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LIGHTNING HAZARD TO ROCKETS DURING LAUNCH I.

Heinz W. Kasemir

The launch of a rocket through thunder, or shower, clouds carries with it a definite lightning hazard - not so much because the rocket will be hit accidentally by natural lightning but because the rocket will trigger off its own lightning as soon as it enters strong electric fields inside the cloud. The larger the rocket the higher the field concentration factor is at the ends of the rocket. The chance that lightning be ignited by the intruding rocket, even in clouds that do not contain fields strong enough to produce natural lightning discharges, increases in the same proportion. It is the purpose of this report to discuss some of the fundamental problems involved in such a situation.

The nature of charge generation and its distribution in different types of clouds is still an open question. For lack of a more accurate and detailed picture, the model of the tripolar thunderstorm that is generally accepted and presented in the literature has to be considered our working hypothesis. Nevertheless, the conclusions drawn from this model can be readily adjusted to any other model, if actual measurement in the cloud suggests a modified version.

The charge distribution and field lines of a tripolar thunderstorm model are given in a qualitative way in figure 1a. The positive and negative main space charges are located in the upper and lower part of the storm. Below the main negative space charge at the base of the storm is another positive space charge pocket. The field at the ground of this arrangement of charges is shown in figure 1b. If the storm would move over the recording station at the ground, the trace of the P. G. (potential gradient) or field recorder would appear similar to that of figure 1b. Only a small fraction of the field lines reach the ground; most of the field lines terminate inside the storm. Note also that at the points marked zero in figure 1b the field changes polarity and goes through zero. This is by no means an indication that the field in the cloud is also zero. To deduce the field in the cloud from ground measurements is an extremely difficult task because the fraction of field lines reaching the ground depends on a number of factors usually not known; their existance is often not realized. However the electric field inside the cloud is the determining agent for the generation of natural lightning discharges, as well as artificially triggered off lightning discharges by rocket penetration, and should be the key parameter of a lightning warning system.

The field at the ground will be weak if (a) positive and negative space charges in the cloud are of equal amount, (b) their mutual distance is small, (c) the distance to ground is large,

