

CHAPTER 2

THE ELECTRIC STRUCTURE OF THE ATMOSPHERE

2.1 IONS

The existence of ions in the atmosphere is the fundamental reason for atmospheric electricity. An absence of ions would mean zero electric field in the atmosphere and most probably no thunderstorms or lightning. The concept of positive and negative ions as charge carriers in the atmosphere was first put forward by J. Elster and H. Geitel (1899) in order to explain the electric conductivity of air. Much work has since been done on ions and their role in atmospheric electric phenomena. Today we know there are mainly three classes of ions, namely small ions, intermediate ions and large ions. Most important are the small ions since their higher mobility allows them to take a more active part in the transfer of charge throughout the atmosphere. The mobility of ions can be measured in metres per second per volt per metre which signifies the velocity that an ion will reach when subjected to an electric field of one volt per metre. For small ions the mobility is of the order of 0.0001 with a slight edge of the negative ion over its positive counterpart. In fact, the negative to positive mobility ratio of small ions is about 1.25 (Wählin 1985) which is a paradox since negative ions are believed to be more massive than positive ions. One explanation (Papoular, 1965) is that for part of its lifetime a negative ion is really an

electron jumping from molecule to molecule. Molecules such as NO and NO₂ are believed to dominate the negative small ion population while oxonium and water might make up the positive small ions in the atmosphere. Their true molecular structure and mass are not well known because it is difficult to get spectroscopic mass analysis of small ions in the lower atmosphere. The problem is their relative short life time, about 100 seconds, which is much shorter than the transit time required for molecules or ions to reach the source end of a mass analyser.

The ionization in the lower atmosphere is mostly caused by cosmic rays and natural radioactivity. Ions are also produced in and near thunderclouds by lightning and corona processes. Cosmic rays originate from solar flares and other galactic objects such as supernovas and exploding stars. One interesting thought is; do stellar events affect our lives here on earth? We know that cosmic rays are by far the major ion producers in the lower atmosphere and if thunderstorms need ions to feed on in order to charge, we certainly would not have thunderstorms if there were no cosmic rays. Ancient man would not have had access to fires and the many thousands deaths each year from lightning strokes would have been avoided.

Cosmic rays originate from deep space and usually consist of very high-velocity atoms that have been stripped of their orbiting electrons. There are also electrons present in space that travel with near-light velocities, but such particles are usually absorbed at very high altitudes in the earth's atmosphere. However, heavy cosmic rays penetrate the atmosphere quite far and often reach the earth's surface. During such an encounter numerous secondary electrons are produced (electron showers) along its track from ionizing collisions with atmospheric molecules. The secondary electrons in turn might ionize a fair amount of molecules themselves before they slow down and attach themselves to atmospheric molecules to form negative ions. The result is that one cosmic particle could be responsible for the creation of as many as one

billion ion pairs. Fig. 7 shows the rate of ion production by cosmic rays as a function of altitude (Wählin 1994). The average production

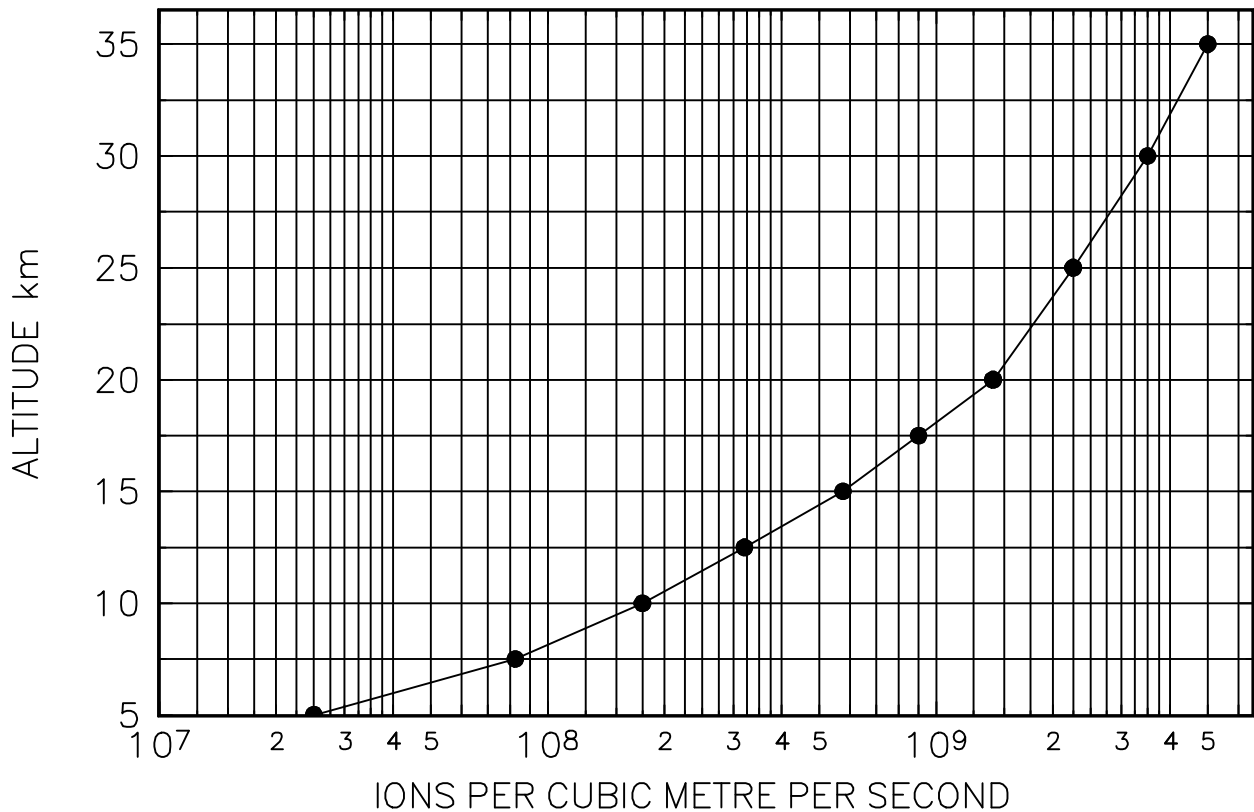


Fig. 7 Ion production as function of altitude.

