunnel.

SMITH, 1963, has reported measurements of positive ion concentrations using a non-saturation probe, where the nosetip of the rocket is insulated from the rest of the rocket body, and kept at a negative potential with respect to the rocket. This probe is the simplest possible construction to be used on a rocket. The limitation of the method is at present caused by difficulties in interpretation of the ion current flow to the nosetip. The principle of this probe is different from that of the Gerdien condenser.

The characteristic feature of the Gerdien condenser is that a saturation current can be obtained, whereas the current to the probe described by SMITH will not saturate. It is felt, however, that the latter probe should be mentioned in this survey as it is the only probe used beside the Gerdien condenser and meshed probe for investigation of ions in the D-region.

The Gerdien condenser can operate as an ion mobility spectrometer. This was demonstrated in Fig. 1.2.1c. It is, however, necessary to have a very accurate current-voltage characteristic for this purpose and with the uncertainties involved in the present rocket measurements with Gerdien condensers, it is very difficult to obtain a reliable ion mobility spectrum. DOLEZALEK & OSTER, 1963, have reported development of an ion mobility spectrometer based on the Gerdien condenser principle. In this construction, the ion intake occurs only at a predetermined radius, and the central electrode, which is the collector, is divided into 16 parts. The outer driving electrode is also divided into 16 isolated parts, and an AC voltage of increasing amplitude along the condenser axis can be set up between the 16 pair of sections. By analyzing the current of the different 16 collector sections, the ion mobility spectrum can be derived. The probe is at present undergoing laboratory and wind-tunnel tests.

2. Ion mobilities

2.1. CLASSICAL THEORY OF ION MOBILITY

If we assume the molecules and ions to be solid elastic spheres of the same diameter, R , scattered isotropically on impact with each other, we can define a mean free path, L , which is the mean distance travelled by an ion or a molecule between collisions. The cross-section for collisions is $\pi(2R)^2 = 4\pi R^2$.

$$L = \frac{1}{4\sqrt{2}\pi R^2 n} \quad (2.1.1)$$

n = number of molecules per unit volume.

The ions and molecules have average molecular velocities $\langle v \rangle$. Following the kinetic theory of gases

$$\langle v \rangle = 0.92 (\langle v^2 \rangle)^{\frac{1}{2}} \quad (2.1.2)$$

$$\frac{1}{2} m \langle v^2 \rangle = 3/2 k_B T \quad (2.1.3)$$

$\langle v^2 \rangle$ = root mean square velocity

m = molecule (ion) mass

k_B = Boltzman's constant

T = temperature.

It has been established experimentally that if an ion is influenced by an electric field, the drift velocity v_E of the ion along the electric field is proportional to the field

$$v_E = kE \quad (2.1.4)$$

k = ion mobility.

Equation (2.1.4) has been found to be valid for small values of E/p . This means that for small values of E/p , the ions do not gain much energy from the electric field.

If we now consider an ion of charge e in an electric field the following expression for k can be derived,

$$k = \frac{eL}{2m\langle v \rangle} = \frac{e}{8\sqrt{2}\pi m\langle v \rangle R^2 n} \quad (2.1.5)$$

Equation (2.1.5) is not a satisfactory expression for ion mobility as it shows poor agreement with experiments. The general variation of k with ion mass and gas density is, however, demonstrated in this equation. In order to obtain a more complete expression for ion mobility, it is necessary to consider the distribution of velocities and mean free paths and also the case when ions and neutral molecules have different masses. To obtain the complete picture of ion mobilities, it is necessary to go further than the classical theory, which assumes ions and molecules to be elastic spheres, and also take into account the forces between molecules and ions.

LANGEVIN, 1905, has presented a more detailed classical theory:

$$\begin{aligned} k &= 0.75 \frac{eL}{M\langle v \rangle} \left(\frac{m+M}{m} \right)^{\frac{1}{2}} \\ &= 0.75 \frac{eL}{m\langle v_i \rangle} \left(\frac{M+m}{M} \right)^{\frac{1}{2}} \end{aligned} \quad (2.1.6)$$

M = molecule mass

$\langle v_i \rangle$ = average velocity of ion.

The mass variation in equation (2.1.6) has been established by experiment, but the numerical values of k are not in agreement with

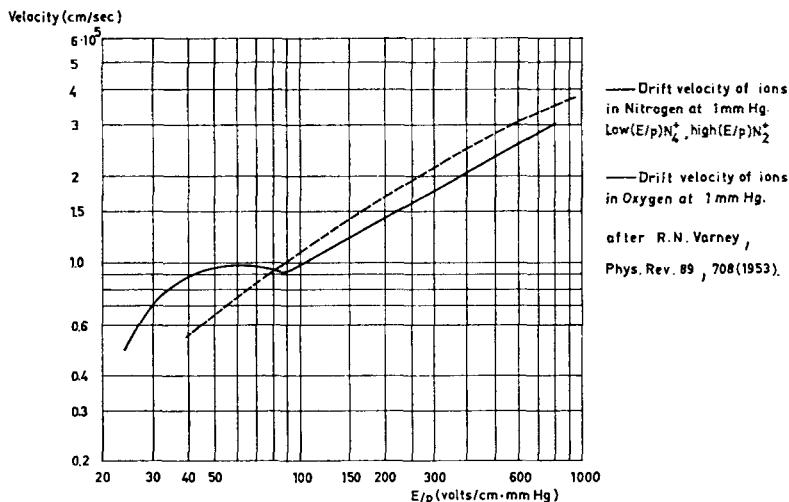


FIG. 2.3.1. Drift velocities of ions in Nitrogen and Oxygen (After Varney).

experiments, the mobilities of some ions as derived from equation (2.1.6) are three to four times the mobilities measured in the laboratory.

2.2. NEW ION MOBILITY THEORIES

In order to obtain a more complete theory for ion mobility, it is necessary to consider forces acting between ions and molecules. Dipole forces will tend to cluster formation between ions and molecules. An ion drifting in an electric field may have a molecule attached to it for part of the distance travelled, and the mobility observed will be intermediate for that of the attached and unattached states of the ion. It is further necessary to evolve the influence of dielectric forces and Van der Waals forces on the collision cross-section and free path between collisions. The field theories by MAXWELL & BOLZMAN were the basis for the new mobility theories, and HASSÉ, 1926, has developed an expression for ion mobility, taking into account the central forces between molecules. More refined theories of ion mobility have been presented by HASSÉ & COOK, 1931, and by MARGENAU, 1941, and WIGHTMAN, 1944.

2.3. VARIATION OF ION DRIFT VELOCITY WITH E/p

The theoretical analysis of WANNIER, 1953, indicates that the ion drift velocity is proportional to $\sqrt{E/p}$ for high values of E/p . The drift velocity at high E/p values is larger than

the random thermal velocity, and the energy gained between collisions is proportional to the ion kinetic energy resulting in an ion drift velocity proportional to $\sqrt{E/p}$. This dependence of ion drift velocity on E/p has been experimentally verified by HORNBECK, 1950 and 1951, and by VARNEY, 1952 and 1953. VARNEY has also investigated the drift velocity of O_2^+ and N_2^+ ions in their own gases. The results of Varney have been copied and are shown in Fig. 2.3.1 as these results are of special interest for the measurements of ions in the atmosphere. The drift velocity of O_2^+ ions shows a shift from dependence of E/p at low E/p values to a dependence of $\sqrt{E/p}$ at E/p values about 200 V/cm mm Hg. The investigation of N_2^+ ions in N_2 shows the same change of the drift velocity between E/p values 50–100 V/cm mm Hg. A more detailed investigation of VARNEY's results has indicated that the ions present at low E/p values are N_4^+ and N_2^+ at higher E/p values. SAPOROSCHENKO, 1958, has reported a more detailed study of ions of N_2 . His measurements indicate the existence of N_4^+ as the dominating ion below $E/p = 45$ V/cm mm Hg. At higher E/p values, there will be a mixture of the ions N_3^+ , N_2^+ , and N^+ . The dominating ions above $E/p = 50$ V/cm mm Hg are N_2^+ and N^+ .

Negative ions are only formed in gases by electron attachment to neutral molecules or atoms. The balance between attachment of electrons and detachment of electrons, which takes place in collisions or by influence of photo-

detachment, makes the electron to be free for part of the time, when it is not attached. The drift velocity in an electric field of a negative ion will thus be larger than the drift velocity of the same positive ion as the negative ion for part of the distance is a free electron. The nature of negative ions makes measurements very complicated, and the knowledge about the variation of negative ion mobilities with E/p is very limited. One must expect, however, that high E/p values will result in detachment of electrons.

Cluster formation is of importance for both positive and negative ions. A molecule can form a cluster with an ion in a three-body collision. The mobility of the cluster will change with the attachment and detachment of molecules. The variation of cluster formation with E/p is far from clear. A survey of this subject has been given by LOEB, 1955.

2.4. HEAVY IONS

Heavy ions are formed in attachment of electrons, or ions to particles and condensation nuclei (aerosols). As the mass of these ions is rather large, their mobility is very small. Small air ions have mobilities in the range $2-0.1 \cdot 10^{-4}$ $\text{m}^2/\text{V sec}$. Their radii are between $0.5 \cdot 10^{-9}$ m and $2 \cdot 10^{-9}$ m derived from a classical elastic sphere theory. Heavy ions found in the atmosphere have mobilities probably as low as 10^{-10} $\text{m}^2/\text{V sec}$ for particles of radius $= 10^{-6}$ m ($= 1 \mu$). For small air ions and the smaller of the condensation nuclei ions, we can say that the ions are suspended in the air, and follow the thermal motion of the gas molecules, as well as the large scale motion of a gas volume. This may not be the case for particles of radius $= 10^{-6}$ m. Thus a mobility measurement will be uncertain, and there are considerable technical difficulties in measuring the small mobilities of these heavy ions.

It is believed that the Gerdien condenser is not a satisfactory instrument for observation of heavy ions in the upper atmosphere. In order to observe the heavy ions, either a long Gerdien cylinder of small radius must be used, or a strong electric field must be used to attract heavy ions to the collector. The air flow through a long thin tube is very difficult to control, and a strong electric field may totally change the original configuration of the heavy ions.

2.5. THE RELATION BETWEEN ION MOBILITY AND DIFFUSION

An expression for self-diffusion of an ion of mass m in a gas with molecules of mass M can be derived from classical theory along the same lines as derivation for ion mobility k .

$$D = 0.75 \frac{\langle v \rangle L}{3} \left(\frac{m+M}{M} \right)^{\frac{1}{2}}. \quad (2.5.1)$$

The coefficient of diffusion in equation (2.5.1) is valid for self-diffusion, i.e. when the number density of ions is small compared with the number density of gas molecules, and no forces act between the ions. By combining equation (2.5.1) and (2.1.9), it can be seen that the ratio of k/D is

$$k/D = \frac{e}{\frac{1}{2} m \langle v_i^2 \rangle} = \frac{e}{\frac{1}{2} M \langle v^2 \rangle}. \quad (2.5.2)$$

It is reasonable to assume that the resistance of the gas to the motion of an ion is independent of the driving force acting to move the ion. In order to find the condition when diffusion or drift in an electric field is the dominant process taking place the ratio between diffusion velocity and drift velocity in an electric field is derived. The number of ions diffusing through a unit area per second in direction x is

$$n_i = -D dN_i/dx. \quad (2.5.3)$$

The velocity of diffusion is $v_D = n_i/N_i$. N_i = ion concentration.

$$v_D = -D/N_i dN_i/dx. \quad (2.5.4)$$

The velocity of an ion in an electric field is $v_E = kE$.

$$\begin{aligned} \frac{v_D}{v_E} &= \frac{D}{k} \frac{dN_i/dx}{N_i E} = \frac{\frac{1}{2} m \langle v_i \rangle}{e N_i E} \frac{dN_i}{dx} \\ &= \frac{k_B T}{e N_i E} \frac{dN_i}{dx} \end{aligned} \quad (2.5.5)$$

k_B = Boltzman's constant.

In the actual experiments, the smallest values of E are of the order of 5 V/m, and N_i is approximately 10^4 cm^{-3} . Even if very high values for dN_i/dx are assumed, v_D/v_E is very small, i.e. of the order of 10^{-5} to 10^{-6} , and self-diffusion of ions can be neglected in the Gerdien condenser experiments discussed here.

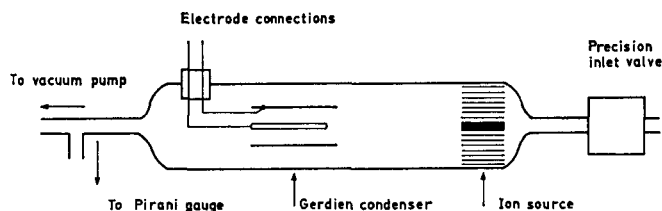


FIG. 3.1.1. Vacuum system for testing of Gerdien condenser models.

It is necessary, however, to consider the effect of space charge in the Gerdien condenser. Close to 80 km height, the main ionic constituents are positive ions and electrons, and the electrons having a very high mobility will be caught rapidly at the front end of the Gerdien condenser, where they first experience the electric field. Positive ions will be left alone for the rest of the passage through the Gerdien condenser and the electric field produced at the inner walls of the Gerdien condenser, when $N_i = 10^4 \text{ cm}^{-3}$, will be of the order of 5 V/m, which is equal to the smallest electric fields applied in the experiments. The result of this electric field is a diffusion of positive charges to the inner walls of the Gerdien condenser cylinder. The space charge effect is discussed more in detail in Chapter 7.5.

3. Laboratory experiments

3.1. VACUUM SYSTEM FOR TESTING OF GERDIEN CONDENSERS

In this section, some experiments with small Gerdien condenser models operated at low pressure will be described shortly. The experiments were not successful because of poor vacuum facilities. But even if the results of these experiments were rather meagre, it is of interest to point out the difficulties encountered in producing ionized air streams at low pressures for simulating the conditions a Gerdien condenser rocket probe will meet in the upper atmosphere.

Fig. 3.1.1 shows the vacuum system for testing of small Gerdien condenser models at low pressures. Air is pumped through a glass tube of 5 cm diameter, where Gerdien condensers of 2 cm diameter are placed. The inlet of air is controlled by a precision inlet valve. For a certain pressure range, a mechanical vacuum pump will have an approximately constant

pumping speed, which means that if the inlet valve is opened the pressure in the glass tube will rise but the velocity of air flow is nearly the same. The pressure was regulated between 0.01 and 1.0 mm Hg in this system. This pressure range covers that part of the upper atmosphere which is of interest for D-region studies. The pumping speed of the system was of the order of 1 liter/sec resulting in air flow velocities a little less than 1 m/sec. Different ion sources were used. Radioactive sources were packed inside rolls of corrugated aluminium foil for ion production by secondary emission as demonstrated in Fig. 3.1.1, and some attempts were done to extract ions from gas discharges. The gas discharges were set up in a tube placed between the inlet valve and the test tube. The experiments using gas discharges were not successful whereas the radioactive source gave a saturation current of the order of 10^{-13} A in the Gerdien condenser at pressures around 1 mm Hg. It was found very difficult to use such small currents for a detailed study of the current-voltage characteristics, and it was also difficult to keep exact equilibrium conditions in the test tube. The experiments were stopped at this stage, as it was realized that it was necessary to have a larger vacuum pump and a more refined method for ion production in order to study the operation of Gerdien condensers in low pressure flow of ionized air. A mechanical pump, or a mercury diffusion pump of a capacity of 1000 liters/sec for pressures between 0.01 and 1.0 mm Hg could give an air flow velocity of the order of 50–100 m/sec in a tube, which is large enough to prevent wall effects to influence the measurements.

The ion source will certainly be one of the main difficulties in the development of such a test system. It is believed, however, that some type of AC or DC gas discharge, or the use of a radioactive ion source at normal temperature

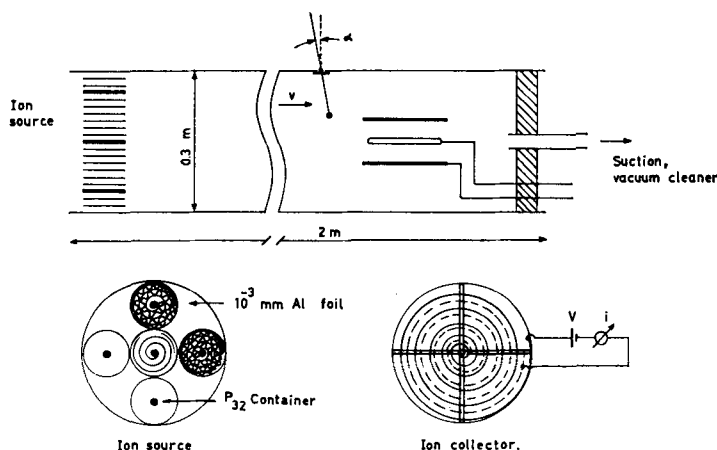


FIG. 3.2.1. Wind tunnel for testing of Gerdien condenser models.

and pressure just before the inlet valve can solve this problem.

The system proposed here would be of importance for the study of various types of ion probes to be used in upper atmospheric research. As for the Gerdien condenser, the end effects and the operation of different electrode arrangements could be tested under the right conditions. It has been mentioned earlier that the Gerdien condenser could be the basic construction for a multielectrode mobility spectrometer. The system sketched above would make it possible to test such mobility spectrometers for example by pumping a clean gas with well defined types of ions through the system.