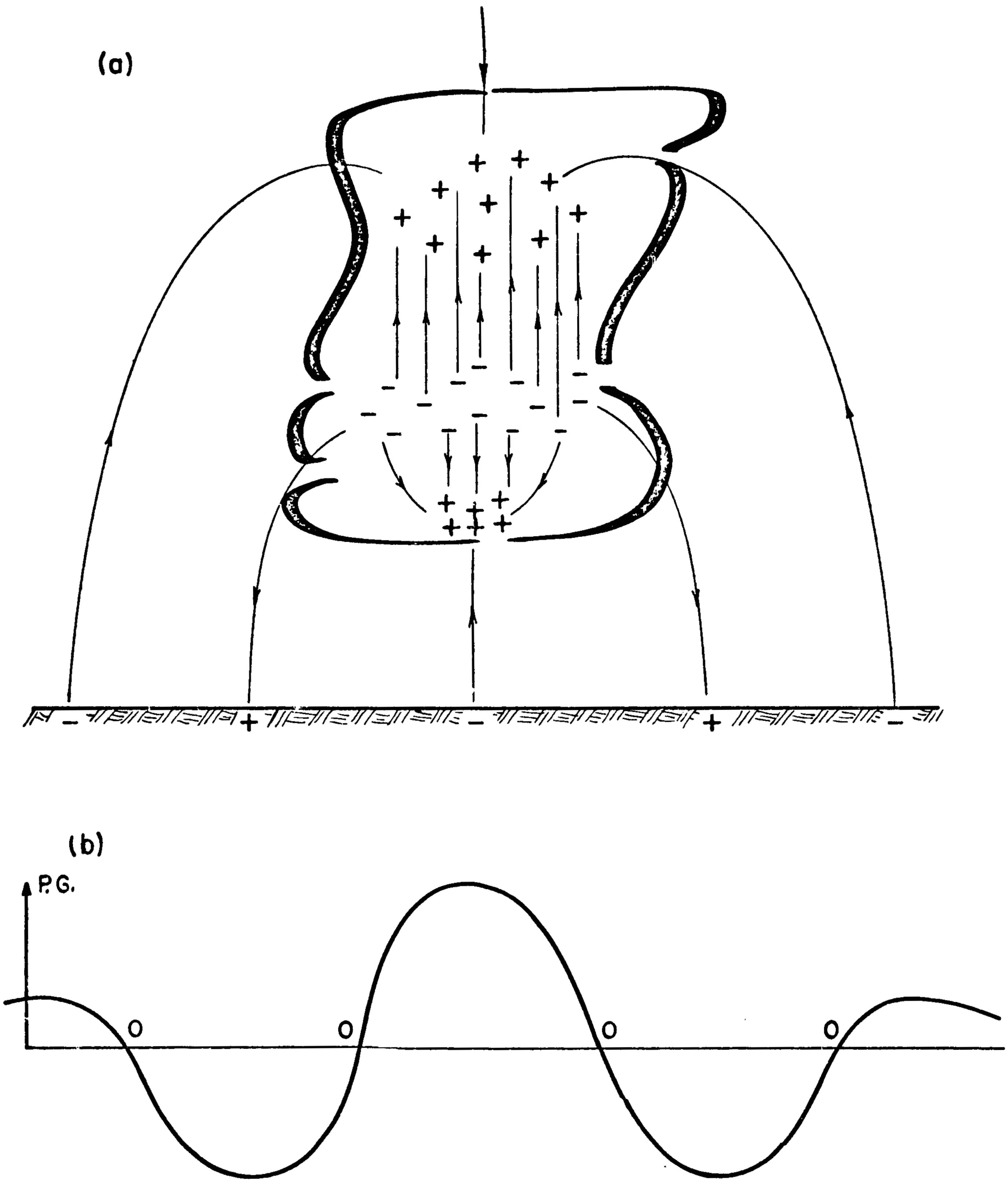

Figure 1. (a) Tripolar thunderstorm model

(b) Potential gradient at the ground below thunderstorm

(d) the space charges are spread more horizontally than vertically, (e) the conductivity in the cloud is much smaller than in free air, which results in a screening surface charge at the cloud-air boundary, (f) the conductivity of the free air increases with altitude, which results in a screening space charge in free air, and (g) a screening space charge blanket exists, resulting from corona discharge at the ground.

At present the only safe means to determine the field inside the cloud is to measure it from an airplane equipped with instruments recording all three components of the electric field vector and capable of cloud penetration. Even this means requires expert knowledge because the airplane has to penetrate the cloud at the right altitude to measure the maximum fields. In the middle of the positive or negative space charge regions, for instance, the field will be close to zero. This can be seen from figure 2a and b, which represent the potential function ϕ and electric field E versus altitude h through the center of the storm. There are two critical altitudes with maximum field values marked by the letters g and c in figure 2a and b; c is the birth place of cloud discharges and g that of ground discharges. These maximum fields always occur between two space charges of opposite polarity. We have now to determine the threshold value of the electric field necessary to ignite a lightning discharge and how much this threshold value is lowered by the intruding rocket.