rate at sea level is about ten million ion pairs per cubic metre per second. However, the average ion population at any given time is nearly one hundred times more, and ion mobility with altitude as air gets thinner has a drastic effect on the electric structure of the atmosphere. Typical conductivity data as a function of altitude are shown in Fig. 8. The conductivity is the inverse of specific resistance and is usually measured with a Gerdien cylinder (Gerdien 1905). The Gerdien apparatus consists of a cylinder with a coaxial mounted electrode (see Fig. 9). Air is drawn through the cylinder at a velocity of a few metres per second by means of a fan. The centre electrode is biased to a few volts via a sensitive electrometer. The amount of current registered on

the electrometer relates to the amount of ions per unit volume of air. Care must be taken not to over-bias the inner

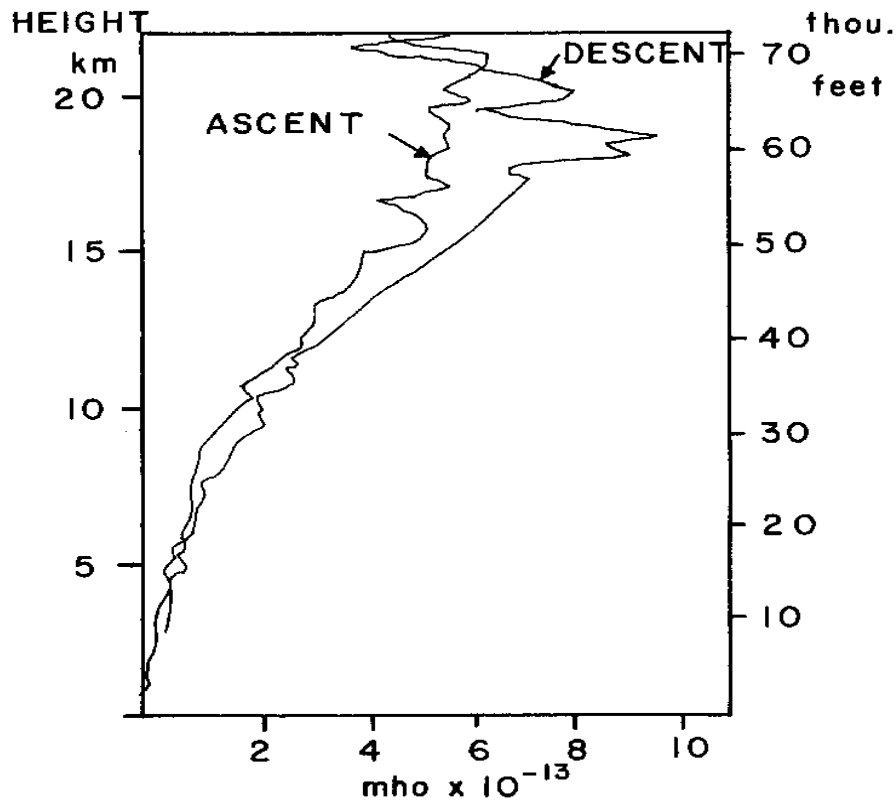


Fig. 8 Conductivity as a function of altitude (Rocket data).

electrode in order to avoid saturation currents. When properly calibrated, the Gerdien instrument can read both the positive and

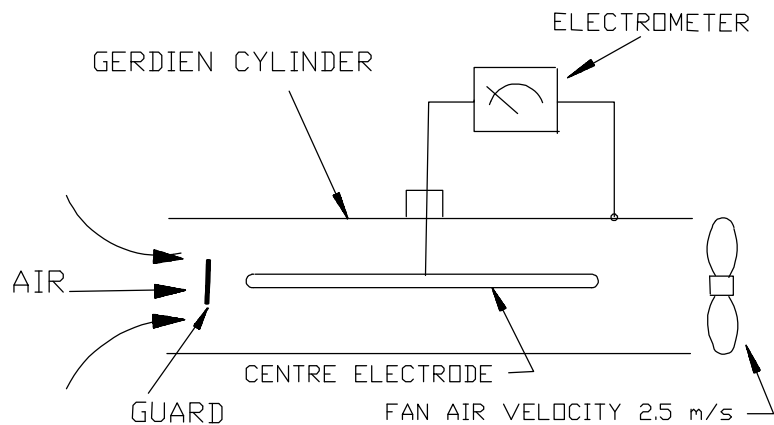


Fig. 9 Gerdien conductivity apparatus.

negative conductivity of air depending on the polarity applied to the centre electrode. A typical ion current plot is shown in Fig. 10 where two identical Gerdien cylinders were tested, the only difference being