3.2. WIND TUNNEL FOR TESTING OF GERDIEN CONDENSERS

The parameter E/p is very important in gas discharges as it is the experimental expression for the energy gained per mean free path. The drift velocity is proportional to E/p if E/p is below a certain value, see Chapter 2.3.

The characteristic parameter for a Gerdien condenser is the ratio between the drift velocity in the electric field, v_r , and the air flow velocity, v_x . From equations (2.1.5) and (2.1.6), it can be seen that the mobility, k , is inversely proportional to molecular density and average molecular velocity so that we can write

$$\frac{v_r}{v_x} = \frac{kE}{v_x} = k_0 p_0 \left(\frac{T}{T_0} \right)^{\frac{1}{2}} \frac{E}{v_x p}$$

k_0 = mobility at pressure p_0 and temperature T_0 .

Assuming T = constant we obtain

$$\frac{v_r}{v_x} = \text{constant} \frac{E}{v_x p} \quad (3.2.1)$$

The parameter $E/v_x p$ determines the path of an ion in the Gerdien condenser, and for the same $E/v_x p$ -values experiments can be compared. This indicates that some experience about Gerdien condenser operation can be obtained from experiments at normal temperature and pressure in a wind tunnel even if this method naturally has some limitations, which will be discussed in the following.

Fig. 3.2.1 shows a sketch of the wind tunnel system. The suction from a vacuum cleaner draws air through a metal tube of 0.3 m diameter at a velocity of approximately 0.5 m/sec. The air is ionized by a P_{32} ion source, which is also shown in Fig. 3.2.1. The β -rays from the 50 mC, 1.7 MeV radioactive source will produce enough ions by secondary emission at the aluminium foil surfaces to give a total ion current in the tube of the order of 10^{-8} A, at a distance of 1.5 m downstream from the ion source. The air flow velocity can be estimated both from information about the vacuum cleaner capacity and a simple measurement shown in Fig. 3.2.1. A very light ball is extended on a thin metal bar into the air stream. The metal bar can rotate freely on a knife, and as the drag forces act on the ball, the metal bar will be bent an angle α , which is a function of the air flow velocity. The air flow velocity was measured at different radii inside the tube and found to be almost

the same all over the cross-section of the tube. This is typical for turbulent flow. By calculating Reynolds number, Re , for the tube it was found to be of the order of 10^4 .

$$Re = \frac{v \varrho_M y}{S} \quad (3.2.2)$$

v = air flow velocity in wind tunnel

ϱ_M = air density

y = typical dimension (diameter of tube)

S = dynamic viscosity = $1.2 \cdot 10^{-3}$ kg/msec,

$T = 200^\circ K$.

For $Re > 3 \cdot 10^3$ the air flow is in most cases turbulent. For the air flow to be laminar, the velocity must be below 0.1 m/sec. For these small velocities, it was found that the ion current was reduced much more than expected, and it was concluded that this was caused by the longer time spent by the air between the ion source and the probe, thus allowing for more ions to recombine. The choice of air speed velocity for the wind tunnel therefore was a compromise between low air flow velocity for having laminar flow, and high air flow velocity for having an ion current that was large enough to secure a reliable current measurement. A velocity of 0.5 m/sec was used in the experiments to be described later.

Because of ion recombination, there will be an ion density gradient from the ion source to the probe. This gradient was investigated by means of the ion collector shown in Fig. 3.2.1. This ion collector consisting of two strips of metal isolated from each other and wound up in a spiral on a glassfiber crossing could be moved along the axis of the tube, and the saturation current was plotted for different positions. The variation of the ion current over the cross-section of the test tube was also investigated by moving a Gerdien condenser to different positions radially in the tube. Variations, which were negligible compared to the fluctuations in the measurements, were recorded over the cross-section of the test tube.

As the air flow velocities expected in a parachute probe experiment (see Chapter 4.4) is varying from about 50 m/sec at 40 km to some hundred m/sec at higher altitudes, and the air flow velocity in the test tube is 0.5 m/sec, the E/p value for the wind tunnel experiments must be less than 10^{-2} of the actual values in the upper atmosphere to make $E/v_x p$ the same.

Thus the drift velocity v_E is certainly proportional to E/p for the wind tunnel experiments.

The wind tunnel is useful for the study of end effects and the general operation of different types of Gerdien condensers. The air flow through the Gerdien condenser in a parachute probe experiment is expected to be laminar (see Chapter 7), whereas the air flow in the wind tunnel is turbulent. For the experiments which were done in the wind tunnel, this caused some fluctuations in the ion current measurements, and was the limiting factor for very accurate measurements.

It is also necessary to be aware of the difference in ionic constituents at ground level and in the upper atmosphere. At ground level, there are a number of medium and heavy ions, which may cause additional effects of clustering and attachment of electrons. Negative ion formation will most certainly be different from that at lower pressures. The presence of N^+ , N_2^+ , N_3^+ , and N_4^+ , which has been thoroughly investigated by Saporoschenko, 1958, for pressures between 10^{-3} and 0.6 mm Hg is of special interest. Nothing is known about these ions at normal temperature and pressure.

3.3. SOME GERDIEN CONDENSER MODEL EXPERIMENTS

Having in mind the limitations of the experiments, three different electrode arrangements of Gerdien condensers were tested in the wind tunnel. The three Gerdien condensers are sketched in Fig. 3.3.1. The current voltage characteristics of the three systems are identical according to the simple Gerdien condenser theory presented in Chapter 1. One must expect, however, that the unwanted end effects are different. Field lines causing the end effects are also indicated in Fig. 3.3.1 for the three types of Gerdien condensers numbered I, II, and III. Current-voltage characteristics were obtained for the three probes, and the result of these experiments is shown in Fig. 3.3.2. It has been shown that the air flow in the wind tunnel is turbulent, this was also seen as fluctuations of the α -values on the simple wind meter sketched in Fig. 3.2.1. Fluctuations of the same order of magnitude and with similar characteristic time changes could be seen in the current recordings. Thus the "error bars" in Fig. 3.3.2 should rather be understood as fluctuations because of turbulent air flow. The largest col-

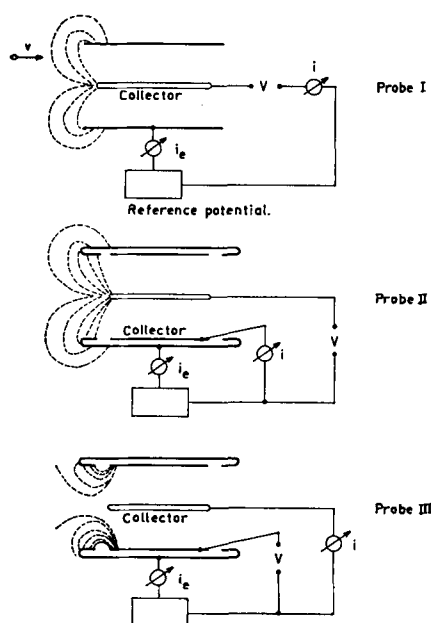


FIG. 3.3.1. Gerdien condenser models.

lector current is found for Probe I; this is most probably caused by the electric field outside the cylinder on the front end (Fig. 3.3.1) making the effective area for ion collection larger than the cylinder opening. This end effect may partly be the reason why the current does not saturate, but the main reason for this is most probably the presence of heavier ions with smaller mobility.

Probes II and III have the outer cylinder

connected to earth. The effect of this outer cylinder is that the field inside the probe is very close to the ideal cylindrical form, but the effect of the field between the electrode at voltage V and outer cylinder may disturb the ions as they enter the Gerdien condenser. The effect of these fields as sketched in Fig. 3.3.1 for probe II and III is to extract ions from the air stream entering the Gerdien condenser opening and lead them directly to ground instead of having them pass the electrometer. This makes the ion current to the collector smaller than it should be in the undisturbed case. In order to find the magnitude of this effect, the current i_e (see Fig. 3.3.1) was measured. The current i_e is mainly caused by ions extracted from the ionized air stream entering the cylinder, and some contribution is also expected from ions picket up outside the cylinder, when V is very high.

It can be seen from Fig. 3.3.2 that i_e is larger for Probe III than for Probe II. The effect on the i - V characteristics is also in agreement with this observation as $i_{III} < i_{II}$ because of more ions picket up at the entrance. An attempt was made to calculate the ion mobility from the rise of the i - V characteristics using formulae (1.2.5). The positive and negative ion densities N^+ and N^- were measured with the ion collector shown in Fig. 3.2.1. The concentrations of small ions in the wind tunnel at the position of the Gerdien condenser models were found to be $N^+ = N^- = (1.6 \pm 0.2) \cdot 10^6 \text{ cm}^{-3}$ for $v = 0.5 \text{ m/sec}$. The mobilities calculated for the three probes are shown in Table 3.3.

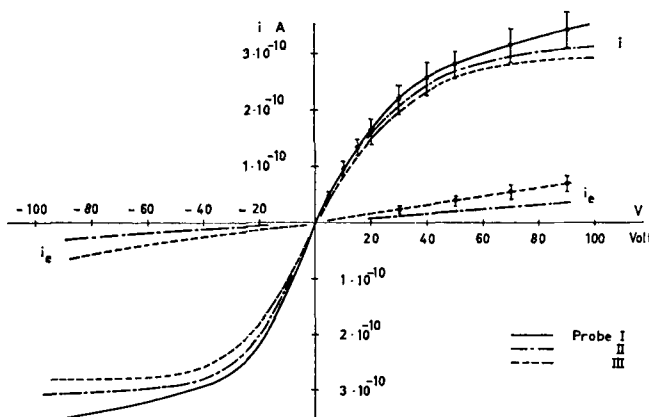


FIG. 3.3.2. Current-voltage characteristics of Gerdien condenser models.

TABLE 3.3

Probe	$k_+(m^2/V \text{ sec})$	$k_-(m^2/V \text{ sec})$
I	$(1.5 \pm 0.3) \cdot 10^{-4}$	$(2.2 \pm 0.3) \cdot 10^{-4}$
II	$(1.4 \pm 0.3) \cdot 10^{-4}$	$(2 \pm 0.3) \cdot 10^{-4}$
III	$(1.3 \pm 0.3) \cdot 10^{-4}$	$(1.8 \pm 0.3) \cdot 10^{-4}$

The mobilities of small air ions are very uncertain and are varying with different parameters as for example air humidity and concentration of condensation nuclei. The results presented in Table 3.3 are, however, in agreement with published data of ion mobilities, SIKSNA & WESTERMARK, 1961.

It is very difficult to point out the probe which gives the most correct current-voltage characteristics from the measurements done here. The measurements of mobility of small air ions are in agreement with mobility measurements performed by other groups, but no conclusion can be reached as to what mobility in Table 3.3 is the most correct. The fact that i_e for Probe III is larger than for Probe II indicates that the end effects of Probe II is smaller, and this electrode configuration is the better. Comparing Probe I and II, it is very difficult from the measured i - V characteristics to see which is the better probe. The larger i -value for Probe I is most probably caused by extra ions caught outside the cylinder by the outer electric field. The i -values for Probe II is most probably reduced relative to those for Probe I because of ions taken away in the electric field at the entrance. Consequently the correct curve should be somewhere between the curves for Probe I and Probe II. However, there is one advantage of Probe II. The voltage source and the electrometer amplifier for measurement of the collector current can both be connected to the reference potential, and it is not necessary to have the voltage source isolated and shielded between the collector and the electrometer input. When the construction of a Gerdien condenser rocket probe was started, Probe II was chosen as the basic model for this construction.

If we consider a Gerdien condenser passing through the atmosphere, we must expect that if the reference potential of the probe is different from the potential of ions in the air, the

ions approaching the Gerdien condenser will be influenced, so that ions are pushed out of and into the cylindrical column of air, which is in front of the probe and later passes through the Gerdien condenser. This unwanted ion current is determined by the field lines going out from the whole instrumentation because of the difference in potential between the instrumentation and its surroundings.

Some experiments were done with Probe I in the wind tunnel in order to find out the magnitude of this effect. The Gerdien condenser was kept at various positive and negative potentials with respect to the wind tunnel test tube, and current-voltage characteristics were measured for the Gerdien condenser. Even for very high potential differences between the Gerdien condenser and the wind tunnel test tube, the changes in the i - V characteristics were negligible. The field pattern around the Gerdien condenser inside the test tube is not the same as it would be around a Gerdien condenser instrumentation in free space. The measurements indicate, however, that the charging of a Gerdien condenser instrumentation in the atmosphere to a potential different from its surroundings will not influence very much the effective ion collecting area of the Gerdien condenser opening.

At last it should be mentioned that there certainly are many other possible electrode configurations for a Gerdien condenser. The ion collector shown in Fig. 3.2.1 can also operate like a Gerdien condenser. This electrode configuration consisting of two isolated metal strips rolled in a spiral has a nearly constant electric field $E = V/d$, where V is the potential, and d is the distance between the strips. It can be shown that the most correct current-voltage characteristic is similar to that for a cylindrical condenser and is also independent of the air flow velocity distribution between the strips.

$$i = N_1 e k c / \epsilon V \quad (3.3.1)$$

where c in this case is the capacity of the roll of metal strips. The advantage of this construction is that small voltages can be used, and the end effects are very small, because the electric field is limited to the narrow space between the metal strips. Further studies will be made for using a probe of this type in upper atmospheric research.

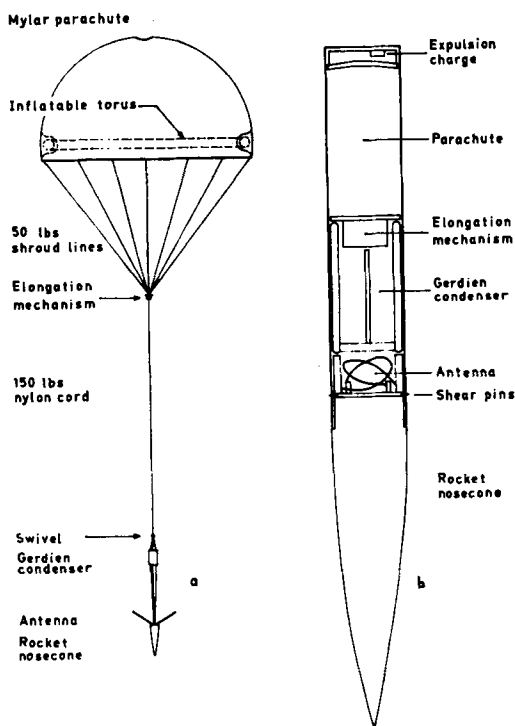


FIG. 4.1.1. (a) Gerdien condenser system hanging under parachute. (b) Packing of the system in an Arcas rocket.

4. Payload construction

4.1. SOME PRECONSTRUCTION CONSIDERATIONS

The main problems with a Gerdien condenser mounted on a rocket are the following. The flow through the cylinder is supersonic, and special care must be taken to avoid disturbances in the air flow through the cylinder. The height resolution of the measurements will be poor as a rocket moves with high velocity, and electrometer time constants is the limiting factor for the sampling frequency.

In order to collect ions from the high velocity flow inside the Gerdien cylinder, it is necessary to have a rather strong electric field. In some cases, this may severely change the sample of ions in the Gerdien condenser and make it different from the surrounding ionosphere. (See Chapter 2.3.)

The payload described here is an attempt to avoid some of the difficulties mentioned above. The basic idea is to separate the Gerdien condenser and connected instruments from the

rocket and do the measurements during descent with the probe hanging under a decelerator, either parachute or balloon. This solution makes it possible to have a subsonic, more well defined, air flow through the condenser, provided a vertical or close to vertical direction can be kept for the Gerdien condenser axis. A relatively weak electric field can be used for ion collection when the probe moves more slowly through the atmosphere, and the possibility of disturbing the true ionic conditions is reduced.

A Gerdien condenser can only work properly giving reliable current-voltage characteristics when the mean free path is smaller than the probe dimensions. This means that measurements can only be done below 80–85 km height. From preliminary calculations of parachute descent (see Chapter 4.4), it can be concluded that the separation of the payload from the rocket ought to be close to 85 km. Higher separation altitudes will cause the payload to accelerate freely to supersonic velocities before it is braked in the more dense atmosphere. Separation altitudes below 85 km will cut out information at the top of the height range of interest.

It is necessary to use inflatable decelerators for the descent as the air drag forces around 85 km are too small to be of help for inflation. The first idea was to use a balloon inflated after separation from the rocket with isopentane alcohol. The isopentane alcohol gas pressure should be such that the balloon collapsed and was transformed into a parachute when descending to 30 km. This idea was left as the balloon system would take too much space and weight. A Mylar parachute with a torus filled with residual air was later developed as decelerator for the payload.

The Atlantic Research Corporation Booster Arcas rocket was chosen for the experiments as this rocket has a fully developed system for expulsion of a parachute payload from the rocket. According to the predicted performance data of this rocket, the peak altitude would be about 85 km for a 12 lbs payload.