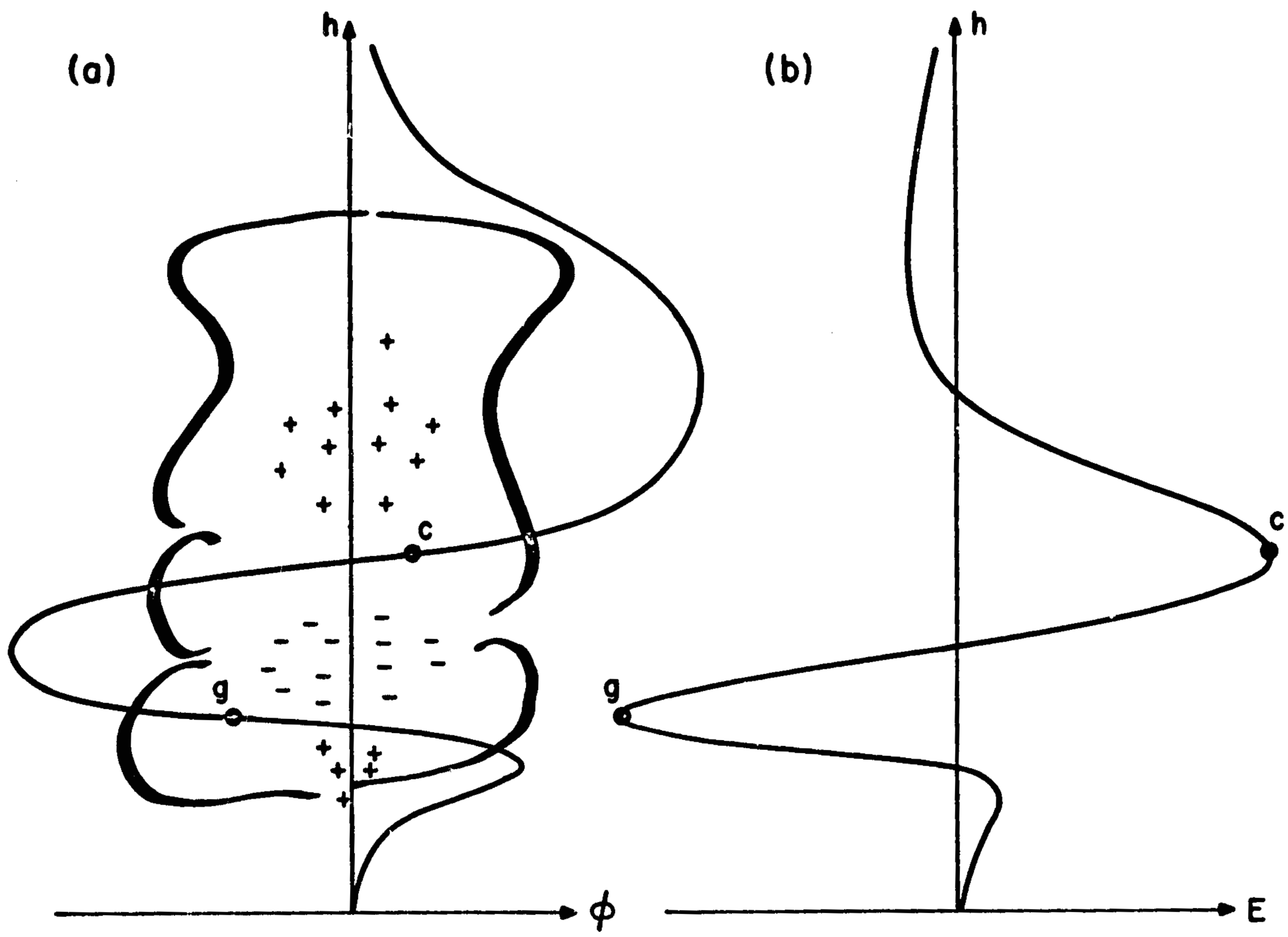

Figure 2. (a) Potential function versus altitude h through the middle of the storm

(b) Electric field E versus altitude h

The break-down field in air under normal pressure is about 3×10^6 V/m. At the altitude of lightning origin the air pressure is only about half of the value at sea level, and the breakdown field may drop to 1.5×10^6 V/m. Furthermore, we have to consider the field concentration caused by the introduction of a conductive body. A precipitation particle, for instance a raindrop, has the field concentration factor of 3 at its highest and lowest points, if we assume that we can treat the raindrop as a conductive sphere. This means that the field around a raindrop falling through an external field of 500 kV/m would just reach the breakdown value of 1.5×10^6 V/m at its top and bottom. Small filaments of corona discharge will emerge from these two points, adding conductive protuberances to the precipitation particle. At the tips of these protuberances still higher field concentration factors will exist, causing further growth accompanied by increasing fields. Once started, this process will rapidly convert the corona filaments into a lightning discharge. There are other factors involved in igniting a lightning discharge that are not outlined in the above oversimplified description. For instance, raindrops are known to deform in strong electric fields into a spheroidal shape that would result in a higher field concentration factor, or two precipitation particles can be close enough together so that they are linked by their corona filaments forming an elongated body. For igniting a lightning discharge, it will also be necessary that the breakdown field value is surpassed over a certain distance ahead of the growing corona filament. Otherwise the corona discharge may remain just that or even be quenched by its own space charge production. This effect can be offset by a sudden field increase caused by turbulent motion of the air, which brings pockets of opposite space charge close together. These are finer details, mostly of a speculative nature, and are not within the scope of this report.