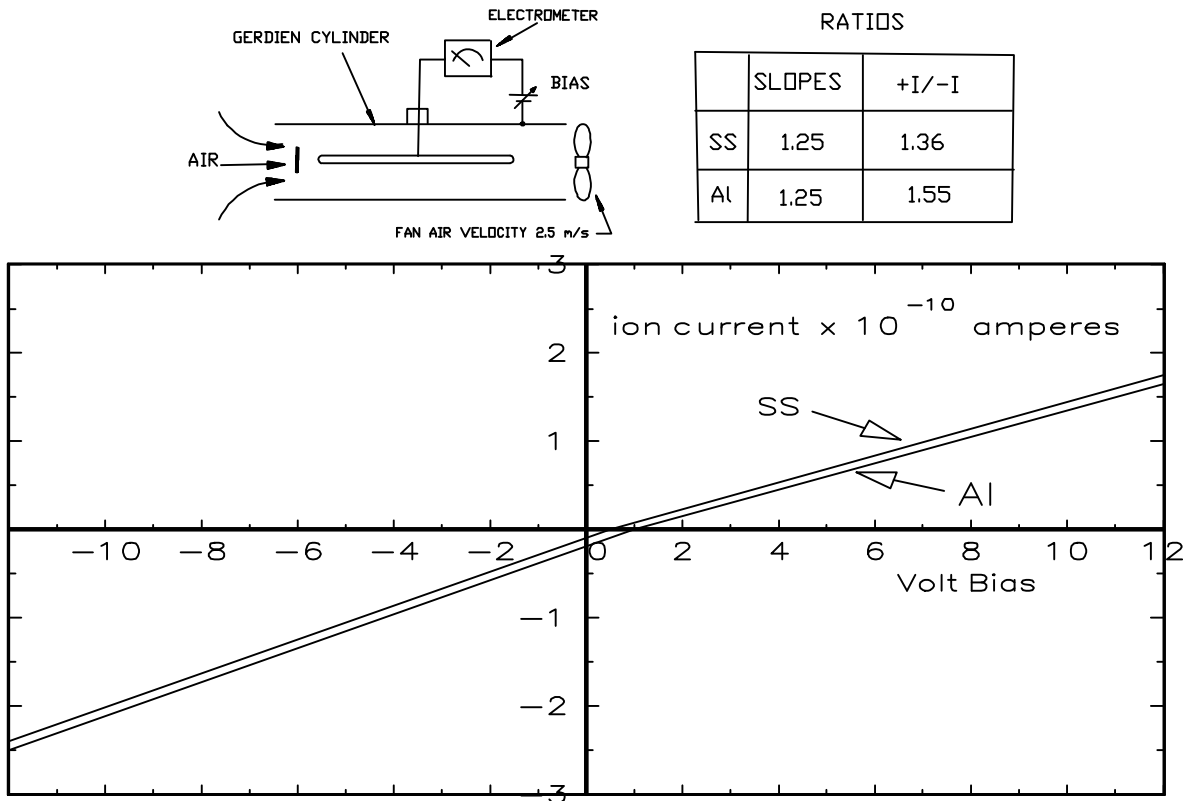


Fig. 10 Typical ion current readings from a Gerdien cylinder.

that one was made of stainless steel and the other of aluminium. Three important features appear from the results shown in Fig. 10. First, the slopes of the two curves are different for negative and positive ion currents. This is due to the difference in ion mobility between negative and positive ions; therefore, the ratio of the slopes equals the ratio of the ion mobilities. Secondly, there is still a negative ion current going to the centre electrode when the electrode is at zero volt bias. Thirdly, the negative ion current at zero bias is higher for a Gerdien instrument made of aluminium than stainless steel. In order to obtain a zero ion current on the electrometer one needs to bias the stainless steel at 0.4 volts and the aluminium at about 1 volt. These results led to the discovery of electrochemical potentials in the atmosphere (Wählin 1971) which appear on material surfaces in contact with ionized air. The

reason why stainless steel and aluminium have to be biased at different positive potentials, to achieve zero ion current, is to cancel out

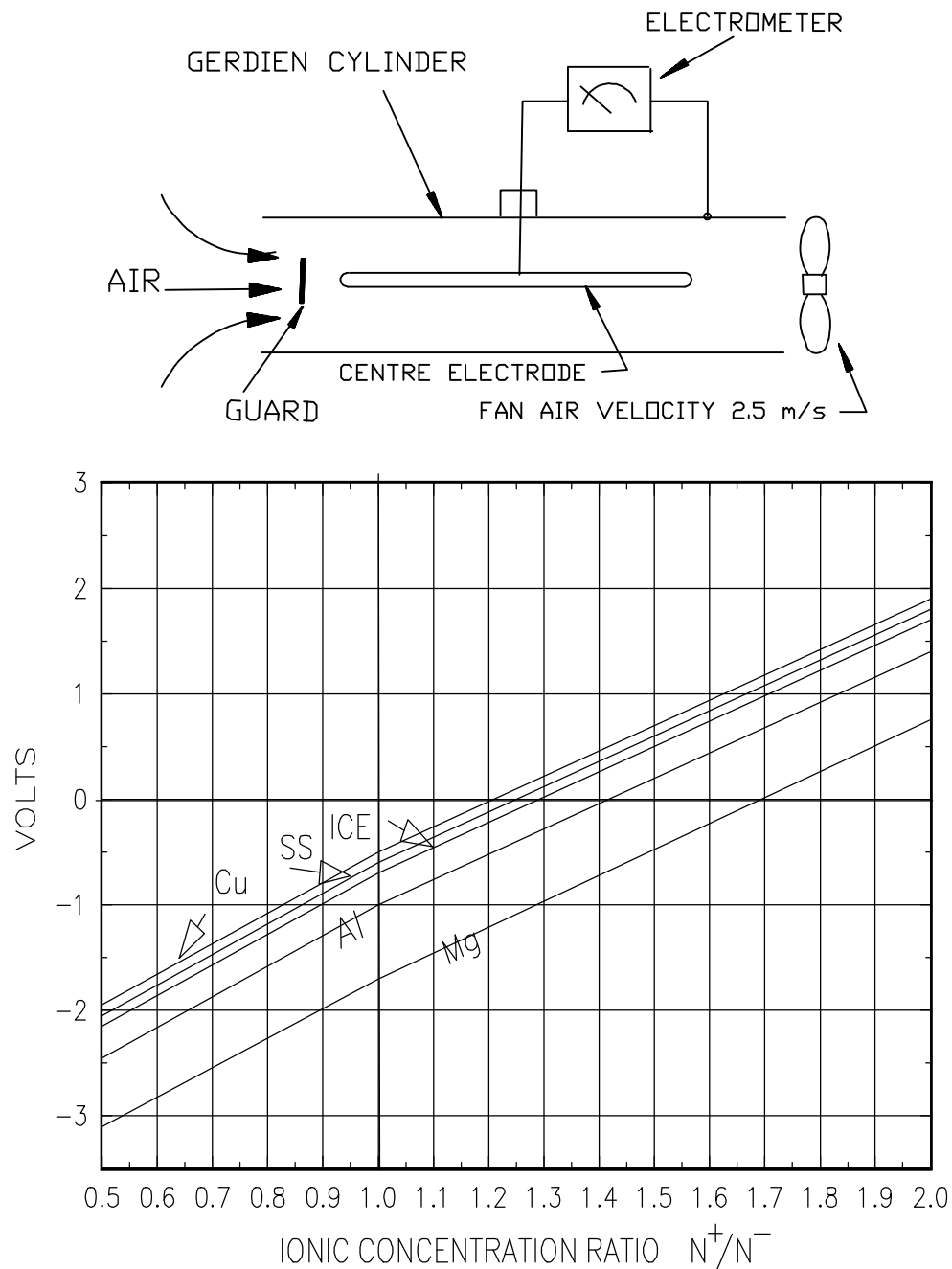


Fig. 11 Electrochemical equilibrium potentials for different materials as a function of ion concentration ratios.