The choice of rocket has very much determined the payload construction. The Arcas expulsion mechanism can be seen in Fig. 4.1.1b. A gas generator charge acting on a piston is ignited close to the top of the rocket trajectory 130 seconds after start. The pressure built up by the gas generator charge is transmitted through

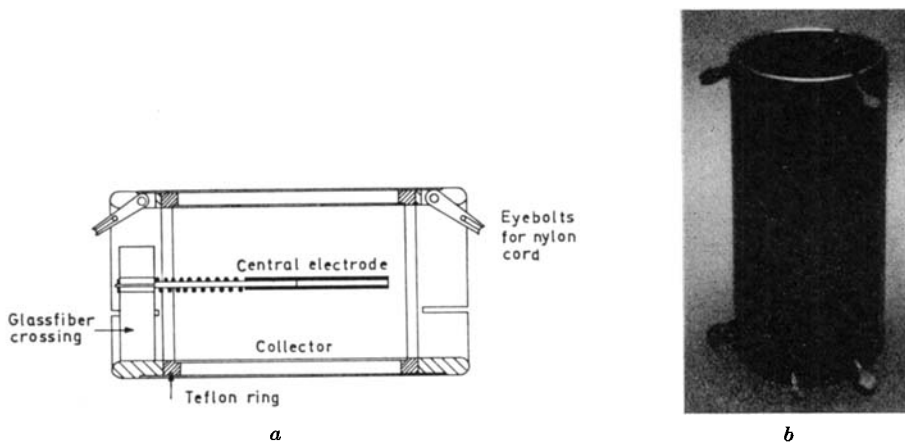


FIG. 4.2.1. Gerdien condenser construction.

the payload to shear pins going through the rocket cylinder into the nosecone base-plate. The shear pins will break, and the payload will be pushed out of the rocket cylinder. Fig. 4.1.1*a* shows the payload after expulsion, and Fig. 4.1.1*b* demonstrates the packing of the units in the rocket. As seen in Fig. 4.1.1*a*, the probe is placed behind the nosecone. This was done in order to have the Gerdien condenser diameter as large as possible, thus having a maximum number of ions collected per second. This arrangement has some disadvantages, however, the wake of the air flow behind the nosecone may disturb the air flow at the Gerdien condenser opening, and further it is complicated to have cable connections between the nosecone containing the electronic equipment and the Gerdien condenser. Concerning air flow conditions, these will be discussed later in Chapter 6.

4.2. GERDIEN CONDENSER

The Gerdien condenser is made from two concentric aluminium cylinders, the inner cylinder, being the ion collector, is isolated by teflon rings. The diameter of the collector is 9,6 cm. A cut through the condenser is shown in Fig. 4.2.1*a*. Fig. 4.2.1*b* is a picture of the condenser. The central electrode is kept in the right position by a glassfiber crossing at the front opening of the cylinder. In order to use some of the space inside the Gerdien condenser, the central electrode can be doubled up. A simple spring arrangement secures that the central electrode has the right length during measurements. Three hinged eyebolts for fasten-

ing of nylon cords are placed on each end of the cylinder. The nylon cords between the Gerdien condenser and the nosecone are 1 m long, and the reinforced cable line between the Gerdien condenser electrodes and the electronic equipment in the nosecone is somewhat longer than the nylon cords in order to resist shocks.

4.3. ELECTRONIC EQUIPMENT

The electronic units are placed in the nosecone, and a cable line connects the Gerdien condenser with the nosecone.

The principal function of the system is shown in Fig. 4.3.1*a*. The central electrode is operated at a sawtooth voltage which changes the electric field in the cylindrical condenser as demonstrated in Fig. 4.3.1*b*. This sawtooth voltage is produced by a special wirewound potentiometer driven by a DC motor. The windings of the potentiometer are split up into separate isolated sections. A simple RC filter is used to prevent noise from the potentiometer to reach the central electrode in the Gerdien condenser. The electrometer is a Keithley 10047C electrometer with a large negative feedback. The small time constant and small effective input impedance of this type of electrometer is described thoroughly by PRAGLIN & NICHOLS, 1960. Switches A, B, and C are mounted at the same axis as the potentiometer and are operated by the same DC motor. Switches A and B are mounted on high quality Araldite in a shielded spacing, and these switches connect resistances R_2 and R_3 in parallel with R_1 in a sequence demonstrated in Fig. 4.3.1*b*. In this way the sensitivity

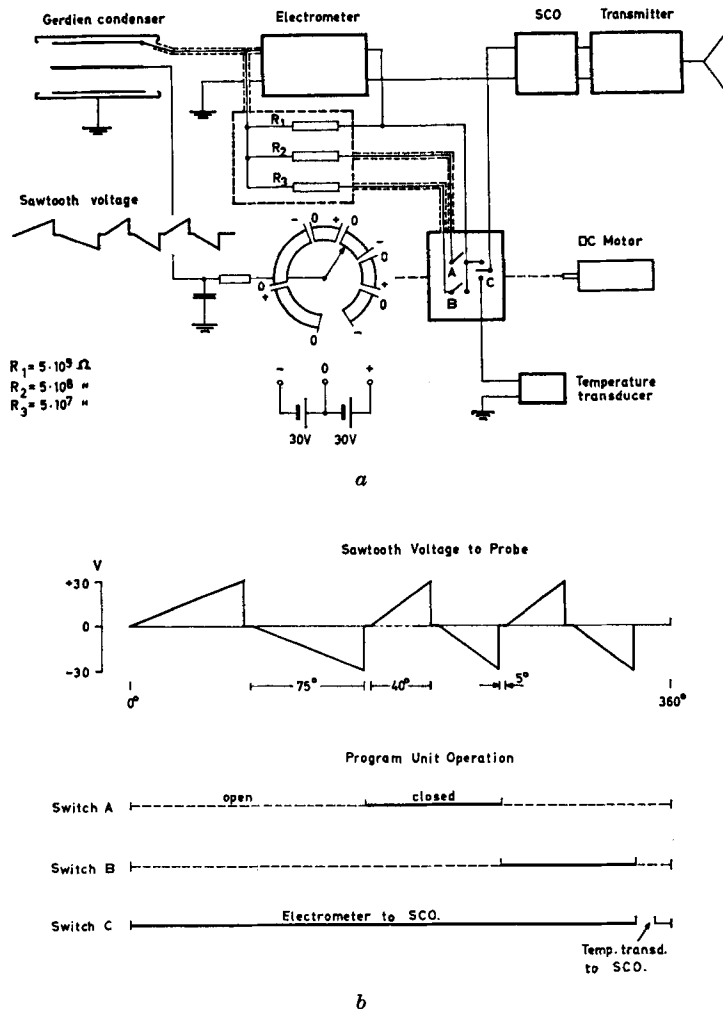


FIG. 4.3.1. (a) Nosecone instrumentation circuitry. (b) Program for sawtooth voltage and switches.

of the electrometer is changed in three steps between 10^{-10} A and 10^{-7} A for each turn of the DC motor. Switch C gives a short temperature information from inside the nosecone for each turn of the DC motor.

The telemetry equipment consists of a Vector subcarrier oscillator and FM FM transmitter TRPT 251 of 250 mW output. One of the main problems with the telemetry system was the telemetry antenna as the ARC Booster Arcas was fired from a launch tube. The launch tube makes it difficult to use an external antenna and it was necessary to find another antenna construction. The solution of this problem was

to use antennas made of beryllium copper springs mounted on the base-plate of the nosecone. The antenna was rolled up in the rocket cylinder, and the transmitter was not operating during ascent. During payload expulsion from the rocket, the transmitter was started and the antenna deployed.

The launching of the ARC Booster Arcas from a launching tube also complicated the preflight check, and it was very difficult to use a pullaway plug for control and change between external and internal power supplies. It was therefore decided to make a switch system which was able to start the operation of the

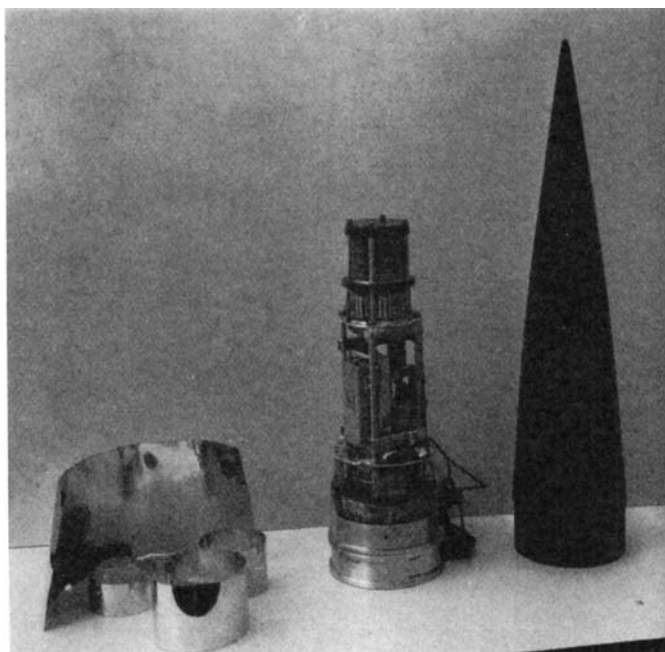


FIG. 4.3.2. Nosecone instrumentation.

probe during the expulsion of the payload from the rocket. However, the electrometer had to be connected to its power supply before start as the electrometer tubes need time for heating. A series of small microswitches were mounted on the base-plate. When the payload is packed in the cylinder, the switches are kept in the off position by two halves pushing against the base-plate. During expulsion the two halves will fall aside, and the springloaded microswitches will connect the batteries to the sawtooth voltage potentiometer, the DC motor, the thermistor circuit and the telemetry subcarrier oscillator and transmitter. The telemetry units and the DC motor have a double set of switches.

Fig. 4.3.2 is a picture of the nosecone instrumentation. The instrumentation rack is fastened to the base-plate. The base-plate also has holes for screwing on the nosecone, and holes for fastening of nylon cords. Further this unit has mountings for the telemetry antenna and operation start microswitches.

The telemetry units including batteries are placed close to the base-plate. The next section includes the potentiometer and switch unit driven by the DC motor and the electrometer.

This section is shown more in detail in Fig. 4.3.3a and b. Fig. 4.3.3a also shows the temperature transducer mounted at the lower horizontal bar and just below it is a potentiometer for regulating the DC motor speed. The glassfiber windings which can be seen on the outer edges of the horizontal decks touch the nosecone walls and keep the instrumentation centered in the nosecone.

Batteries for electrometer, DC motor and potentiometer are placed in the two front sections.

The temperature in the nosecone was expected to be quite high. Measurements done by Atlantic Research Corporation indicated air temperatures in the nosecone of about 90° – 100°C before expulsion. During these experiments, the nosecone volume had very little air circulation with the other parts of the payload and with the surrounding air. In this payload, it was decided to have air circulation between the nosecone volume and the rocket payload cylinder, which has pressure equilibrium with the surrounding atmosphere through small 2 mm diameter holes. In this way heat transport by convection will be reduced, and heat transport

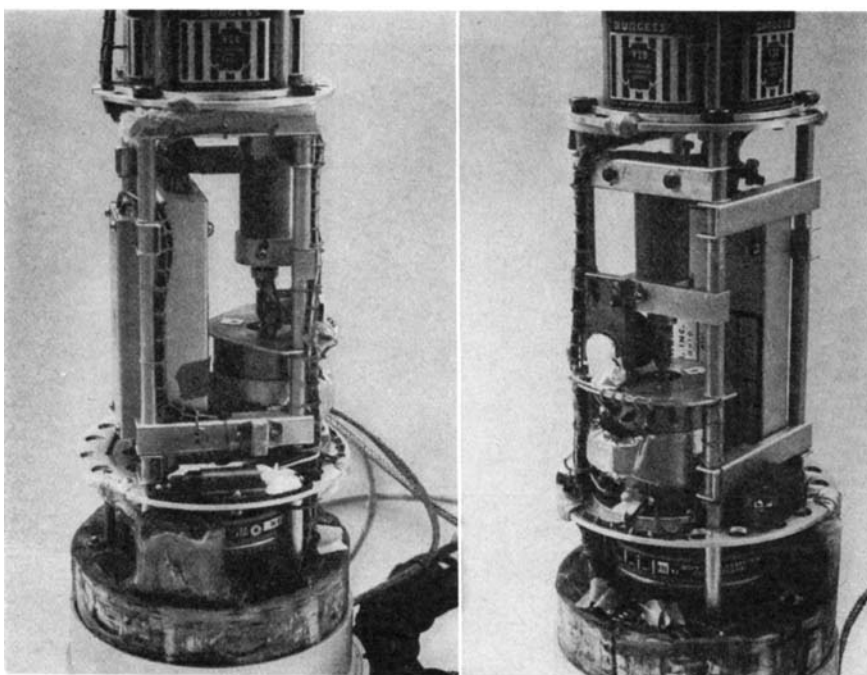


FIG. 4.3.3. Nosecone instrumentation details.

by radiation from the nosecone walls will be the main difficulty. In order to prevent some of the radiated heat to reach the instruments, aluminium foils are placed around each section of the rack, see Fig. 4.3.2. In this way the heat is conducted more directly to the whole metal body of the payload. The aluminium foils also serve as electric shielding of the instruments.

4.4. PARACHUTE

The packing volume for the parachute is about 1.4.1. On correspondence with the Schjeldahl Company in Minnesota, U.S.A., this firm agreed to make a 3.3 m diameter parachute of metallized Mylar $1.25 \cdot 10^{-3}$ mm thick. The parachute is reinforced with bands of GT 38 material, which is a Mylar material fastened to a thin nylon cord net. The top of the parachute has a circular opening of 0.3 m diameter. A torus with about 100 cm³ residual air is fastened close to the leading edge as demonstrated in Fig. 4.1.1a. This torus will have an overpressure of 3 mm Hg in vacuum, which is sufficient to help inflate the parachute after expulsion. The idea with the metallized Mylar is to help tracking of the payload during descent.

The behaviour of parachutes at high altitudes is not very well determined. BOWMAN, 1961, and JOHNSON, 1960, have reported on measurements with parachute and balloon models in a low pressure wind tunnel at subsonic and supersonic speeds. However, the information, which can be extracted from these measurements, is rather limited. The drag coefficient at high altitudes and velocities around that of the sound is very uncertain.

In order to have some feeling for the performance of a parachute descent from high altitudes and in order to know the sawtooth voltage setting for the Gerdien condenser, some calculations were done for a 3.3 m diameter parachute with a payload weight (including parachute) of 3.7 kg. These numbers refer to the system described here. Calculations of height as a function of time and velocity as a function of height were done for start of the descent from 80 and 90 km assuming that the parachute is fully inflated and moves smoothly downwards without any oscillations. Drag coefficients $c_D = 0.5$ and 1.0 have been used for the calculations. The air drag force, F_D , is found from the equation;

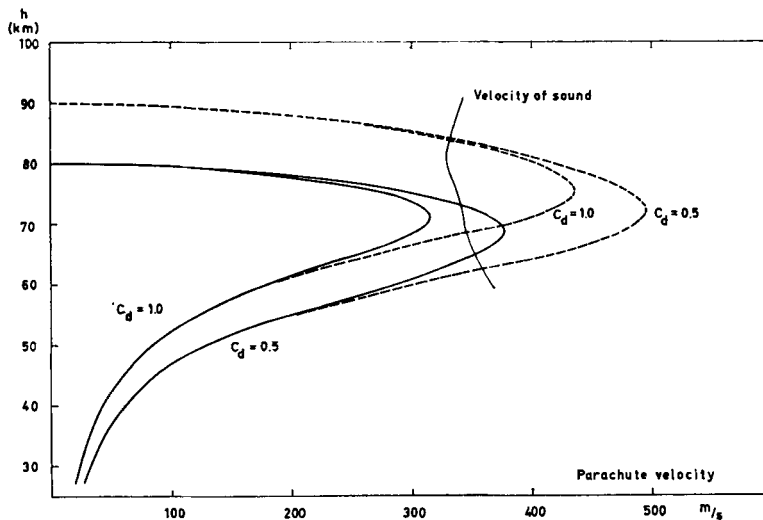


FIG 4.4.1. Calculated descents of a parachute (3.3 m diameter, total weight 3.7 kg) assuming start from 80 km and 90 km and drag coefficients 0.5 and 1.0.

$$F_D = c_D P \varrho_M \frac{v^2}{2}. \quad (4.4.1)$$

P is the projected opening area of the parachute, ϱ_M is the air density, and v is the relative velocity between the parachute and the surrounding air. A more detailed description of the procedure used in the numerical calculations of the parachute descent will be found in PEDERSEN, 1964. Fig. 4.4.1 shows the result of the calculations. It is evident that the start of the descent should not be higher than 85 km if a longer period at supersonic speeds must be

avoided. This is valid only if the drag coefficient is somewhere between 0.5 and 1.0, and the descent is smooth without oscillations. However, the parachute does certainly not descend in such a regular manner. One must suppose that the parachute has very complicated coning, oscillating and sliding movements, which are difficult to understand. These movements will influence the orientation of the Gerdien condenser during descent, and in order to have as little coupling as possible between the motion of the parachute and probe a special elongation mechanism was constructed so that the distance

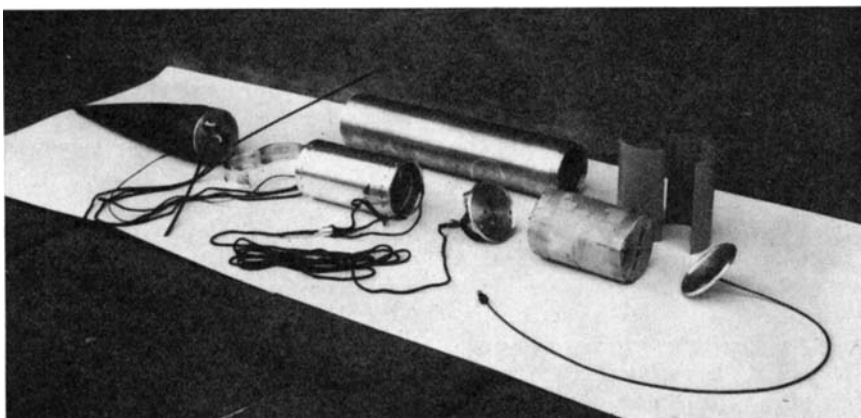


FIG. 4.5.1. Probe ready for packing.