We are interested in a rough estimate for the electric field intensity necessary to produce lightning discharges and will accept for the time being the value 500 kV/m as a maximum. It may be mentioned in this respect that the author recorded from an airplane a field strength of 290 kV/m right under the base of a cumulonimbus for about 30 min and that this cloud did not produce a single lightning discharge. This means that the lightning igniting field value has to be higher than 290 kV/m and the right value will lie somewhere between 300 and 500 kV/m.

The upper end of the cloud discharge, which penetrates into the positive space charge region of the cloud, accumulates negative induction charge. Also, the lower end of the cloud discharge penetrates into the negative space charge region of the cloud and accumulates positive induction charge. These induction charges are formed by electrons flowing in the highly ionized channel from its lower into its upper part under the influence of the external electric field. This flow of electrons results in a surplus of positive ions in the lower part and builds up a negative surplus charge in the upper part of the channel. It is not necessary or even physically plausible that the lightning has to collect cloud charges by a wide spread streamer process, funnel these charges into the channel, and transport them from one charge center of the cloud to another or to ground. We are dealing here only with a charge separation inside the lightning channel. The cloud charges remain practically stationary during the short lifetime of the lightning discharge. They generate only the electric field that furnishes energy for the lightning. There is much confusion and misinterpretation on this point in the literature.

The amount and distribution of these influence charges are determined by the external field of the cloud and the length and shape of the lightning channel. The current that flows in the channel of a cloud discharge to build up these induction charges is in the order of 100 ampere. This would also be the current that flows through the rocket, if it, instead of a precipitation particle, triggers the cloud discharge. We will see later that a large rocket with a much larger field concentration factor can ignite a cloud discharge in much weaker fields. Correspondingly the induction charges, as well as the current producing them, would be less.

We turn now to the discussion of a ground discharge that would start at point g in figure 2a or b. The leader stroke, which is the first part of the ground discharge and occurs before it makes contact with the ground, will form in a manner similar to that of the cloud discharge. The difference is that the upper part of the leader stroke will grow into the negative cloud charge region accumulating positive induction charge, and the earth bound part growing through the lower positive space charge pocket will carry negative induction charge. Currents in the leader stroke of a ground discharge will be of the same order as those in a cloud discharge but will flow in the reverse direction. The situation however changes drastically as soon as the leader stroke touches ground. The lightning channel has the large negative potential of its origin in the cloud, which is in the order of many millions of volts against ground, and if ground contact is made the lightning is recharged to ground potential during the return stroke. In this phase lies the greatest danger to the rocket if it happens to trigger off a lightning discharge at point g, that grows into a ground discharge. Being in the middle of the lightning channel the rocket will experience the strong current surge of 10000 A or more of the return stroke. The rocket, however, with its high field concentration factor may trigger a comparatively weak ground discharge, and the current may be smaller than that of the average natural return stroke.

For the calculation of the field concentration factor, we may substitute for the rocket a conducting spheroid of equivalent length and thickness. The formula for the field concentration at the ends of an uncharged spheroid in an electric field is not as well known as that for a sphere.

It is

$$A = \frac{c^2}{b^2\left[\frac{a}{2c} \ln \frac{a + c}{a - c} - 1\right]} , \qquad (1)$$

where

a = long axis of the spheroid,

b = short axis of the spheroid,

$c = (a^2 - b^2)^{1/2}$ = excentricity,

E = electric field at the end points,

F = external field of the cloud,

$A = \frac{E}{F}$ = field concentration factor.

The only uncertain parameter in equation (1) is the length of the rocket, because it is not known to what length the exhaust flames can be considered a conductor. If we assume for numerical evaluation that the thickness of the rocket is 2b = 10 m = 33 feet, and the length is 2a = 100m = 330 feet, the field concentration factor is about 50. If we add another 100 m to the length of the rocket to include the exhaust flames it becomes 150. This would mean that cloud fields as low as 10 to 30 kV/m have to be considered potentially dangerous. Compared with the lightning igniting fields of about 300 to 500 kV/m, one has to expect that practically every non-thundering rain shower is capable of producing fields strong enough for rocket ignited lightning.

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