the electrochemical or oxidation-reduction potentials which are characteristic of each material and appear when exposed to an ionized environment. The effects of contact potentials are eliminated since both the inner and outer electrodes of the Gerdien instrument are made of

the same material. The graphs in Fig. 11 show electrochemical potentials on different materials as a function of positive to negative ion concentration ratio. Electrochemical and contact potentials will be discussed further in Chapter 3.

2.2 THE FAIRWEATHER ELECTRIC FIELD

The fairweather electric field discovered by Lemonnier and Beccaria (see Chapter 1.2) is almost entirely due to the excess of positive ions over negative ions in the atmosphere.

The fairweather field is best understood if we assume that the earth's surface has absorbed a certain number of negative ions from the atmospheric ion pair population. It will create a slight excess of negative charge on the earth's surface with an equal excess of opposite charge in the form of positive ions left behind in the atmosphere. If we imagine that each captured charge on the earth's surface will produce

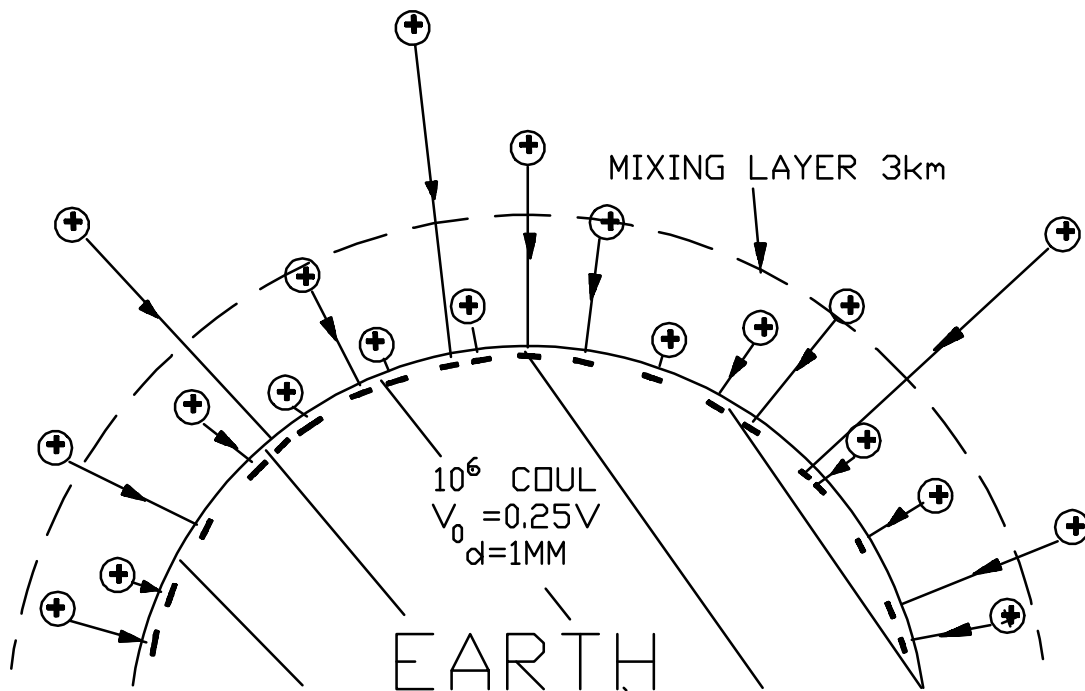


Fig. 12 The fairweather electric field in the atmosphere.

an electric field line which must terminate on a positive excess ion left behind in the atmosphere one obtains a fairly accurate picture of the electric fairweather field in the atmosphere, such as shown in Fig. 12. The excess positive ions are more or less uniformly mixed in the lower 3 km of the atmosphere which, to the meteorologist, is known as the "Austausch" or mixing region. The mixing is produced by convection and eddy-diffusion and the ionic distribution follows the mixing patterns of other constituents in the atmosphere such as radon for example. Radon is a radioactive gas emitted by the earth's surface and is constantly released into the atmosphere. Fig. 13 shows the vertical

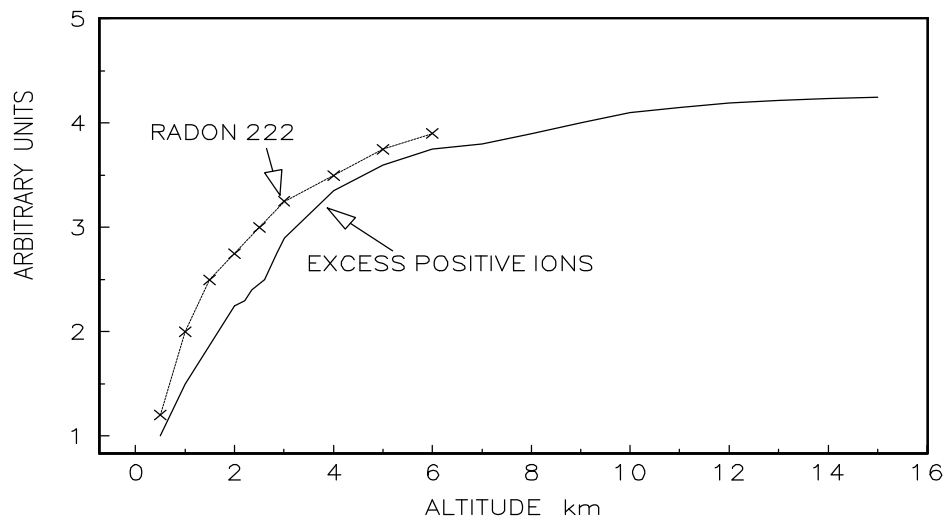


Fig. 13 Relative distribution of radon atoms and excess positive ions as a function of altitude.

distribution profile of excess positive ions compared to that of the radon gas. The positive ion distribution is determined from electric field measurement at varying altitudes and by applying Poisson's equation. The radon profiles are obtained from airborne radioactive counters that detect the daughter products of the decaying radon gas.