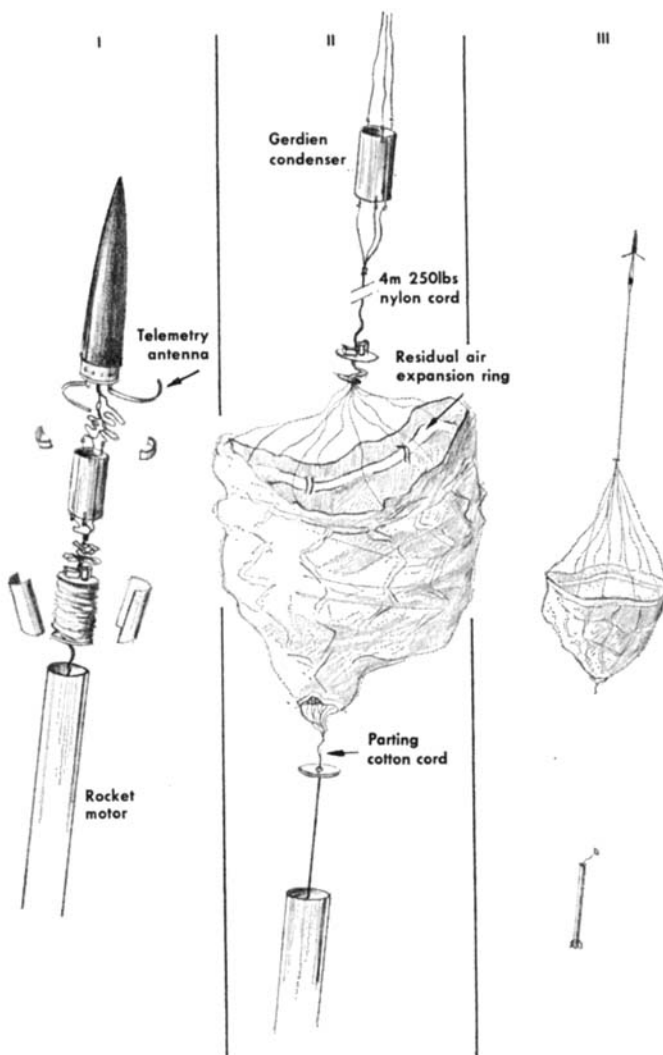


FIG. 5.1. Payload expulsion from rocket.

between parachute and probe can be made 20 m longer with a 150 lbs nylon cord.

4.5. PAYLOAD ASSEMBLY AND PACKING

A picture of the different units in the payload can be seen in Fig. 4.5.1. Three 250 lbs nylon cords of 1 m length connect the nosecone to the Gerdien condenser. Three nylon cords of the same type run from the back side of the Gerdien condenser to a ball bearing swivel which compensates for the different roll rates of the parachute and the rest of the payload. A four meter long 250 lbs nylon cord connects

this swivel unit with the front closure of the parachute pack where also the parachute shroud lines are fastened.

The parachute with the back and front closures and the Gerdien condenser are first packed in the rocket cylinder, and pins are placed through the rocket cylinder in the front of the Gerdien condenser to keep the Gerdien condenser and the parachute pack in the right position when doing adjustments on the nosecone instrumentation before launching. The procedure before launching includes telemetry check and plug-in of electrometer batteries and

balancing of the electrometer. The next step is to screw on the nosecone, roll up the antenna, the nylon cords and the cable line inside the two halves before sliding the nosecone and the two halves into the rocket cylinder. With the nosecone pressed down into the rocket cylinder, three holes are drilled for shear pins through the rocket cylinder into the nosecone base-plate. When the shear pins have been pressed into the base-plate, the pins in front of the Gerdien condenser are removed, and the holes left in the rocket cylinder from these pins serve as vent holes.

5. Separation of payload from the rocket

The expulsion of the payload from the rocket is started by the charge acting on the back closure of the parachute pack. The shear pins in the nosecone base-plate are broken, and the payload is pushed out of the rocket cylinder at a speed of approximately 10 m/s. With the standard Arcas expulsion charge, the time for expulsion will be 130 seconds after start. When using an ARC Booster Arcas which reaches top altitude 140–160 seconds after start, the expulsion will take place before reaching the top altitude. Fig. 5.1 is a sketch of the separation of the payload from the rocket. After expulsion, the payload is stretched out as the back closure is linked to the rocket motor, and the top of the parachute is connected with a parting cotton cord to the back closure. The parting cotton cord will break at 4 lbs loading, and the payload is free from the rocket.

We will consider the possibility of the rocket hitting the parachute after separation. The parachute will be retarded after separation due to drag forces, and the rocket motor being less influenced by the drag forces may overtake

the parachute. For a flight angle of 83° , the horizontal velocity after rocket burn-out will be approximately 130 m/sec. The vertical velocity will be of the same order of magnitude when the expulsion of the payload takes place 130 seconds after start. If the rocket has a vertical velocity v_0 just before expulsion, the vertical velocities of the payload and the rocket just after expulsion will be

$$v_1 = v_0 + \frac{m_2}{m_1 + m_2} v_e \quad (5.1.1)$$

$$v_2 = v_0 - \frac{m_1}{m_1 + m_2} v_e \quad (5.1.2)$$

m_1 = parachute payload weight (3.7 kg)

m_2 = burnt-out rocket motor weight (10.7 kg)

v_e = payload expulsion velocity.

The difference in apogee altitude for the payload and the rocket motor cylinder Δh can easily be calculated for the case when we neglect the drag forces.

$$\Delta h = \frac{1}{2g} (v_1^2 - v_2^2) \approx \frac{1}{g} \frac{m_2 - m_1}{m_1 + m_2} v_0 v_e. \quad (5.1.3)$$

The influence of the drag forces in retarding the parachute payload can be calculated for different expulsion heights and different rocket velocities at the moment of expulsion. The result of the calculation is given in Table 5.1. The Δh values obtained when we neglect drag forces on the parachute are first given for different values of v_0 to be expected during expulsion. The influence of drag on the parachute becomes critical for expulsion heights below 70 km and rocket velocities higher than 100 m/sec during expulsion. In this case the rocket may

TABLE 5.1. *Height difference Δh between parachute payload and rocket motor cylinder at apogee altitude.*

Expulsion height	Rocket velocity at the moment of expulsion m/sec				
	$v_0 = 50$	$v_0 = 100$	$v_0 = 150$	$v_0 = 200$	$v_0 = 250$
∞ , no drag	25 m	50 m	75 m	100 m	125 m
90 km	24.96 m	49.3 m	71.7 m	90 m	100 m
80 km	24.75 m	46 m	54 m	44 m	c
70 km	24 m	30 m	c	c	c

c = Collision possible.

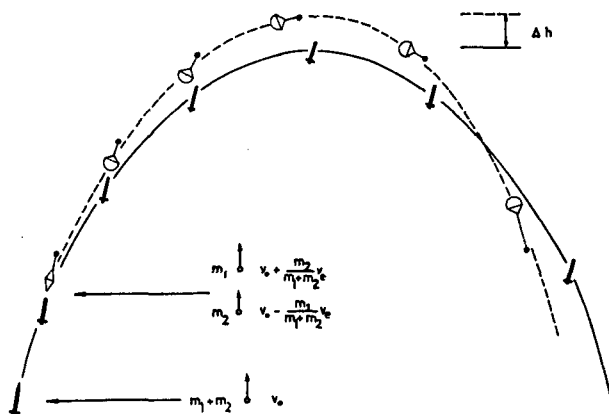


FIG. 5.2. Rocket and parachute trajectories after expulsion.

overtake the parachute payload and rip the parachute. The horizontal velocity of the rocket will, however, be of some help. The parachute will be retarded more than the rocket motor cylinder, and the horizontal separation between these two units should be sufficient even at steep flight angles to prevent the rocket motor cylinder from hitting the parachute. Fig. 5.2 demonstrates the behaviour of the parachute payload and the rocket motor cylinder after expulsion. It can be shown that the time for the parachute to swing into an angle tangential to the trajectory is of the order of 10 seconds for expulsion between 80 and 90 km height. PEDERSEN, 1964.

6. Aerodynamic flow behind a rocket nosecone

The aerodynamic flow conditions behind the rocket nosecone during the descent of the payload are of importance for the Gerdien condenser ion measurements as the Gerdien condenser is placed in the wake 1 m behind the rocket nosecone. In order to clarify the problems in connection with the flow behind the nosecone, Mr. S. G. Hedman at the Aeronautical Research Institute of Sweden was asked to give an orientation of the problem, and if possible present calculations of the wake behind the nosecone. A preliminary calculation of the velocity of a parachute payload during a descent from 100 km was done. At the time of this calculation, neither the exact payload weight nor the parachute dimensions were known, and the

calculations were done assuming the most probable numbers and a drag coefficient of 1.0 for the parachute. The result of this calculation can be seen in Fig. 6.1. If this figure is compared with more exact calculations of the parachute payload descent, see Fig. 4.4.1, we find that the velocities during descent as given in Fig. 6.1 are satisfactory for the aerodynamic flow considerations, which must necessarily include several approximations. What will be said in the following is referred to Mr. Hedman's paper, HEDMAN, 1963. Fig. 6.1 is copied from this report, and Fig. 6.2 and 6.3 are based on calculations in the same report.

In order to find out the principal features of the aerodynamic flow behind the nosecone, the velocity profile of the nosecone has been plotted in a Mach number—Reynolds number diagram, which can be divided into different flow regimes after TSIEN (1946). This plot is shown in Fig. 6.1. It can be seen that during the main part of the descent slip flow conditions characterized by surface air velocities different from zero are dominating. Below 50 km the flow is of the continuum type. The flow in the wake behind the nosecone most probably is laminar above 40 km. It has been assumed that Navier Stokes equations describe the flow conditions in the slip flow and continuum flow regimes. Three equations have been used for calculations of the wake behind the rocket nosecone. The result of these calculations have been summed up in Fig. 6.2 and 6.3. Fig. 6.2 shows the velocity distribution in the wake at different altitudes. The lines demonstrate shells

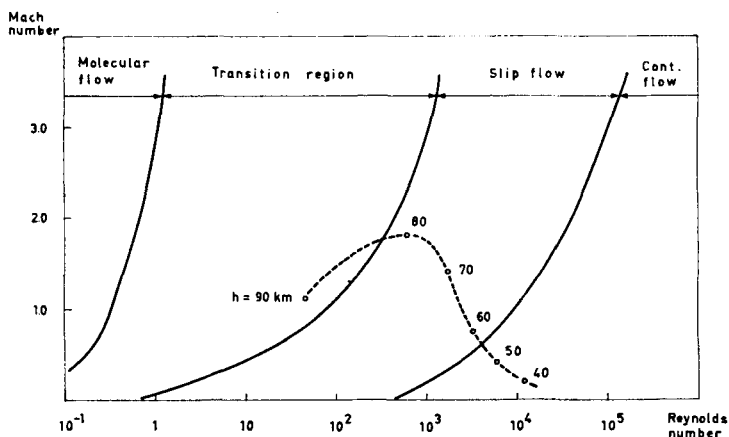


FIG. 6.1. Aerodynamic flow regimes for the probe during the descent.

of rotation, where the velocity of air is 0.25, 0.5, and 0.75 of the free flow velocity. The wake will be more concentrated in a narrow cylinder behind the nosecone at low altitudes. Based upon the velocity distributions for the wake, the amount of air passing per second through a cylinder of the same diameter as the rocket nosecone has been calculated for different distances behind the rocket nosecone. This flow of air, Q , has been compared with the free flow of air in an undisturbed atmosphere Q_∞ and the ratio Q/Q_∞ has been plotted in Fig. 6.3 as a function of height for distances 0.5 m and 1.0 m behind the nosecone.

The ratio Q/Q_∞ gives the flow of air at the entrance of the probe for a smooth vertical descent, when the nosecone and the Gerdien condenser axis both are vertical. The distance of 1.0 m behind the nosecone corresponds to the actual payload configuration. In order to obtain a correct picture of the flow through the Gerdien condenser, it is necessary to consider the influence of the Gerdien condenser on the wake, and also consider the flow resistance inside the cylinder. This has not been done in this calculation.

The calculations referred to above have at least given a qualitative picture of the flow conditions to be expected in the probe. It is necessary, however, to consider what effect the pendling motion of the probe hanging under the parachute may have on the flow through the Gerdien condenser. If the nosecone and the Gerdien condenser have an angle of $\varphi = 10^\circ$ off

vertical, and the descent velocity for the whole payload including parachute is vertical, the wake will pass beside the Gerdien condenser, even at high altitudes, when the wake is more broad behind the nosecone. The effective open-

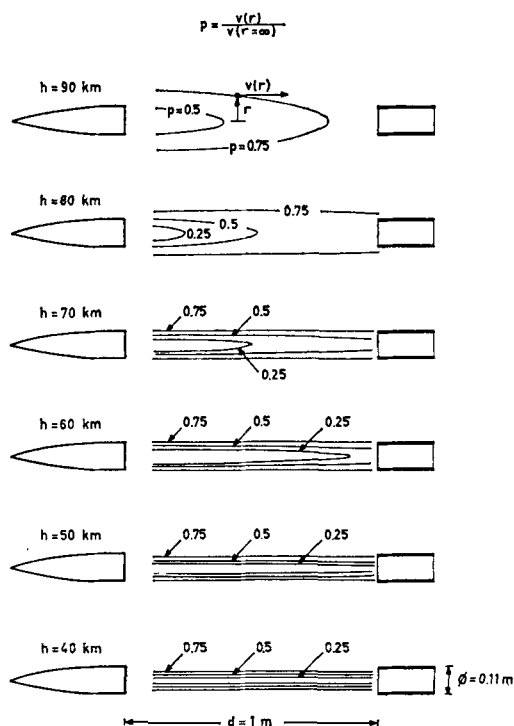


FIG. 6.2. Air stream velocity in the wake behind the nosecone compared with free air stream velocity.

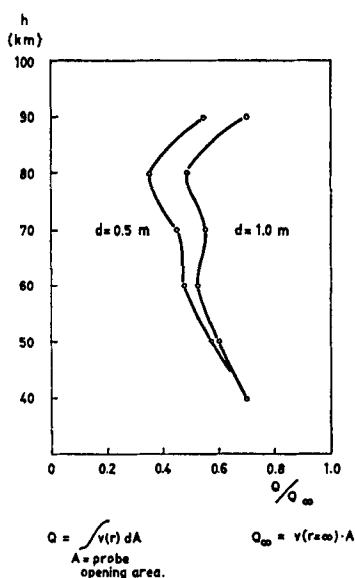


FIG. 6.3. The ratio between air flow at the Gerdien condenser opening in the wake and in free flow at different altitudes.

ing area of the Gerdien condenser normal to the air flow will in this case be 0.985 of the opening area for $\varphi = 0^\circ$. As a free undisturbed flow exists at the front of the probe in this case only the flow resistance inside the probe and front effects must be thought of. These effects are not probably dominating, and the flow through the probe in this case is close to free flow. When the nosecone and the Gerdien condenser is pendling at large angles φ , the situation will be more complicated. The wake will be seriously different from the model calculated above, and the conditions at the Gerdien condenser opening will not be well defined. One can expect that air flow conditions in the probe are well defined up to values of $\varphi = 30^\circ$. Still the Gerdien condenser opening area is 0.870 of the area for $\varphi = 0^\circ$, and the wake should not be much different from the calculated model.

7. Rocket measurements at White Sands Missile Range

7.1. ARRANGEMENTS FOR ROCKET LAUNCHINGS AT WHITE SANDS

The Gerdien condenser experiments were from the beginning planned for a D-region study in the auroral zone, or close to the auroral zone. Rocket launchings were planned to take place

at a rocket test range in northern Sweden. It turned out, however, that this field, which was the only field available in Sweden, was too small for firing a Booster Arcas as this rocket has a considerable wind sensitivity and spread of the impact points.

On contacts between NASA and the Swedish Space Committee, which is the sponsor of the Gerdien condenser project, arrangements were done for a cooperative program between NASA and the Swedish Space Committee. NASA should request all the launch facilities as telemetry reception, tracking and launch pad work at White Sands Missile Range, and Uppsala Ionospheric Observatory should be responsible for two Gerdien condenser payloads and two Booster Arcas rockets.

These two rockets were fired at White Sands on 8 and 10 October, 1963. As a prolongation of the cooperative program, another experiment using the Gerdien condenser payload was done on 13 December, 1963. In this experiment, NASA sponsored the Booster Arcas rocket and made arrangements for the launch facilities at White Sands. The Uppsala group was responsible for the payload.

7.2. ROCKET AND PARACHUTE SYSTEM PERFORMANCE

When arriving in the United States for the October launchings, information was obtained at Atlantic Research Corporation in Alexandria, Virginia, and at the Meteorology Rocket group at White Sands that new experiments had indicated that the expulsion charge of the Arcas was burning much too fast. Payload shocks of the order of 500–1000 g for approximately 1 m sec were measured during expulsion. In order to give the instrumentation in the rocket nosecone a chance to survive, it was mounted on four teflon washers. The distance tubes of the instrumentation rack close to the base-plate were shortened and replaced by the four teflon washers, 3 mm thick.