The number of field lines per unit surface area produced by the positive charge or space charge above the earth's surface is also a measure of the electric field strength. Obviously the electric field strength reaches a maximum at the earth's surface since it contains the largest number of field lines per unit area. The average field

strength at the earth's surface is on the average 100 volts per metre and decreases to less than 10 volts per metre at an altitude of 3 km. If one integrates the electric field as a function of altitude one obtains the total potential difference V at different heights. A typical value of V at 3 km is 200 kV with respect to the earth's surface. The total charge Q on the earth's surface is

$$Q = AEe_0 , \tag{1}$$

where A is the surface area of the Earth, E the electric field strength at the surface and e_0 the permittivity of free space ($e_0 = 8.85 \times 10^{-12}$ Farad m^{-1}). The total energy of the fairweather field is

$$W = \frac{1}{2} VQ . \tag{2}$$

Fig. 14 shows the total electric energy, charge and potential in the atmosphere as a function of altitude. More than 90% of the energy is confined to an altitude below 3 km which together with the charge distribution curve in Fig. 13 seems to indicate that convection and eddy diffusion play a predominant part in the distribution of the fairweather electric field and that the bulk of its energy is distributed throughout the mixing region by the so called "Austausch Generator" (Kasemir 1950).

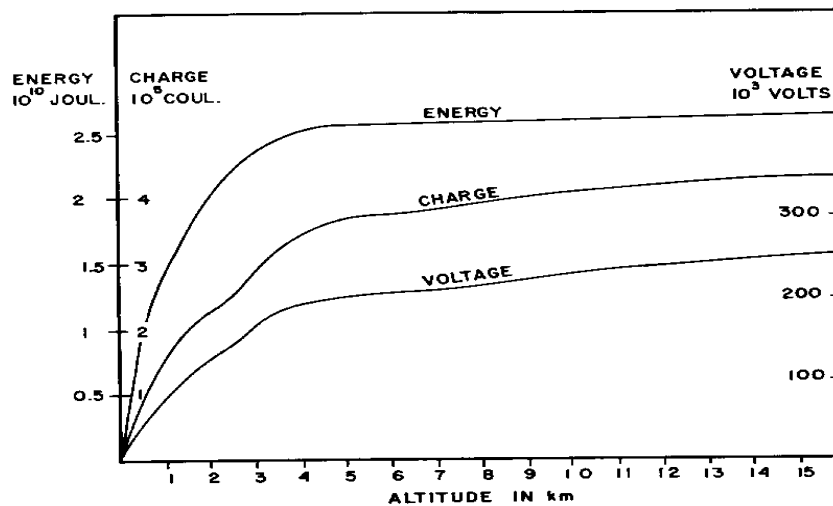


Fig. 14 Electric energy, charge and potential vs. altitude.

One crucial question still remains to be answered. What causes the positive space charge in the atmosphere and how is the opposite negative charge maintained on the earth's surface? As mentioned before there are two schools of thought on this

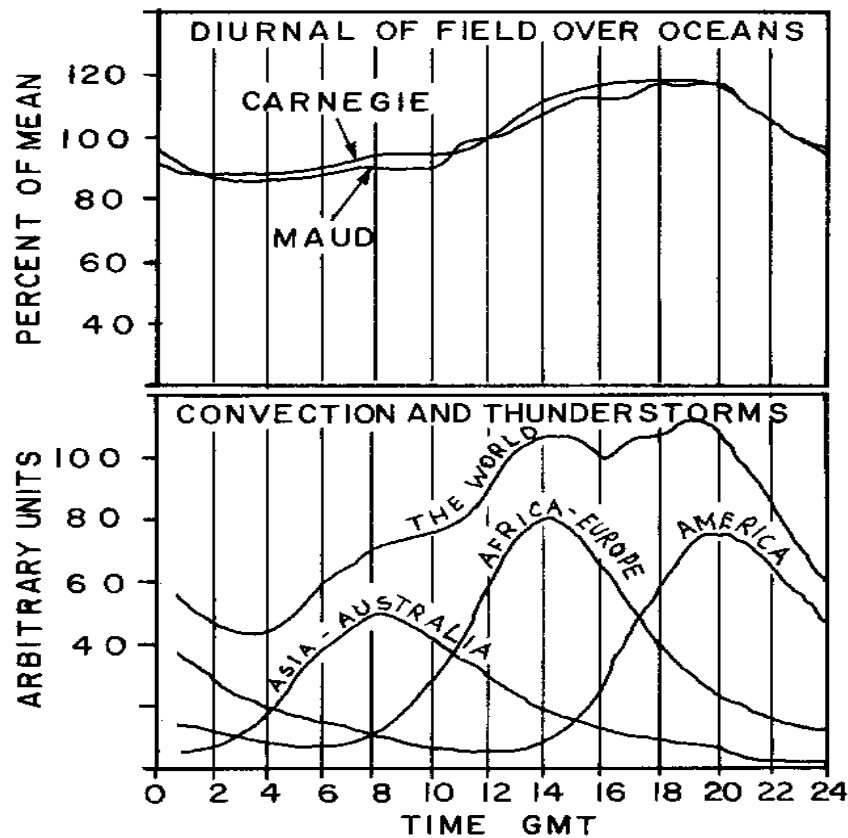


Fig. 15 Diurnal variations in the fairweather field compared to world-wide convection.