The rockets were all fired at launch angles of 82° – 83° and they all reached peak altitude without serious malfunctions. However, the spread of the peak altitudes obtained was very pronounced as can be seen in Fig. 7.2.1, which is a plot of the height as a function of time for the rocket ascents and parachute descents. Trajectory data for both rockets and parachutes were obtained with the tracking radar system

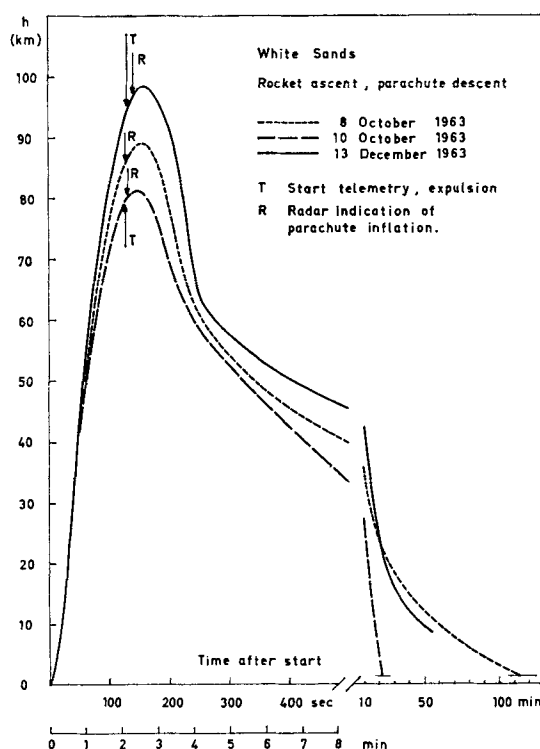


FIG. 7.2.1. Rocket ascent and parachute descent for three experiments at White Sands.

at the Missile Range. Parachute inflation and elongation of the line between parachute and probe could be followed by the radar.

The peak altitude of the first shot on 8 October was close to 89 km. The radar reported parachute inflation and operation of the elongation mechanism, but no telemetry signal was received from the rocket. Three quarters of an hour after launching, the parachute could be spotted in the clear sky from a recovery truck, which was going out to pick up the payload. As can be seen in Fig. 7.2.1, the parachute hit the ground one hour and fifty-five minutes after launching. The winds were very favourable for recovery, and the parachute landed about 20 km from the launch pad. On the first inspection of the payload, it was found that the telemetry antenna was broken, and only small stubs were left of the beryllium copper springs. In a later control, it was found that the whole instrumentation had been operating normally during the descent. Both electrometer and telemetry equipment were in perfect condition. It

was rather difficult to see the reason for the antenna to be broken, but after a study of the surfaces of fracture and by doing some strength tests with the antenna, it was concluded that the antenna was broken during expulsion because of the high spin rate of the rocket. When the antenna springs, which are rolled up in the rocket cylinder, are released during expulsion, they will try to straighten to full length, but as their moment of inertia is increased, they cannot keep up with the rocket angular velocity, and are bent opposite to the direction of the spin.

During the payload construction period, information was obtained that a Booster Arcas could have a minimum spin of 8–10 rps by adjusting the rocket fins. The normal fin setting gives the rocket a spin of 25–30 rps. The two Booster Arcas rockets delivered to White Sands had the normal fin setting, and we learnt that this could not be changed at White Sands, but had to be done during the rocket construction. The unexpected high spin rate most certainly caused the antenna to break.

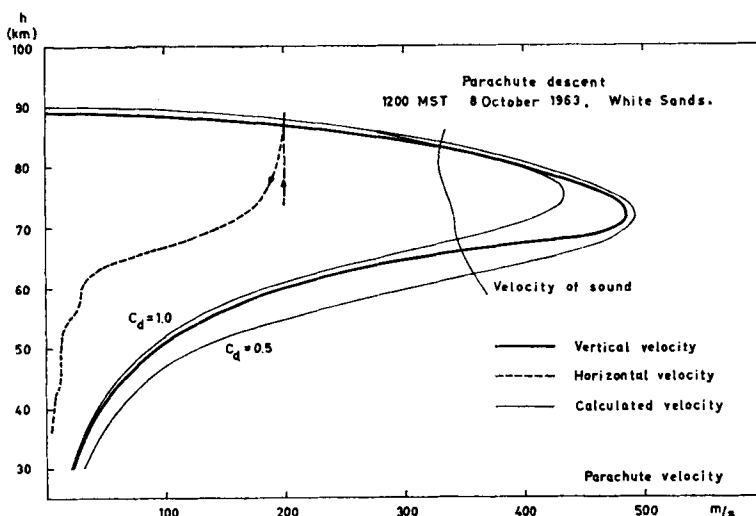


FIG. 7.2.2. Parachute velocity as a function of height, 8 October 1963.

The parachute was in good condition when hitting the ground. Some burnholes from the expulsion charge could be seen on the Mylar material, and the torus containing residual air for parachute inflation was punctured by two holes, each of 1 cm^2 size. It is uncertain, whether this put the torus out of operation or if the torus still could help inflate the parachute. The vertical velocity of the parachute payload is shown in Fig. 7.2.2 together with calculated curves for descent from 90 km (see Chapter 4.4) for the drag coefficient $c_D = 0.5$ and $c_D = 1.0$. It can be seen that the velocity is close to the curve for $c_D = 0.5$ in the upper part of the descent, and gradually comes very close to the curve for $c_D = 1.0$ in the lowest part. This certainly means that the parachute has a drag coefficient of about 1.0 below 60 km, which is a typical drag coefficient for a good parachute. As very little is known about parachutes at higher altitudes, it is difficult to tell, if the descent at altitudes above 60 km can be interpreted as a reduction of drag coefficient to a value between 1.0 and 0.5, or if the parachute is only partly inflated at these altitudes. The horizontal velocity of the parachute is also plotted in Fig. 7.2.2. This curve indicates that the horizontal deceleration of the payload takes place at the same time as the vertical deceleration, and the horizontal wind jets at low altitudes are negligible.

For the second shot, which took place on 10

October, the antenna was reinforced and the parachute was repacked in the rocket cylinder with extra protection. The peak altitude for this shot was 81 km and just before reaching peak altitude, both telemetry receiving stations and radars reported expulsion of the payload. As can be seen in Fig. 7.2.1, the telemetry signal was picked up about 6 seconds before the radar could observe the parachute inflation. This gives approximately the time between expulsion and parachute inflation. Data were obtained from about 70 km down to 30 km.

The vertical velocity of the payload is shown in Fig. 7.2.3 together with calculated curves for descent from 80 km. The parachute behaved similar to the first parachute down to 55 km. Around this altitude, the payload started to deviate from the calculated velocity, and the payload hit the ground after 22 minutes, approximately 40 km from the launch pad. After an excellent job by the radar people, the impact point was determined, and the parachute was spotted from a helicopter and later recovered by a truck. The following payload inspection revealed that the parachute had hit the ground like a streamer. The elongation mechanism had not worked and was distorted. The central electrode was also slightly distorted.

Inspection of the payload lead to the following explanation being the most probable. The parachute was packed rather hard in the rocket cylinder because of the extra protection added

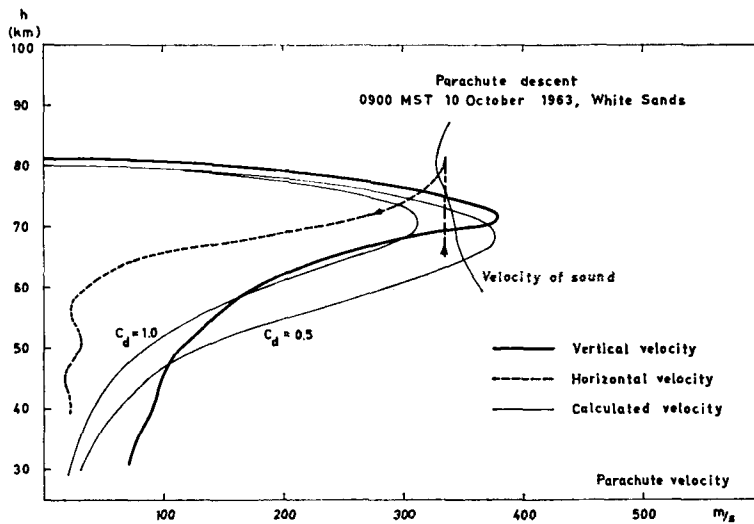


FIG. 7.2.3. Parachute velocity as a function of height, 10 October 1963.

to the parachute cover. During the expulsion, the parachute pack was jammed in the cylinder, and the expulsion charge blew up the back closure. The force of the charge was then transmitted through the parachute pack and broke the front closure and distorted the elongation mechanism, as well as the central electrode of the Gerdien condenser. Metal pieces from the back closure most probably penetrated the parachute pack leaving a number of holes all over the parachute surface. These holes caused no serious damage to the parachute at high altitudes, but when the drag forces increased deeper in the atmosphere, the holes caused a stripping of the parachute until only the reinforcement bands were left.

Also this nosecone instrumentation was found in perfect condition after the impact into a sand dune.

Before the third firing, the parachute was repacked to a smaller diameter, and a new torus with residual air was placed on the parachute. The parachute was protected with a cotton cover, and more space was made for the parachute by shortening the Gerdien condenser. A new antenna was made from laminated steel springs. The rocket used for this launching had a reduced spin of 8–10 rps. From Fig. 7.2.1 and 7.2.4, it can be seen that the rocket reached a peak altitude of 99 km. The telemetry started and indicated expulsion some 4 km before the peak, and about 10 seconds

later the radar reported parachute inflation. The elongation could be observed about 30 seconds after expulsion. In this flight, it is quite certain that the torus with residual air caused the inflation as the drag forces at the altitude of expulsion were negligible. One must expect, however, that the centrifugal force caused by the payload spin contributed to the inflation. Because of the high altitude of the rocket, the descent was very close to a free fall down to about 80 km when the drag forces in the more dense atmosphere reduced the velocity. The deceleration was very pronounced between 70 and 65 km and of the order of 3–4 g. During this period, the transmission of current-voltage characteristics from the Gerdien condenser was interrupted. The telemetry transmitter continued its operation, but an analysis of the output of the electrometer amplifier indicated that the electrometer had an open input circuit, i.e. the cable line between the Gerdien condenser and the nosecone was most probably broken during the twisting and stretching of the lines, which most certainly took place during the deceleration period.

The curve for the vertical velocity during descent shown in Fig. 7.2.4 is remarkable in that it shows velocities lower than the calculated curve for $c_D = 1.0$. When the horizontal velocity was plotted for this flight, it was found that strong horizontal winds caused the parachute to drift sideways below 60 km at velocities

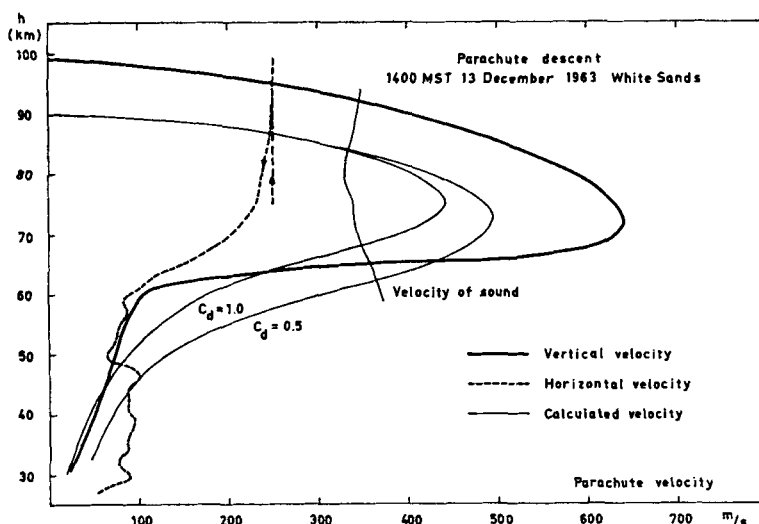


FIG. 7.2.4. Parachute velocity as a function of height, 13 December 1963.

close to 100 m/sec. The effect of this horizontal wind most probably was to produce an air flow pattern around the parachute, which resulted in an upward force acting on the parachute. Below 45 km the descent was very close to the calculated curve for $c_D = 1.0$.

The strong horizontal winds caused the parachute payload to drift far to the east, and telemetry signals and radar tracking were lost before the payload hit the ground some 170 km from the launch site on the other side of the mountains east of White Sands. It was foreseen that this payload should disappear as high altitude wind jets are more dominant in the winter months than in the autumn.

7.3. PAYLOAD OSCILLATIONS DURING DESCENT

It was expected that the payload hanging under the parachute should oscillate during the descent. Some information was obtained from the field strength data of the telemetry transmitters on the flights of 10 October and 13 December. In the first of these flights, the elongation mechanism was destroyed, and the line between the probe and the parachute shroud lines was only 4.5 m long. For both flights, the period of oscillations as seen on the field strength record was of the order of 5–10 seconds for the first 100 seconds of the descent changing to a period of 0.5–2 seconds for the rest of the descent. The information obtained

in this way was not satisfactory, and for the last flight of 13 December arrangements were done to get amplitude gain control records from the radar in order to see parachute motions, and a very simple direction sensor was fastened to the nosecone base-plate.

The direction sensor was made from two light sensitive semiconductor diodes, which were shielded so that they were activated only when sunlight was coming into the solid angles Ω_1 and Ω_2 in Fig. 7.3.1. The voltages from the diodes (0.4 V) were sampled in two successive 50 msec intervals for each turn of the switch unit in the nosecone (see Fig. 4.3.1a and b). In this way, a very short information about the nosecone direction relative to the sun was obtained once each 2.5 seconds. By analysing the amplitude of the signals from the two diodes, the deviation of the nosecone from the vertical direction can be found. A plot of this deviation is also shown in Fig. 7.3.1, and it can be seen that the nosecone seldom is more than 30° off the vertical direction. Even if the plot is based on data sampled at intervals, this result is valid for the whole descent period as the time of observation is independent of the swinging motion, and the observation points are numerous.

For the Gerdien condenser experiments, the direction of the Gerdien condenser and not the nosecone is of interest. One must expect, how-

ever, that the deviation from the vertical direction for the Gerdien condenser is the same, or smaller than that for the nosecone.

For the flight of 10 October with a shorter line between parachute and payload, one must expect that the oscillations were more pronounced.

7.4. NOSECONE INSTRUMENTATION TEMPERATURES

During the two flights of 10 October and 13 December, information about the surface temperature at the instrumentation rack in the nosecone was obtained with the thermistor transducer described in Chapter 4.3. The results of these measurements are shown in Fig. 7.4.1. In a control of the thermistor used in the first flight, it was found that it had a poor isolation to ground. This caused irregular data about 400 seconds after start. The curve of 13 December looks more like the one expected. The temperature rises to about 52°C, and is then reduced as the heat is radiated and conducted from the payload into the more dense atmosphere. The higher temperature of the first flight may be caused by higher air temperature before start (25°C on 10 October, 15°C on 13 December).

7.5. MEASUREMENTS OF ION CONDUCTIVITIES AND CONCENTRATIONS

From the foregoing description, it can be inferred that Gerdien condenser data were obtained between 30 and 70 km height in the flight which took place at 09^h00^m MST on 10

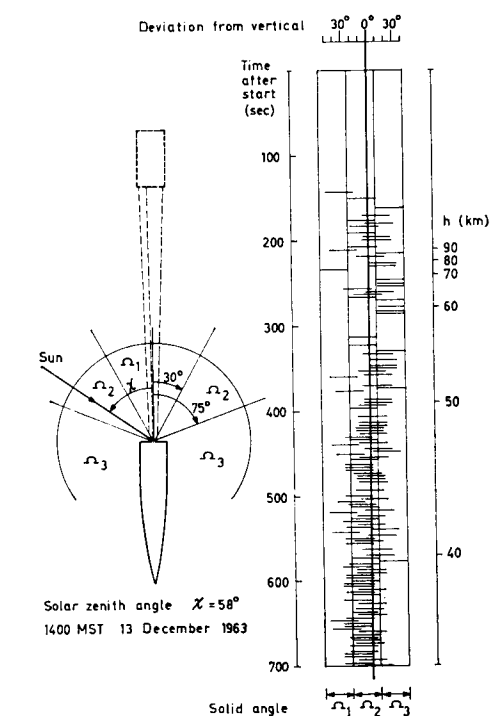


FIG. 7.3.1. Measurement of nosecone oscillations with two photodiodes sensitive for sun in solid angles Ω_1 and Ω_2 respectively.

October 1963, and additional data were obtained between 70 and 99 km for the flight 14^h00^m MST on 13 December 1963. The data obtained above 80–85 km height in the latter

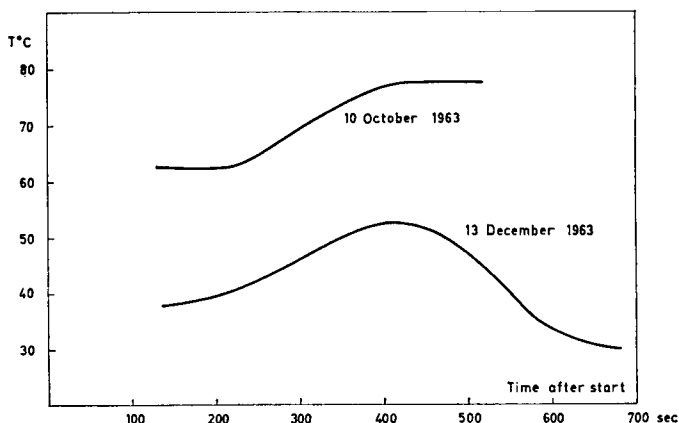


FIG. 7.4.1. Measurements of nosecone instrumentation surface temperatures.

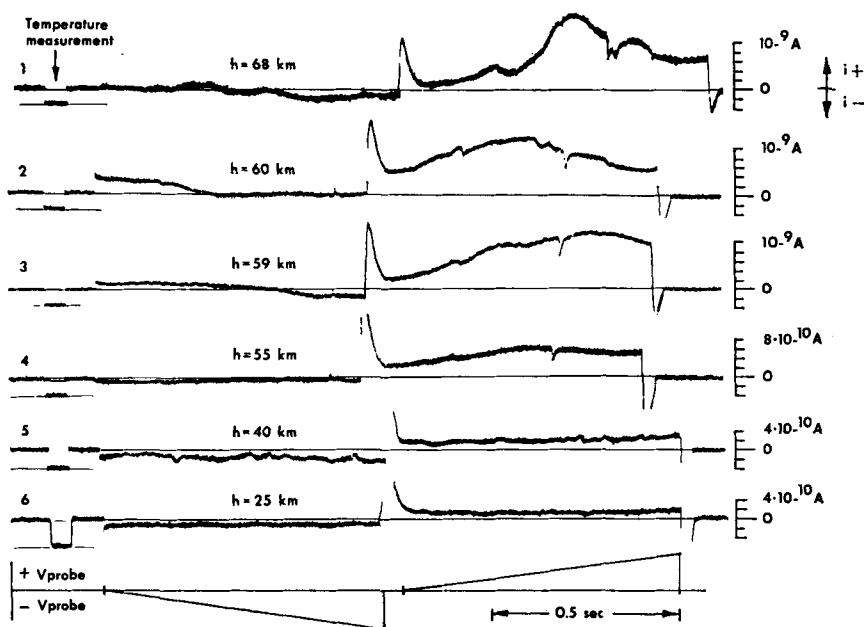


FIG. 7.5.1. Some examples of Gerdien condenser current-voltage characteristics obtained during the flight of 10 October, 1963.

experiment cannot be interpreted using the simple Gerdien condenser theory. The saturation current to the collector will, however, give some information about the ion concentrations.

Before giving the results of the measurements, it is necessary to mention some effects, which influence the measurements.

Displacement current

When sweeping the voltage to the central electrode in the Gerdien condenser, a displacement current will go to the electrometer. This current is given by the equation

$$i_d = C \frac{dV}{dt} \quad (7.5.1)$$

C = capacity between central electrode and electrometer input

$\frac{dV}{dt}$ = constant for a sawtooth voltage sweep.

The displacement current was calibrated before flight and reached a maximum of $\pm 1.3 \cdot 10^{-10}$ A for the peak of the sawtooth voltage being ± 28 V for the latter part of the descent. Fig. 7.5.1 is a copy of parts of the strip chart

record from the flight of 10 October showing the electrometer current for the negative and positive voltage sweep, respectively. At 25 km, when the ion current to the collector electrode in the Gerdien condenser was very small, only the displacement current was left. As the displacement current was in agreement with the preflight calibration, it was concluded that both the sawtooth voltage generator and the electrometer were operating normally. Every measurement during the descent was corrected for displacement current, using the values obtained in the preflight calibration.

Space charge effect

If ions of one polarity are collected more quickly in the Gerdien condenser than the other polarity, a space charge will be present between the electrodes of the Gerdien condenser. The effect of this space charge is to produce an additional electric field near the collector, and in this way influence the collector ion current. At high altitudes above 70 km, it is expected that positive ions and electrons are the dominating charged particles. As the electrons have a very high mobility, they are easily caught by

the electric stray field between the central electrode and the outer cylinder. The positive ions will follow the air stream into the Gerdien condenser, where they represent a space charge. SIKSNA & LINDSAY, 1959, have discussed the effect of a uniform space charge in a cylindrical condenser, Poisson's equation,

$$\frac{d^2 V}{dr^2} + \frac{1}{r} \frac{dV}{dr} = - \frac{N^+ e}{\epsilon}$$

can be solved resulting in the following equation for the space charge electric field,

$$E(r) = \frac{N^+ e}{2\epsilon} \left(r - \frac{r_o^2 - r_i^2}{2r \ln(r_o/r_i)} \right) \quad (7.5.2)$$

r_o = radius of outer cylinder (5.0 cm)

r_i = radius of inner cylinder (0.4 cm)

$\epsilon = 8.85 \cdot 10^{-12}$ Fd/m.

The electric field produced at the outer cylinder (collector) by some typical space charges has been calculated and is shown in Table 7.1.

The maximum of the sawtooth voltage is approximately 7 V at the start of the descent increasing to 28 V in the lower part of the measuring range. This corresponds to electric fields at the collector of 55 V/m and 220 V/m, respectively. Consequently it can be seen that the space charge will only influence the measurements in the upper part of the measuring range, where electron densities of the order of 10^4 – 10^5 cm $^{-3}$ can cause positive ion space charges of the same order of magnitude in the Gerdien condenser if electrons are removed from the air flow at the opening of the Gerdien condenser. In Fig. 7.5.1, it can be seen that for some of the records (60 km and 59 km), the current is positive for the first part of the negative voltage sweep, when particles of negative charge are expected to go to the collector resulting in a negative current in the electrometer. This effect may be caused by a positive space charge. From what was recently said about the order of magnitude of the space charge effect, it is hard to see, however, that a space charge can be the only reason for the positive current during the negative voltage sweep. This assumption is supported by the fact that the electrometer current during the negative voltage sweep sometimes shows the effect mentioned above and sometimes not. The

TABLE 7.1

N^+	$E(r_o)$
10^3 cm $^{-3}$	0.5 V/m
10^4 cm $^{-3}$	5 V/m
10^5 cm $^{-3}$	50 V/m

explanation probably is that a photo current caused by solar ultraviolet radiation and varying with the swinging motion of the payload is present in the Gerdien condenser.

Photo effect

Electrons will be kicked off the metal surfaces of the probe when it is irradiated by solar ultraviolet light and solar X-rays. The outer cylinder of the Gerdien condenser, which is connected to the metal parts of the nosecone is the reference potential and will be at a potential, which represents equilibrium between currents to and from this body. The difference between the reference potential and the potential of the surroundings is supposed to be less than 1 V.

When the direction of the Gerdien condenser is such that solar radiation hits the collector, electrons will be released, and some of these electrons may be drawn out of the cylinder by the air flow. It will then be a need for a negative current to the collector to balance this effect, and part of this negative current may pass from the reference potential through the electrometer to the collector, in this way causing a positive current reading of the electrometer.

Contact potential

The contact potential between the central electrode in the Gerdien condenser and the collector was measured and found to be less than 0.1 V.

After this survey of the effects, which are to be expected when doing a Gerdien condenser measurement in the upper atmosphere, it should be more easy to understand the copies of strip chart records in Fig. 7.5.1. As can be seen from this figure, the revolution of the small DC motor has changed somewhat during the measurements. The pulses, which can be seen between the negative and positive voltage sweeps, are caused by the filter between the potentiometer and the central electrode of the probe. The

current to the collector is rather irregular, because of the swinging motion of the probe, but good information about the current-voltage characteristics can all the same be obtained by thoroughly analyzing the numerous sweeps. It is a characteristic feature that the positive current reaches a maximum and then decreases at the end of the sweep. This is most probably caused by the stray field between the central electrode and the outer cylinder, which collects some of the positive ions and leads them directly to metal parts, which represent the reference potential. It was difficult to foresee this effect in the laboratory experiments, because heavy ions present in the ground level experiments masked this decrease of small ion current.

Ion concentrations derived from measurements

Fig. 7.5.2 shows the ion density profiles derived from the current-voltage characteristics obtained in the measurements of 10 October and 13 December. Ion concentrations have been calculated both from approximations of saturation currents and from the conductivity measurements, i.e. the use of the current-voltage characteristics. From equations (1.2.5) and (1.2.6) we find,

$$N^{\pm} = \frac{1}{ec/\epsilon k_{\pm}} \left(\frac{di}{dV} \right)_{\pm} \quad \text{for } V < V_0 \quad (7.5.3)$$

$$N^{\pm} = \frac{i_{0\pm}}{e v_x \pi r_0^2} \quad \text{for } V > V_0. \quad (7.5.4)$$

Equation (7.5.3) has been used for calculation of the ion concentrations assuming that the mobility is given by the equations,

$$k_{+} = k_{0+} \frac{p_0}{p} \left(\frac{T}{T_0} \right)^{\frac{1}{2}} \quad (7.5.5)$$

$$k_{-} = k_{0-} \frac{p_0}{p} \left(\frac{T}{T_0} \right)^{\frac{1}{2}} \quad (7.5.6)$$

$$k_{0+} = 1.8 \cdot 10^{-4} \frac{\text{m}^2}{\text{V sec}}$$

$$k_{0-} = 2.3 \cdot 10^{-4} \frac{\text{m}^2}{\text{V sec}}.$$

The k_{0+} and k_{0-} values have been taken from a survey given by SIKSNA & WESTERMARK, 1961. T_0 , k_0 , and p_0 are ground level values of tem-

perature mobility and pressure. Values for p and T have been taken from the ARDC 1959 Model Atmosphere.

Equation (7.5.4) has been used for calculation of ion concentrations from the saturation current. The effective opening of the Gerdien condenser for the air flow was assumed to be the same as the geometrical opening area, πr_0^2 . Further it was assumed that the air flow velocity in the condenser was between half and equal to the free air flow. This uncertainty of air flow velocity is demonstrated in Fig. 7.5.2 by marking the ion density value with a line. The disturbance from what is believed to be a photo effect and partly a space charge effect will cause some uncertainty in the determination of saturation current. This is not so important for determination of the positive ion saturation current, which is large compared with this disturbance, as for determination of the negative saturation current. Because the interpretation of the disturbance effect is rather uncertain, the negative ion concentrations have been plotted in two ways. First the saturation current is assumed not to be influenced by any space charge or photo effect (dotted line). In the cases where a disturbance effect can be observed for example in the record from 60 km in Fig. 7.5.1, the saturation current is supposed to be the difference in current for $V=0$ and $V=V_{\max}$ (wavy line).

Independent of what is the right interpretation, it can be seen that the concentration of small negative ions is about one order of magnitude below the concentration of small positive ions between 45 and 70 km height.

The measurements on 13 December gave no results below 70 km. The current-voltage records looked similar to that from 60 km in Fig. 7.5.1 only that the disturbance effect, which can be seen in this record, was much more pronounced. This can be explained as an increase of solar ultra-violet radiation and also as an increase of the space charge effect because of more electrons being present at higher altitudes. Because of the uncertainty in the negative ion current readings, they were considered of no value, and only positive ion concentrations were derived. The values of positive ion concentrations close to 100 km were derived from saturation current readings, which were smooth and well defined. It can be seen in Fig. 7.5.2 that these values are in agreement with the

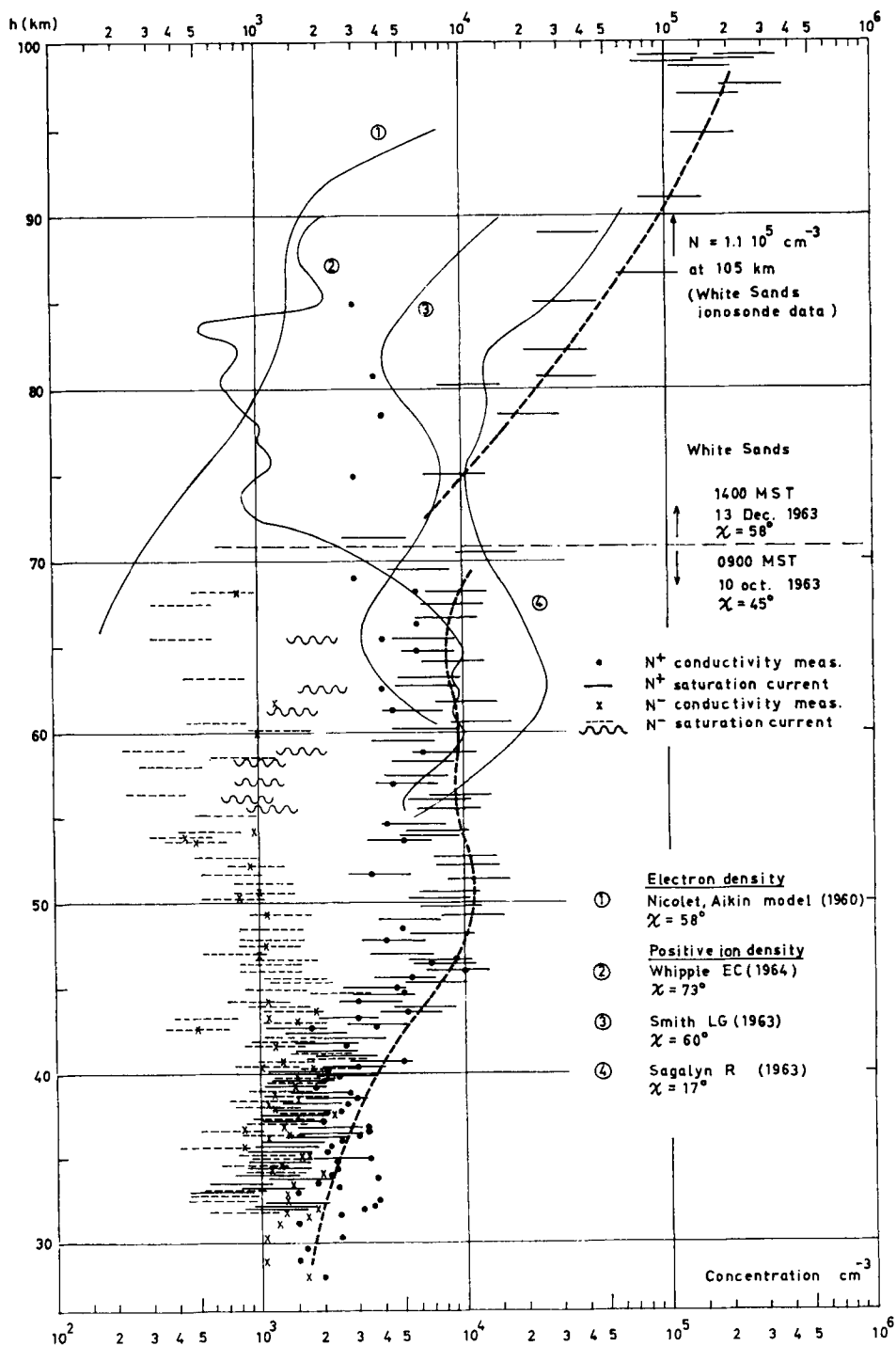


FIG. 7.5.2. Ion concentrations derived from the Gerdien condenser current-voltage characteristics of 10 October and 13 December 1963, compared with other experiments.

ionosonde observations of the *E*-layer at White Sands. The *E*-layer was observed at a virtual height of 105 km and with a critical frequency of 3 Mc/s, which corresponds to an electron concentration of $1.1 \cdot 10^8 \text{ cm}^{-3}$.

With reference to Chapter 2.3, it is evident that the simple formula (7.5.3) does not hold for the upper part of the measuring range. E/p -values of the order of 100 V/cm mm Hg will be obtained in the probe above 60 km, and it can be seen that the positive ion concentrations derived from conductivity measurements are smaller than the saturation current measurements in this height range. This is in agreement with what is said about variation of mobility with E/p in Chapter 2.3.

For the lower part of the measuring range, the conductivity measurements can be considered with some confidence, as E/p is quite low. It can be seen that there is a general agreement between ion concentrations derived from the saturation currents and ion concentrations derived from the conductivity measurements.

The swinging motion of the probe will add to the spread of the points in Fig. 7.5.2. Some of the observation points, which have a marked deviation towards lower values, are certainly observations during periods, when the probe is far from the vertical direction.

The most probable values for positive ion concentrations have been marked in Fig. 7.5.2. For comparison, the observations of positive ion concentrations done by WHIPPLE, 1964, SMITH, 1963, and SAGALYN, 1963, have also been plotted in Fig. 7.5.2. These observations are taken for different solar zenith angles and at different days, which most certainly have different spectral intensities of solar radiation. There is a general agreement in all these observations that the positive ion density is of the order of 10^4 cm^{-3} in the height range 55–70 km. It is hard to say, however, if the differences in the various measurements are caused only by different conditions, or if the observation techniques themselves cause some of the differences between the profiles.

The measurements on 10 October and 13 December were both performed during quiet solar conditions. The electron density profile for a quiet sun and a solar zenith angle of 58° corresponding to the measurement of 13 December is plotted in Fig. 7.5.2 after the model of NICOLET & AIKIN, 1960.