one in which all thunderstorms around the world are believed to charge the earth-atmosphere system (Wilson 1929) and a more recent theory proposed by the author (1973) which considers the electrochemical effect as a charging mechanism where negative atmospheric ions are preferentially captured by the earth's surface leaving a space charge of positive ions behind in the surrounding atmosphere. Both theories might be supported by the evidence of a small systematic diurnal variation in the fairweather field, which is believed to be related to the world-wide atmospheric convection activity. The effect was first discovered in Lappland 1905 by Simpson whose findings were later augmented by Hoffmann (1923) and Mauchly (1923). The effect is

illustrated in Fig. 15 where the average variation in the world-wide potential gradient is compared to the estimated world-wide convection activity at different times of day (by GMT). The top graph shows the global variations in the electric field measured at sea in the absence of local disturbances such as pollution, fog, etc. The top graph seems to coincide with the lower graph which gives an estimate of the world-wide convection activity produced by the heat of the sun during a diurnal period. The steady convection over oceans, however, is thought to smooth out the electric field variations as is evident from the top graph. Before discussing the electrochemical and global thunderstorm circuits as possible generators of the fairweather field, it is necessary to examine the global leakage current and its implications.

2.3 THE AIR TO EARTH CURRENT

As already mentioned, the atmosphere is conducting and the earth's electric potential or field must cause a current to flow in the atmosphere. Since there is an excess of positive ions residing in the atmosphere and an opposite negative charge bound on the earth's surface, charge must flow to earth in the form of a positive ion current.

Direct measurements of electric currents in the atmosphere are difficult if not impossible. Therefore, ion current values at different altitudes are almost always computed indirectly from conductivity and electric field data by the use of Ohm's law. Direct current measurements can be made, however, at ground level by isolating a portion of the earth's surface and measure the charge collected over a given time. Several methods can be used (Wilson 1906, 1916, Simpson 1910, Mühleisen 1953 and Kasemir 1951) but in almost all cases the indirect current gives a value often twice as large as the direct method (Lutz 1939, Israel 1954). Whipple (1932) pointed out that the discrepancy in currents can be explained by the fact that there is always convection and eddy diffusion in the atmosphere which will mechanically

move charges upwards in the atmosphere thus generating a mechanical or convection current in the opposite direction of the leakage current (the Austausch generator). As later explained, the question whether or not the convection and leakage current on the average are equal is crucial to the electrochemical charging theory and is a problem which has not yet been settled.

From direct current measurements it is possible to estimate the total fairweather current over the whole earth to be nearly 2000 amperes which corresponds to a current density of about 4×10^{-12} amperes per square metre. Other charge transfer mechanisms in the atmosphere of importance are point discharges, precipitation currents and lightning discharges.

2.4 POINT DISCHARGE CURRENTS

It is difficult to determine the total charge brought to the earth's surface by means of point discharge currents under electrified clouds. Wormell (1930) has made some estimates from the amount of charge brought down by a single point over a period of 4 years. He made a guess that the total point discharge current around the world brings negative charge to the surface at a rate of about 1500 amperes which would supply about 75% of the total fairweather leakage current. Other investigators give slightly lower values for the average point discharge current but not less than 25% of the fairweather current. The source of point discharge currents are the electrified clouds which of course also bring charge to ground by lightning. The point discharge current is, to a certain extent, canceled by the large amount of positive lightning flashes to ground and through positive charge reaching the earth's surface by precipitation.

2.5 PRECIPITATION CURRENTS

The electricity of precipitation has played an important role in atmospheric research due to the belief that charging of precipitation particles in some way must relate to whatever charging mechanism is active in clouds. Paradoxically, this is not always true because the final charge on a cloud drop is determined in the space between the cloud base and ground and is usually of opposite sign to the charge of the cloud base where it came from. This peculiar phenomenon is called the mirror-image effect and is demonstrated in Fig. 16 by the two curves which show the change in electric field strength and amount of precipitation charge reaching the earth's surface as a function of time.

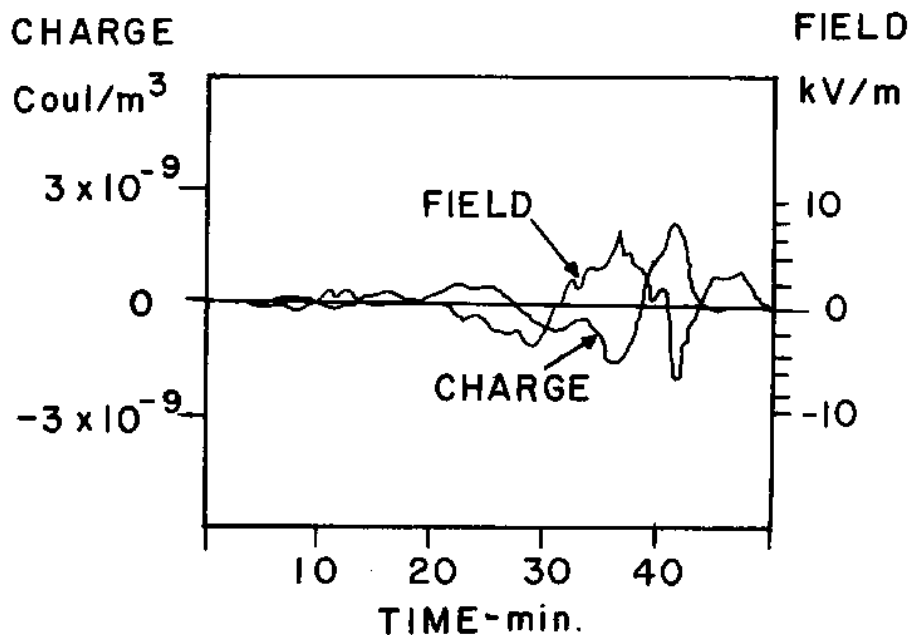


Fig. 16 The mirror-image effect.

One can easily see that when the electric field goes negative (negative charge in the cloud base) the precipitation current becomes positive and vice versa. As pointed out by Chalmers, a drop must take several minutes to fall from the cloud base to ground. Since the precipitation charge changes with the potential gradient below the cloud, it must mean that the drops also obtain their final charge below the cloud or very near ground. The electrochemical charging process can

possibly explain the mirror-image effect if one assumes that the positive to negative ion concentration ratio near ground is affected by the strong electric field under the cloud. For example, a positive charge on the earth's surface, caused by a strong negative cloud charge above, would attract and remove part of the negative ion population near the surface. The result would be a higher than normal positive to negative ion concentration ratio at lower levels. When the positive to negative ion ratio exceeds 1.2 (see Fig. 11) it will produce a positive electrochemical potential on water drops falling through such a region as demonstrated by the Gerdien apparatus experiments in section 2.1. On the other hand, a positive cloud charge above would reverse the effect because drops now fall through an environment containing a higher negative to positive ion concentration ratio which will generate negative electrochemical charges on their surfaces. Other explanations of the mirror-image effect take the Wilson charging mechanism into consideration. This charging mechanism is based on the idea that rain drops become electrically polarized when immersed in an electric field such as under an electrified cloud. A negative cloud charge above will induce a positive charge on the top surface of a drop and the bottom surface will acquire a negative charge induced by the positive charge on the earth's surface. The total net charge on the drop, however, would remain zero. As the drop falls through the ionized region below a cloud it would preferentially sweep up positive ions by its negatively-charged bottom. Calculations, however, show that the Wilson mechanism is too feeble to account for the amounts of charge normally collected by drops (the Wilson charging mechanism is discussed further in Chapter 3). In contrast to rain, precipitation currents carried to ground by snow are usually always negative under potential gradients between ± 800 V/m (Chalmers 1956). The total precipitation current around the earth is estimated to be about +340 amperes.

2.6 LIGHTNING CURRENTS

The charge brought to earth by lightning is estimated to average -340 amperes which would cancel the precipitation current. It must be remembered that a mean current of -340 amperes represents the excess of negative charge over positive charge reaching ground by lightning and that the ratio of negative to positive ground strokes equals about 10:1. The average current in a negative lightning stroke to ground is about 25,000 amperes but the total charge averages only 25 coulomb. Positive ground strokes usually carry as much as 10 times more charge and current than do negative strokes although they are outnumbered by 10:1. The ratio of negative to positive ground strokes seems to vary with global location.

It is believed that about 2,000 thunderstorms are active at one time around the earth which amounts to a total number of 50,000 thunderstorms per day.

2.7.1 THE ELECTRIC BUDGET

Where does the energy of nearly 200 million watts come from that is required to maintain the earth-atmosphere electric fairweather field? Are thunderstorms generating the fairweather field by leaking off positive charge from cloud tops to the conducting ionosphere and by bringing negative charge to earth in the form of negative ground strokes and point discharge currents? Or is the electric charge on the earth's surface maintained by the electrochemical charging mechanism in close collaboration with convection and eddy diffusion? These are some of the basic questions that are still in need of answers. Both mechanisms are, in the author's opinion, certainly capable of supplying enough charge and energy to the earth-atmosphere system, but new ideas and more sophisticated measuring techniques are needed in order to find the right answers.

2.7.2 THE GLOBAL THUNDERSTORM CIRCUIT

The concept that all thunderstorms around the world generate charge to the earth-ionosphere system was first suggested by C.T.R. Wilson in 1920. The diagram in Fig. 17 shows the global thunderstorm system

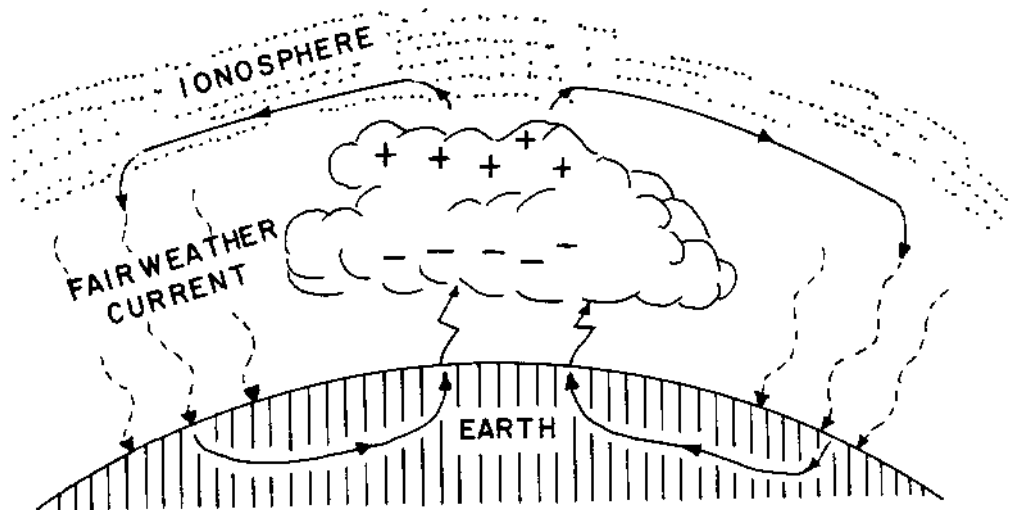


Fig. 17 The global electric circuit by C.T.R. Wilson.

as interpreted by Wilson. Electric field lines extend from the top of a cloud to the highly conducting upper layers of our atmosphere (50km and higher). Charge is presumed to leak along the field lines from the top of the cloud to the surrounding ionosphere. Note that field lines also go from the top of the cloud to ground thus leaking positive charge to ground. Negative charge is brought to ground mainly by lightning strokes and point discharge currents. The number of field lines between the cloud top and ionosphere compared to the number between cloud top and ground is an unanswered but crucial question which will determine the amount of charge supplied to the global fairweather circuit. For example, if the number of field lines going from the top of the cloud to earth would equal the number of field lines returning from earth to the bottom of the cloud, no current can flow to the ionosphere.