8. Discussion of the Gerdien condenser measurements

8.1. CONTINUITY EQUATIONS

For the following discussion, it is necessary to write the continuity equations, and first we consider the case when we have a clean atmosphere, and the ions included are O_2^- , O_2^+ , N_2^+ , and NO^+ .

$$\frac{dN}{dt} = q - \alpha_d NN^+ - \eta n_1^2 N + \rho N^- + \kappa n N^- \quad (8.1.1)$$

$$\frac{dN^-}{dt} = \eta n_1^2 N - \rho N^- - \kappa n N^- - \alpha_i N^- N^+ \quad (8.1.2)$$

$$\frac{dN^+}{dt} = q - \alpha_d NN^+ - \alpha_i N^- N^+ \quad (8.1.3)$$

q = ion production

N = electron concentration

$N^- = N(\text{O}_2^-)$

$N^+ = N(\text{O}_2^+) + N(\text{N}_2^+) + N(\text{NO}^+)$

n_1 = concentration of O_2

n = total concentration of molecules

α_d = ion-electron dissociative recombination coefficient

α_i = ion-ion mutual recombination coefficient

η = coefficient for attachment of electrons to n_1

ρ = photodetachment coefficient

κ = collisional detachment coefficient.

For discussion of the measurements, only equilibrium conditions in a sunlit ionosphere will be considered. The following set of equations describe the ionospheric D-region when $dN/dt = dN^-/dt = dN^+/dt = 0$.

$$q = \alpha_d NN^+ + \eta n_1^2 N - \rho N^- - \kappa n N^- \quad (8.1.4)$$

$$0 = \eta n_1^2 N - \rho N^- - \kappa n N^- - \alpha_i N^- N^+ \quad (8.1.5)$$

$$q = \alpha_d NN^+ + \alpha_i N^- N^+ \quad (8.1.6)$$

$$N^+ = N + N^- \quad (8.1.7)$$

Equation (8.1.7) states that we have assumed positive and negative charges to have the same concentrations.

It is necessary to have knowledge about the rate coefficients in order to determine the balance between ion and electron production and loss terms. As the rate coefficients are far from well determined, the calculations presented

TABLE 8.1

$\alpha_d(N_2^+) = (2.8 \pm 0.5) \cdot 10^{-7} \text{ cm}^3/\text{sec}$	BIONDI, 1964
$\alpha_d(O_2^+) = (1.7 \pm 1) \cdot 10^{-7} \text{ cm}^3/\text{sec}$	BIONDI, 1964
$\alpha_d(NO^+) = 10^{-6} \text{ cm}^3/\text{sec}$ ($p \approx 0.1$ mm Hg 300°K)	GUNTUN & INN, 1961
$\alpha_i = 10^{-8} \text{ cm}^3/\text{sec}$	NAWROCHI & PAPA, 1961
$\eta = 1.5 \cdot 10^{-30} \text{ cm}^6/\text{sec}$	CHANIN, PHELPS & BIONDI, 1959
$q = 0.44 \text{ sec}^{-1}$	SMITH, BURCH & BRANSCOMB, 1958
$\kappa = 4 \cdot 10^{-17} \text{ cm}^3/\text{sec}$	HOLT, LAND-MARK & LIED, 1961
$\kappa = 4 \cdot 10^{-20} \text{ cm}^3/\text{sec}$	PHELPS & PACK, 1961

NOTES

$\alpha_d = 2 \cdot 10^{-7} \text{ cm}^3/\text{sec}$ seems to be a representative value for all positive ions.

It seems to be reasonable to accept $\kappa = 10^{-17} \text{ cm}^3/\text{sec}$ as an upper limit.

here will be approximations using the available data on rate coefficients. The problem of ionization and recombination in the D-region has been reviewed by several authors. CRAIN, 1961, NICOLET & AIKIN, 1960, NICOLET & SWIDER, 1963, and WHITTEN & POPPOFF, 1964, have discussed the physical parameters measured in laboratories and what laboratory measurements can best be used as the ionospheric rate coefficients in the continuity equation.

The rate coefficients used in this work are shown in Table 8.1 with their references.

It should be observed that equations (8.1.1–8.1.3) are only two independent equations for determination of N^+ , N , and N^- . Equation (8.1.3) can be obtained by addition of equations (8.1.1) and (8.1.2). From equation (8.1.5) we find

$$\lambda = \frac{N^-}{N} = \frac{\eta n_1^2}{q + \kappa n + \alpha_i N^+}. \quad (8.1.8)$$

The ratio between concentrations of negative ions and electrons, λ , is a constant for equilibrium conditions and $\alpha_i N^+ \ll q + \kappa n$. For a quiet day $\lambda \approx \eta n_1^2/q$ in the D-region for altitudes above 50 km. During night-time $\lambda \approx \eta n_1^2/\kappa n$ in the lower part of the D-region, but λ is most probably dependent upon N^+ for the higher D-region, especially during disturbed conditions.

8.2. INFLUENCE OF DUST PARTICLES ON ION CONCENTRATIONS

The ion density profiles measured with the Gerdien condenser probe are shown in Fig. 7.5.2, and the positive ion concentration is typically one order of magnitude above the negative ion concentration. In principle this effect can be caused by a high concentration of electrons, which are caught in the fringe field at the entrance of the probe and do not reach the collector. However, the ion density profiles cannot be interpreted so that the difference between measured positive and negative ion concentrations is due to electrons. This will give electron densities several orders of magnitude higher than expected from previous observations, for example D-region absorption measurements. The explanation more probably is that negatively charged dust particles, or unknown heavy negative ions are present in the ionosphere and cannot be observed in the Gerdien condenser.

The importance of dust particles as recombination surfaces in the ionosphere has been described in earlier reports by BOURDEAU, WHIPPLE & CLARK, 1959, and WHIPPLE, 1954.

Before proceeding with a discussion of the influence of dust on the continuity equations, it will be necessary to review the information available on concentrations and size distributions of dust particles at different heights. In the upper part of the D-region, the dust most probably originates from meteors and cosmic dust whereas pollution from industries is the main source for dust at lower altitudes. Considerable information on dust particles has been obtained up to 20 km with airplanes (Lockheed U2 Aircraft) and with balloonborne instruments, JUNG, 1961, and JUNG & MANSON, 1961. These measurements indicate that particles of radii less than 0.1μ ($1 \mu = 10^{-6} \text{ m}$) have concentrations of about 100 cm^{-3} at 15 km decreasing to about 1 cm^{-3} at 20 km. Particles larger than 1μ are very scarce. Chemical analyses indicate that the particles up to 20 km are sulfate particles.

VOLZ & GOODY, 1962, have tried to obtain information about dust in the mesosphere from spectrometric observations during twilight. Their measurements show the presence of dust up to 65 km. The mixing ratio between dust and air molecules has a maximum at about 20 km and, then decreases to a lower value and

is approximately constant between 30 and 65 km. If we assume dust particles to be $0.1\text{--}1.0\ \mu$, their concentrations will be about $10^{-4}\ \text{cm}^{-3}$ at 60 km. It should be added that smaller particles could hardly be observed by this method. FIOCCO & SMULLIN, 1963, have reported measurements of dust layers between 60 and 140 km indicating the presence of dust. Rocketborne instruments for collecting dust particles during noctilucent cloud conditions have provided valuable information about dust concentration at high altitudes, WITT, HEMENWAY & SOBERMAN, 1963. The collection of particles between 72 and 92 km showed a total number of about 10^7 per cm^2 column of particles with radius $R > 0.025\ \mu$. These measurements indicate a mean concentration of $5\ \text{cm}^{-3}$ in the actual height range. Most probably the dust layers as observed in connection with noctilucent clouds are stratifications with higher concentrations than the mean value quoted here. The differential size distribution has the approximate form $N \sim R^{-2}$. Very few particles of radius smaller than $0.025\ \mu$ were observed, the size distribution leveling off at this particle size. During conditions when no noctilucent clouds could be observed the dust particle concentrations were measured to some two orders of magnitude below that for noctilucent cloud conditions.

It should also be mentioned in this connection that extraordinary concentrations of dust were present in the atmosphere at the time of the rocket firings at White Sands in October 1963. Professor A. B. Meinel of the Stuard Observatory in Arizona has reported, at a Rochester Seminar in New York, that spectroscopic observations have indicated the presence of extraordinary dust in the atmosphere during the autumn of 1963. Two maxima could be observed at 15 km and at 45 km. Most probably this dust originated from an Indonesian volcano eruption in March 1963.

If we consider uncharged dust particles of radius R and concentration N_M , the mean free path for collisions between these dust particles and an ion which is small compared with the dust particle, is

$$L_M = 1/\sqrt{2\pi} R^2 N_M. \quad (8.2.1)$$

The ion has the mean thermal velocity

$$\langle v_i \rangle = \left(\frac{8 k_B T}{\pi m} \right)^{1/2}. \quad (8.2.2)$$

If we assume that an ion will attach to a dust particle upon each collision, we can write the following expression for ion loss to dust

$$\frac{dN_i}{dt} = N_i \frac{\langle v_i \rangle}{L_M} = \left(\frac{16\pi k_B T}{m} \right)^{1/2} R^2 N_i N_M. \quad (8.2.3)$$

The combination coefficient for the ions to dust particles then is

$$\beta_0 = \left(\frac{16\pi k_B T}{m} \right)^{1/2} R^2. \quad (8.2.4)$$

Equation (8.2.4) is valid only when we have a mixture of dust particles of concentration N_M and ions of concentration N_i . When other neutral molecules are present, the collisions between these molecules and the ions will influence the combination of ions and dust particles. Further it has been assumed that dust particles and ions are solid elastic spheres. This is an approximation as dipole forces and Van der Waals forces must be considered in a more detailed study.

Several authors have studied the combination of particles and ions taking into account the central forces and the influence of collisions with surrounding gas molecules. GUNN, 1954, BRICARD, 1962, SIKSNA, 1963, and SIKSNA, 1964.

The mean free path for collisions between ions and molecules varies between $2 \cdot 10^{-5}$ m and $5 \cdot 10^{-3}$ m in the height range 40 km to 80 km, which is of interest for this discussion. It is found from the detailed theories referred to above that equation (8.2.4) can be used at these gas densities as a first approximation of the combination of ions to dust particles. This means that ions and dust particles can be considered as free particles with little interaction with the gas molecules.

When the dust particles are charged, the ions will either be repelled or attracted by the dust particles. If the dust particle has a single charge e , the energy of the Coulomb field $e^2/4\pi\epsilon r$ will be equal to the kinetic energy of the gas, $\frac{3}{2}k_B T$ at a distance r_c .

$$r_c = \frac{e^2}{6\pi\epsilon k_B T}. \quad (8.2.5)$$

For $T = 200^\circ\text{K}$, $r_c = 5 \cdot 10^{-8}$ m.

If we assume that the surface potential of a dust particle is similar to the kinetic energy

of the gas, this means that a typical dust particle of radius $R = 10^{-7}$ m = 0.1μ can hold three charges at the surface. Larger dust particles can hold several charges and the particles of radius $R = 5 \cdot 10^{-8}$ m most probably can hold only one charge.

The effective capturing cross-section, πr_c^2 , for typical charged dust particles is similar to that for a neutral dust particle with a radius of the order of 10^{-7} m. This means that also charged dust particles can be treated in a first approximation as if interaction with molecules can be neglected in the height range 40–80 km, i.e. the mean free path is large enough for an ion to be considered to move in vacuum when moving inside the effective capturing Coulomb field of the charged dust particle. Then it is possible to derive combination coefficients for charged dust particles and ions from the theory of LANGMUIR & MOTT-SMITH, 1926. In this theory of ion collection in a low density plasma, it is assumed that the probe dimensions are small compared with the mean free path so that, on the way to the collecting surface, the ions experience no collisions with any other particles. Further it is necessary that the collector (dust particle) is small compared with the shielding distance of ions surrounding the collector, the so-called Debye length.

$$d = \left[\frac{3\epsilon k_B T}{2 N_i e^2} \right]^{\frac{1}{2}}. \quad (8.2.6)$$

The Debye length d is typically of the order of 10^{-4} m in the ionospheric D-region and $R < d$. After Langmuir and Mott-Smith the following expression can then be used for combination of charged dust particles and ions.

$$\beta = \beta_0 \exp \frac{\Phi_e}{k_B T} \quad (8.2.7)$$

Φ is dust particle surface potential. The signs of the ion and of Φ determine if the ion will be repelled or attracted.

For investigating the influence of dust on the ion and electron densities in the D-region, the more simple expression in equations (8.2.4) and (8.2.7) will be used. These expressions can be considered as satisfactory for a study of gross effects of dust in the ionosphere.

In the case when we have a concentration

of dust particles, some of the dust particles, or all dust particles will have a negative charge as the thermal velocity of the electrons is much higher than for the ions. The net current to a dust particle will be negative until the dust particle has acquired a negative charge. At equilibrium the net current to the dust particle will be zero. Photodetachment will reduce the negative charging of dust particles. When the concentration of dust particles is N_M , and σN_M is the concentration of negatively charged dust particles, the continuity equations (8.1.4) to (8.1.6) will have terms for ion combination to dust added to them.

$$q = \alpha_d N N^+ + \eta n_1^2 N - \varrho N^- - \kappa n N^- + \beta_e N \sigma N_M + \beta_e N (1 - \sigma) N_M \quad (8.2.8)$$

$$0 = \eta n_1^2 N - \varrho N^- - \kappa n N^- - \alpha_i N^- N^+ - \beta_- N^- \sigma N_M - \beta_0 N^- (1 - \sigma) N_M \quad (8.2.9)$$

$$q = \alpha_d N N^+ + \alpha_i N^- N^+ + \beta_+ N^+ \sigma N_M + \beta_0 N^+ (1 - \sigma) N_M \quad (8.2.10)$$

$$N^+ = N + N^- + Z \sigma N_M \quad (8.2.11)$$

Z is the number of charges on a dust particles
 β_+ = combination of attracted ions and particles
 β_- = combination of repelled ions and particles
 β_e = combination of electron and particle
 β_{e-} = combination of repelled electron and particle.

It is quite clear that the dust particles will have a distribution of no charge, one charge, two charges, etc. For simplicity we assume that we have a mixture of dust particles with only Z charges and no charge. From equation (8.2.9) we find that the ratio $\lambda = N^-/N$, which in this case is the ratio between small negative ions and electrons, will have the form

$$\lambda = \frac{\eta n_1^2}{\varrho + \kappa n + \alpha_i N^+ + \beta_- \sigma N_M + \beta_0 (1 - \sigma) N_M}. \quad (8.2.12)$$

In the following we will try to find out if λ is changed very much from the value of λ in a clean atmosphere. If we consider the available information on dust in the atmosphere, we will find that we are very unlikely to have concentrations of more than a few particles per cm^3 of particle radius 0.1μ . Smaller particles of a radius of about 0.01μ will most probably

TABLE 8.2

N_M	R	β_0	$\beta_0 N_M$
1 cm ⁻³	0.1 μ	$2 \cdot 10^{-5}$ cm ³ /sec	$2 \cdot 10^{-5}$ sec ⁻¹
10^4 cm ⁻³	0.01 μ	$2 \cdot 10^{-7}$ cm ³ /sec	$2 \cdot 10^{-3}$ sec ⁻¹

coagulate to larger units, but the effect of possible high concentrations of these small particles has to be investigated.

Table 8.2 shows some approximate calculations for rate coefficient to dust. $N_M = 10^4$ cm⁻³ for the smallest dust particles has been chosen in Table 8.2 as this is the number of heavy ions which can explain Fig. 7.5.2.

As $\beta_- \sigma N_M + \beta_0(1 - \sigma)N_M < \beta_0 N_M$, it can be concluded that the rate of ions diffusing to dust is small compared with $\varrho = 0.4$ sec⁻¹ in the equation for λ , and λ is unchanged during daytime, even if dust is present in the atmosphere in exaggerated concentrations given in Table 8.2. One must expect, however, that dust may have considerable influence on λ during nighttime. The effect of dust particles is to reduce λ to a value smaller than that for a clean atmosphere.

The easiest way to discuss the continuity equations is to derive an expression for N^+ from equations (8.2.10) and (8.2.11) and afterwards find N and N^- from equation (8.2.11). It is then necessary to put $\lambda = \text{constant}$ independent of the presence of charged and neutral dust particles.

$$N^+ = (q/A + B^2/A^2)^{1/2} - B/A \quad (8.2.13)$$

$$A = \frac{\alpha_d + \lambda \alpha_i}{1 + \lambda}, \quad q/A = (N_0^+)^2$$

$$2B = N_M(\sigma \beta_+ + (1 - \sigma) \beta_0 - \sigma Z A).$$

N_0^+ is the positive ion density in a clean atmosphere as described in 8.1. $N^+ < N_0^+$ for B positive, $N^+ > N_0^+$ for B negative. If we analyze the expression for B , we find $A \approx 10^{-8}$ – 10^{-7} cm³/sec for the whole range 30–80 km (see Fig. 8.3.1) and consequently β_+ and β_0 in the expression for B must be very small, i.e. we must have small particles of radius less than 0.01 μ to make B negative.

It can be seen from equation (8.2.13) that N^+ deviates most from N_0^+ when the ionization is small, i.e. q is small.