Another problem presents itself when one examines the charge distribution of the fairweather field. Figs. 12 and 14 illustrate that about 90% of the fairweather field and charge is confined within an altitude of 2 km which is far below the conducting ionosphere. The situation is usually explained as follows: consider two conducting surfaces such as the ionosphere and the earth's surface carrying opposite charges at a potential difference of several hundred kilovolts, the earth's surface being negative and the ionosphere positive (see Fig 17). A current driven by thunderstorm generators is flowing in the form of negative ions towards the ionosphere and positive ions towards the earth's surface. Since conductivity and ion mobility increase with altitude, it is believed that negative ions (which flow upwards) will disappear faster on the positive electrode, the ionosphere, than positive ions can disappear on the earth's surface. Positive ions which

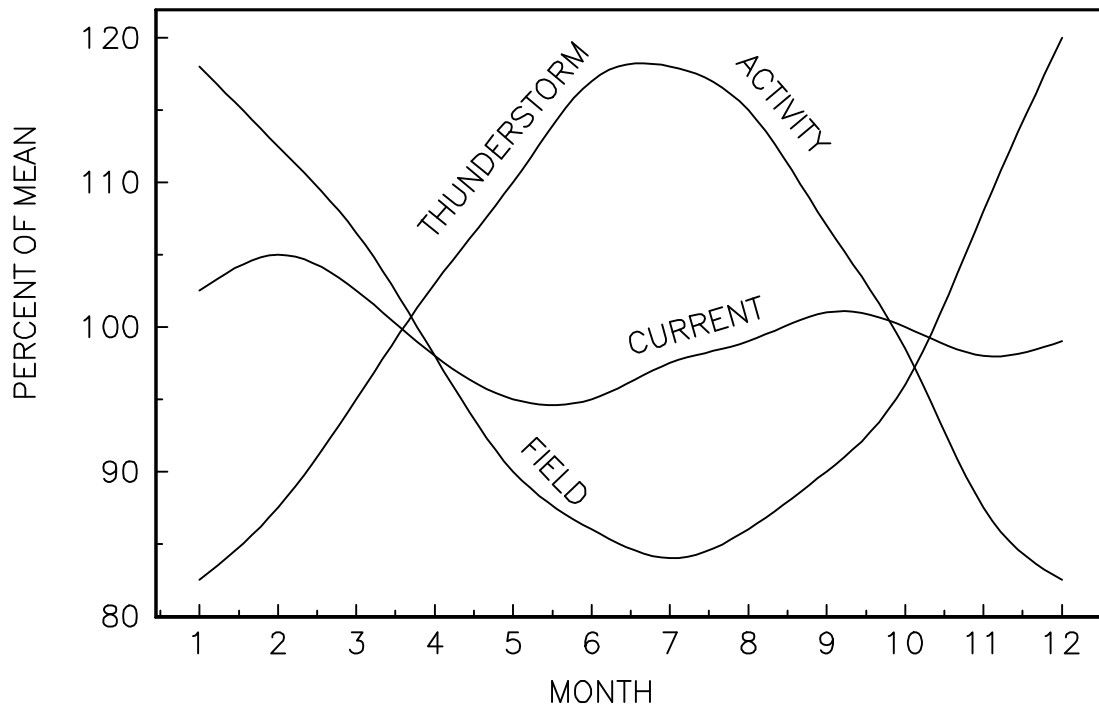


Fig. 18 Variation in fairweather field and current compared to thunderstorm activity.

face an increase in resistance are believed to slow down and congregate in a space charge cloud near the earth's surface. This is believed to produce an excess of positive ions near the earth's surface and could

explain the observed positive space charge distribution of the fairweather electric field. Plasma physics does not allow ions of one kind to disappear faster on one of the electrodes because it would mean that one of the electrodes or conductors in question would carry more current than the other, which is impossible. Theory and experiments require that an opposite and equal amount of space charge must build up near the other electrode as well (see Papoular 1965). In the case of the fairweather electric field, such a negative space charge near the ionosphere or near tops of thunderstorm generators, have never been found.

Data presented by Imyanitov and Chubarina (1967) provides little support for the closed circuit idea since they show that annual variations in the fairweather field are not in phase with typical thunderstorm activity throughout the world for the same period (see Fig. 18). Furthermore, Kasemir has pointed out that the curve showing diurnal variations of the fairweather field in Fig. 15 is much too smooth to fit the world-wide thunderstorm activity data, because recent satellite data show that thunderstorms are mainly active over continental land masses rather than over oceans (Turman, 1978, Turman and Edgar, 1982). The smooth curve in Fig. 15 might be more representative of the world-wide atmospheric convection and follows the field variations of the Austausch generator, a situation which would favour the electrochemical charging theory.

2.7.3 THE ELECTROCHEMICAL MECHANISM

The electrochemical charging mechanism considers the earth as an electrode immersed in a weak gaseous electrolyte, the naturally ionized atmosphere. The earth's surface will adsorb negative ions and achieve an electrode potential of about -0.25 volts which will appear at the earth-atmosphere interface in form of an electric double layer. This is analogous to a battery cell where an electrode becomes charged relative

to an electrolyte. The thickness of the electric double layer is very small, about 1mm in the normally ionized atmosphere. The double layer can be pictured as containing field lines which connect each captured negative ion on the earth's surface with an excess positive ion left behind in the atmosphere. As convection and eddy diffusion lift the excess positive ions to higher elevations the field lines stretch thus increasing the potential with altitude. The result is an electric field build-up which will follow a pattern completely dictated by the mixing and diffusion mechanisms in the atmosphere such as shown in Figs. 12 and 13. The field strength at the earth's surface will equal the electrochemical potential divided by the double layer thickness ($0.25 \text{ volts/mm} = 250 \text{ V/m}$) which is in close agreement with measurements. With a few exceptions (Griffiths and Vonnegut (1975), Moore and Vonnegut (1977) and Willet (1980)) no serious criticism has yet been directed against the electrochemical charging mechanism perhaps because it is relatively new theory. The above investigators believe that contact potentials rather than electrochemical potentials are responsible for the results reported by the author and that such a charging mechanism is too insignificant to play any major part in atmospheric electricity.