In order to discuss the possibility of having negatively charged dust particles the equations for electron density will be considered

$$N = (q/C - D/C + E^2/C^2)^{1/2} - E/C \quad (8.2.14)$$

$$C = (\alpha_d + \lambda \alpha_i)(1 + \lambda), \quad q/C = (N_0)^2$$

$$D = Z \sigma N_M^2 [\sigma \beta_+ + (1 - \sigma) \beta_0]$$

E = Function not of interest for the discussion. This equation for N has only meaning for $q > D$.

$$D > Z(\sigma N_M)^2 \beta_+ \quad q > Z(\sigma N_M)^2 \beta_+.$$

The upper limit for q in a quiet ionosphere is 1–10 cm³/sec for the height range 30–80 km, see later discussion of ion production function in 9.3. If we consider dust particles of radii 0.1 μ and 0.01 μ the β_+ values for these dust particles will be $6 \cdot 10^{-5}$ cm³/sec and $6 \cdot 10^{-7}$ cm³/sec respectively. This means that the concentration of negatively charged dust particles σN_M cannot exceed 10^3 cm⁻³ for particles of a radius of 0.1 μ and cannot exceed 10^5 cm⁻³ for particles of a radius of 0.01 μ .

This rough survey of rate coefficients indicates that even if dust is present in extraordinary high concentrations the negatively charged dust particles cannot have concentrations of the order 10^4 cm⁻³, which is necessary in order to explain Fig. 7.5.2. It is also very unlikely that the effect in Fig. 7.5.2 is caused by multiple charging of large dust particles as the measurements of dust in the upper atmosphere indicate that the concentration of the large dust particles is very low. The heavy negative ions which most probably are present in the ionosphere must be large negative molecules or clusters of smaller molecules with one or several charges. This effect will be discussed later.

Even if the space charge on dust is very small, dust particles will influence the ion and electron densities being effective recombination surfaces. From the foregoing survey of rate coefficients, it can be seen that B in equation

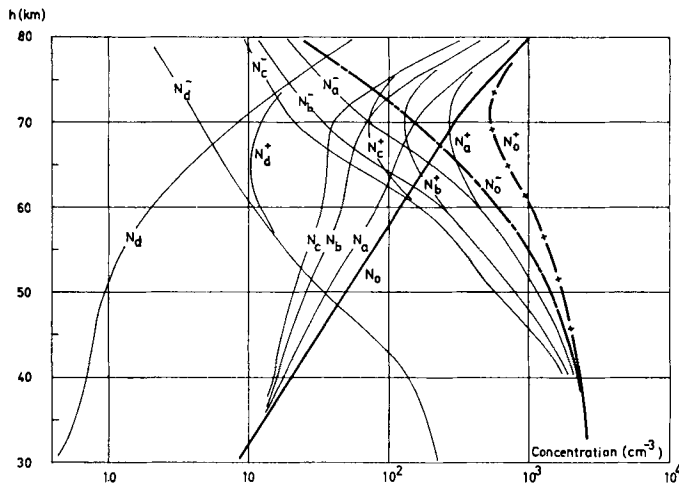


FIG. 8.2.1. Reduction of ion and electron concentrations when introducing dust particles acting as recombination surfaces.

(8.2.13) is positive, and $N^+ < N_0^+$. This means that the ion and electron concentrations are reduced when dust is present. In order to demonstrate this effect, electron and ion densities have been derived from equation (8.2.13) in the case when there is no charge on dust, i.e. $2B = N_M \beta_0$, and $N^+ = N + N^-$. An arbitrary model for the clean ionosphere has been chosen so that N_0^+ , N_0 , and N_0^- are reasonable values to be expected in a quiet ionosphere during daytime. These values are shown in Fig. 8.2.1. If we assume concentrations of dust $N_M = 50 \text{ cm}^{-3}$ ($R = 0.025 \mu$) and $N_M = 2 \text{ cm}^{-3}$ ($R = 0.1 \mu$) in the whole range 30–80 km, this represents roughly ten times the concentrations observed at the mesopause during noctilucent cloud conditions. N_a^+ , N_a , and N_a^- show the ion and electron profiles when only the 0.1μ particles are present, and N_b^+ , N_b and N_b^- are the profiles when the 0.025μ particles are present. N_c^+ , N_c , and N_c^- are the ion and electron profiles when both 0.1μ and 0.025μ particles are present as recombination surfaces. N_d^+ , N_d , and N_d^- are the same curves when a concentration of 1 cm^{-3} of dust particles of radius 0.1μ is present in the whole range 30–80 km.

8.3. HEAVY NEGATIVE MOLECULES

Heavy negative molecules can be formed in one of the following processes.

Electrons attach to heavy molecules which have been formed by clustering or by chemical reactions.

Small negative ions (O_2^- , O_- , (or) and NO_2^-) attach to molecules. This possibility has been mentioned by PHELPS, 1963, in the case of O_2^- combining with CO_2 to form CO_4^- .

During the ascent of large rockets, one must expect that some 100 to 1000 kg of CO_2 is ejected from the rocket into the D-region. If 500 kg CO_2 is spread out over a 50 km part of the rocket trajectory this corresponds to a concentration of 10^5 cm^{-3} in a volume of $1000 \cdot 1000 \cdot 50 \text{ km}^3$. White Sands Missile Range where the Gerdien condenser measurements were done is situated some 1000 km from the Vandenberg Base in California. Contributions from large rockets fired at this launch site and the numerous small rocket firings at White Sands Missile Range most certainly can produce high CO_2 concentrations in the D-region above White Sands. It is, however, difficult to reach any firm conclusion as to CO_4^- being present during the Gerdien condenser measurements.

We will in the following discuss the influence on small ion and electron density profiles if heavy negative ions are present in the D-region. If the heavy negative ions are produced by attachment of an electron to a molecule the ratio $\lambda = N^-/N$ which is the ratio between the concentrations of small negative ions and electrons, will be the same as for the small ion model ionosphere. When the heavy negative ions are formed by attachment of small negative ions to a molecule, as in the case of CO_4^- , we will have

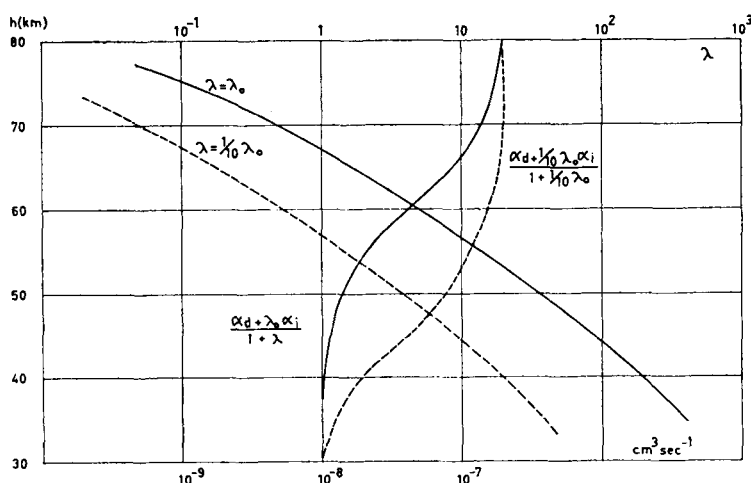


FIG. 8.3.1. Variation of $A = (\alpha_d + \lambda \alpha_i)/(1 + \lambda)$ and λ with height for coefficients given in 8.1.

$$\lambda = \frac{\eta n_1^2}{q + \alpha n + \alpha_i N^+ + \gamma n_x} \quad (8.3.1)$$

γ is the attachment coefficient for small negative ions to molecules of concentration n_x assuming a twobody attachment process. It is impossible to make any estimate of the rate coefficient γn_x , and all that can be said is that λ is equal to, or smaller than the λ -value for the situation discussed in 8.1 where only small ions and electrons are present in the ionosphere.

We will make the following assumptions for discussion of an ion density model which includes the presence of heavy negative ions.

Heavy negative ions are formed in one of the processes suggested above. These ions have electron affinities exceeding that for ions like O_2^- so they are less sensitive to photodetachment and collisional detachment. At last λ is supposed to be a constant.

For such a model, equations (8.2.10) and (8.2.11) will take the form

$$q = \alpha_d N N^+ + \alpha_i N^- N^+ + \beta_x N_x^- N^+ \quad (8.3.2)$$

$$N^+ = N + N^- + N_x^- \quad (8.3.3)$$

β_x = recombination coefficient for positive ions and heavy negative ions

N_x^- = concentration of heavy negative ions.

These equations lead to the following expression for N^+ .

$$N^+ = (q/A + B_x^2/A^2)^{1/2} - B_x/A \quad (8.3.4)$$

$$A = \frac{\alpha_d + \lambda \alpha_i}{1 + \lambda} \quad q/A = (N_0^+)^2$$

$$2 B_x = N_x^- (\beta_x - A).$$

If we compare the N^+ values with N_x^- which is the positive ion concentration in the small negative ion model described in 8.1 we find

$$N^+ \gtrless N_0^+ \quad \text{when} \quad \beta_x \lessgtr A. \quad (8.3.5)$$

The expression A can be denoted an effective recombination coefficient for the small ion model. If we take values for α_d and α_i from 8.1, and also calculate a λ -value named λ_0 from equation (8.1.8) using constants from 8.1, we find that A varies with height as shown in Fig. 8.3.1. Equation (8.3.1) indicates that λ may be smaller than λ_0 when heavy negative ions are present, and A is therefore also shown in Fig. 8.3.1 when $\lambda = 1/10 \lambda_0$. There is a general tendency for A to increase from about 10^{-8} cm³/sec at 30 km to about $2 \cdot 10^{-7}$ cm³/sec at 80 km. If we consider ion-ion recombination at the low pressures in the D-region, the Coulomb fields of the ions determine the recombination cross-section. It is possible that two small ions of opposite charge will recombine more easily than a small positive ion and a negative heavy ion. One must expect, however, that β_x does not differ very much from α_i , the ion-ion recombination coefficient for small ions. In the following we therefore use as the most probable value $\beta_x = \alpha_i = 10^{-8}$ cm³/sec. From equation

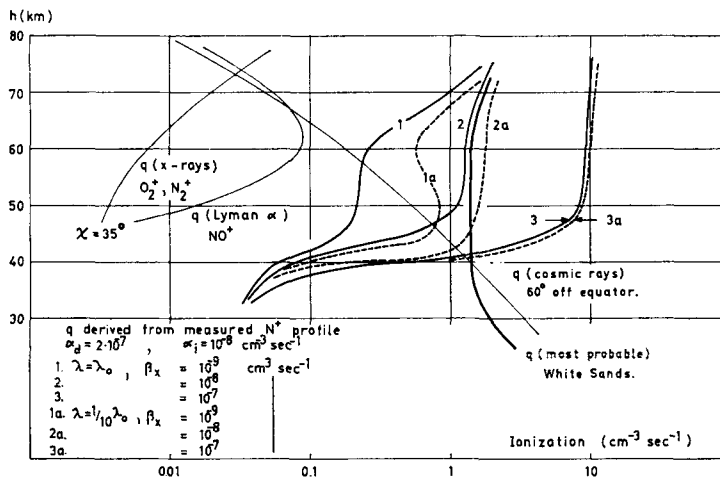


FIG. 8.3.2. Ion production functions calculated from the positive ion density profile in Fig. 7.5.2 compared with ion production functions for X-rays, Lyman α -ionization of NO and cosmic rays.

(8.3.5) and Fig. 8.3.1, it can then be seen that $\beta_x < A$, and consequently $N^+ > N_0^+$ above 50 km, whereas $N^+ \approx N_0^+$ below this height.

If equation (8.3.4) describes the equilibrium conditions in the ionospheric D-region, it is possible to obtain some information about the ion production function q from the measured ion density profiles in Fig. 7.5.2. Values of N^+ and N_x^- can be taken from these profiles, and by assuming the values for β_x and A used in the previous discussion, q can be derived from equation (8.3.4). The result of this calculation is shown in Fig. 8.3.2. To demonstrate how the choice of β_x and A influences the calculation, several q -curves are drawn for various values of β_x and A . For comparison the production function to be expected from cosmic rays and solar Lyman α radiation and X-rays (Solar zenith angle $\chi = 35^\circ$) is plotted in the figure, HOLT, 1963, and NICOLET & AIKIN, 1960. It can be seen from Fig. 8.3.2 that the ion production function is about 10 to 100 times the value to be expected for Lyman α ionization of NO^+ . β_x and A are very unlikely to be so far from the values chosen for Fig. 8.3.2 that this conclusion is wrong. As can be seen in Fig. 7.5.2, there is a general agreement between several measurements with different types of probes that the positive ion density is of the order of 10^4 cm^{-3} between 60 and 70 km. Even if there is no information about N_x^+ in the other experiments, it is quite clear that a positive

ion concentration of the order of 10^4 cm^{-3} must be caused by a larger ion production function than that used in the theory of Lyman α ionization of NO^+ .

Below 50 km, the q -values as derived from equation (8.3.4) are much smaller than the values to be expected from cosmic rays. This probably means that equation (8.3.4) does not completely describe the conditions at these heights. If dust particles are present in high concentrations at lower altitudes, equation (8.3.4) must also include terms representing extra recombination at the dust surfaces. These terms will increase the calculated q -values to a better fit with the cosmic ray production function. It was mentioned in 8.1.2 that extraordinary concentrations of dust were observed at 45 km at the time of the Gerdien condenser measurements. These dust layers have most probably caused the bend of the N^+ curve in Fig. 7.5.2 to smaller values below 50 km.

In Fig. 8.3.3 an attempt has been made to illustrate what may be the effect of dust below 50 km. The most probable ion production function in Fig. 8.3.2 which is mainly determined by cosmic ray ionization below 50 km results in a positive ion profile as the one shown in Model I in Fig. 8.3.3. Model I is then the observations which should have been obtained, had the dust been removed from the lower atmosphere, but the conditions moreover were the same as during the actual experiments.

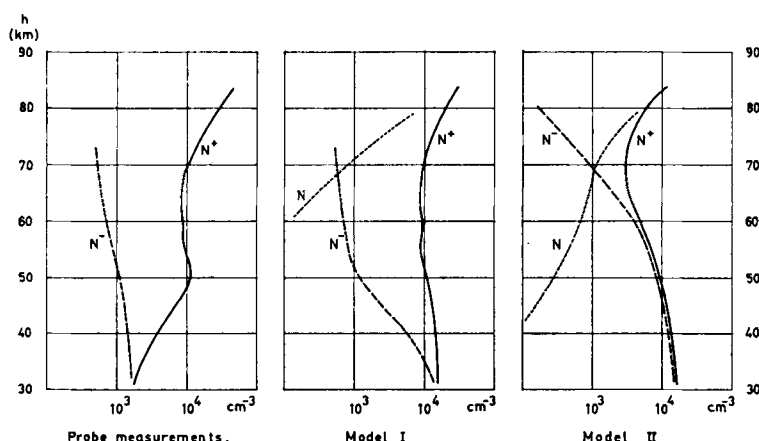


FIG. 8.3.3. Some ion density models, see text for discussion.

Model I seems to have some meaning as other rocketborne Gerdien condenser experiments have resulted in positive ion concentrations of the order of 10^4 cm^{-3} at 30 km, WHIPPLE, 1960, 1964. Model II shows the ion density profiles obtained when we use the same ion production function as for Model I, and assume that there is no dust and no heavy negative ion formation. N and N^- have been calculated assuming $\lambda = \lambda_0$. The electron density N in Model II seems to be rather high thinking of experience from radiowave observations. The reason may be that $\lambda = \lambda_0$ is not a correct value. It may also be that Model I is a more correct model, i.e. a stable heavy negative ion is always present. This stable negative ion will push N more towards the lower values for N as indicated in Model I.

The numerical calculations presented here are based on rate coefficients which so far are uncertain. It has also been necessary to make several assumptions. The calculations must therefore be considered as an attempt to study gross effects and more general tendencies. In spite of the limitations mentioned here, it seems clear that the main conclusions are correct. A heavy negative ion is present in the D-region during the experiments, and recombination to dust influences the ion density below 50 km. Further it can be concluded that the ion production function above 50 km most probably is larger than that expected from theoretical considerations.

8.4. CONCLUDING REMARKS

Positive and negative ion concentrations have been derived from Gerdien condenser measurements in the D-region of the ionosphere. These measurements indicate that positive ions have concentrations of the order 10^4 cm^{-3} between 50 and 70 km and that negative particles which are too heavy to be collected by the Gerdien condenser electric field were present in a concentration of about $8 \cdot 10^{-3} \text{ cm}^{-3}$ in the same height range during the measurements. This high concentration of negative particles is very unlikely to be due to dust as observations of dust indicate much lower values, and it can also be shown that dust cannot carry such high concentrations of electrons. The negative particles are probably heavy ions formed by attachment of an electron, or a small negative ion to a heavy molecule, or a cluster of molecules. It is possible that O_2^- and CO_2 combine to CO_4^- as the concentrations of CO_2 in the D-region are expected to be of the order of 10^4 cm^{-3} in the vicinity of a rocket launch site. The possibility of CO_4^- influencing the measurements could be determined by doing other experiments in areas with smaller concentrations of CO_2 in the atmosphere.

The ratio between small negative ions and electrons, λ , will not be changed very much during daytime if dust is present in the atmosphere. The presence of heavy negative molecules (like CO_4^-) formed in attachment of small negative ions to a molecule may, however, change

the parameter λ to values smaller than λ for a situation with only small ions and electrons in the ionosphere.

The shape of the N^+ curve and comparison of the measured N^+ values below 50 km with ionization from cosmic rays indicate that extra recombination due to dust is effective below 50 km. This dust may be caused by rockets over the launch site or by extraordinary dust layers which most probably originated from a volcano eruption. The latter dust layers were observed at about 45 km at the time of the Gerdien condenser measurements.

The ion production function q can be estimated above 50 km from the Gerdien condenser measurements, and it is found that q is 10–100 times larger than the value calculated for Lyman α ionization of NO.

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