PHYSICS OF ATMOSPHERIC ELECTRIC DISCHARGES IN GASES: AN INFORMAL INTRODUCTION

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Abstract.

A short account of the physics of electrical discharges in gases is given in view of its historical evolution and application to planetary atmospheres. As such it serves as an introduction to the articles on particular aspects of electric discharges contained in this book, in particular in the chapters on lightning and the violent discharges which in the recent two decades have been observed to take place in Earth’s upper atmosphere. In addition of briefly reviewing the early history of gas discharge physics we discuss the main parameters affecting violent atmospheric discharges like collision frequency, mean free path and critical electric field strength. Any discharge current in the atmosphere is clearly carried only by electrons. Above the lower bound of the mesosphere the electrons must be considered magnetized with the conductivity becoming a tensor. Moreover, the collisional mean free path in the upper atmosphere becomes relatively large which lowers the critical electric field there and more easily enables discharges than at lower altitudes. Finally we briefly mention the relation of such discharges as sources for wave emission.

Keywords: Atmosphere, quasi-stationary electric fields, discharges, sprites, jets, elves, weakly ionised plasmas

1. Introduction

1.1. A CASUAL HISTORICAL OVERVIEW

The physics of electrical discharges in gases has a long history (Bowers, 1991; Bowers, 1998) reaching back into the 17th century when in 1672 Otto von Guericke reported the production of static electric sparks when rubbing sulphur balls with the hand. A few years later in 1675 the astronomer Jean Picard reported that shaking a mercury barometer caused the tube to emit some glow. At the end of that century (around 1698) sparks from rubbed amber had been extracted and formed the subject of intense investigation by the Comte Charles François de Cisternay du Fay. Based on Picard’s observation Johann Heinrich Winckler in Leipzig invented the first what we can call ‘fluorescent tube’ in 1745, and in 1802 Vasili Petrov in St Petersburg produced electric arcs between two carbon electrodes independently but almost at the same time as Sir Humphry Davy (Knight, 1992) in London who invented the carbon arc lamp and presented it in 1807 to the Royal Institution and by which he established arc physics (Davy, 1807). They both used A. Volta’s 1799 invention of the chemical battery for their experiments. But even earlier date the famous experiments of Benjamin Franklin in 1750 on sparks which led him to coin

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the notions of positive and negative charging which were destined to survive until today and to invent the lightning rod. Mikhail V. Lomonosov in 1743 (Lomonossov, 1748) had already suggested that lightning, and polar lights as well, would be atmospheric electric discharge phenomena. With respect to the similarity between lightnings and sparks they were both right, while they could not know that auroral discharges are phenomena quite different from spark discharges. Charles-Augustin de Coulomb (1785) discovered dark discharges (Gillmor, 1971). In the 19th century the interest in gas discharges increased due to Michael Faraday’s and James Clerk Maxwell’s formulation of the physics of electromagnetic phenomena. Faraday himself even experimented with sparks and glow or coronal discharges thereby uncovering the dependence of the latter on the pressure in the tube (Faraday, 1833; Faraday, 1834). It is interesting to note that such investigations became possible by the improved glass blowing technique and the progress in evacuating glass tubes, separating gases and production of vacuum.

Experimenting on dilute gases, Johann Hittorff (Hittorff, 1879) determined the electrical conductivity of air and different gases which in 1900 culminated in Paul Drude’s seminal formula for the electrical conductivity of a gas introducing the concept of a collision frequency \( \nu_c \). The collision frequency received its physical explanation when Ernest Rutherford found the famous Rutherford collisional cross section, \( \sigma_c \), in terms of which the collision frequency can be written \( \nu_c = n \sigma_c v \) where \( n \) is gas density, and \( v \) the velocity of the moving particle. Equivalently this allowed for the introduction of the collisional free flight distance \( \lambda_{ff} = v/\nu_c \) of a particle between two collisions. When \( v \) was taken to be the thermal velocity \( v_{th} \) this became the mean free path \( \lambda_{mfp} = v_{th}/\nu_c = 1/n\sigma_c \).

Hittorff somewhat later published the first investigations on cathode rays which were crucial for the later formulation of atomic physics. Indeed, any deeper understanding of gas discharges had to wait for the advent of atomic physics, which on the other hand became possible only through reference to the investigation of gas discharges. William Crookes (Crookes, 1879) found that cathode rays were deflected by magnetic fields and called them the fourth state of matter, claiming that their investigation would lead to the deepest insight into the nature of matter. This prediction was in fact true. From the deflection of cathode rays in the magnetic field and based on the electrodynamics of charged particle motion in electromagnetic fields, J. J. Thomson (Thomson, 1897) was able to determine the elementary charge-to-mass ratio which led to the discovery of the electron. One year earlier Wilhelm Conrad Roentgen (Roentgen, 1895) experimenting with cathode rays had discovered X-rays, and these whole last decades of the century and the first decade of the next were devoted to the investigation of spectral phenomena with the help of diluted gas tubes, leading on the one hand to the determination of the Johann Balmer (Balmer, 1885), Walther Ritz (Ritz, 1908), Theodore Lyman (Lyman, 1914) and Friedrich Paschen (Paschen, 1908) spectral line series, and on the other hand to the precise mapping of the temperature dependence of black body radiation, and the energetic discreetness of collisional excitation of electrons by James Franck and Gustav Hertz (Franck and Hertz, 1914), investigations that ultimately culminated in the formulation of quantum and atomic theory and going hand in hand with the development of gas discharge physics. It is thus no surprise that most of the Nobel laureates of the first few decades of the 20th century had worked in the physics of gas discharges, among them Rutherford, John S. Townsend, Owen W. Richardson, Karl Compton, Irving Langmuir, Peter Debye and others. In particular Townsend’s (Townsend, 1901; Townsend, 1915) and Richardson’s (Richardson, 1908; Richardson, 1928) investigations of the different types of discharges were crucial for the further development of gas discharge physics. Clearly the high time of
gas discharge physics coincided with the development of atomic physics and the quantum mechanics, i.e. with the quantum theory of the atomic shell.

The first three decades of the past century saw the physics of gas discharge blossoming. With the investigation of the various processes of ionisation of gases by either radiation or collisions, the understanding of atomic spectra and the excitation processes it achieved quite a high level of sophistication and maturity. At the same time the physics of gaseous discharges bifurcated into two quite separate disciplines, proper gas discharges and plasma physics. The notion of a plasma was introduced by Irving Langmuir in 1927 (Mott-Smith, 1971) reserving it to highly ionized gases with only a small residual admixture of a non-ionised neutral component or even lacking such a component. Due to the dominance of the electromagnetic interaction in a plasma its physics turned out to be completely different from that of neutral gases. Peter Debye and Erich Hückel (Debye and Hückel, 1923) showed that electrical charges in a plasma become readily screened over a distance $\lambda_D = v_e/\omega_{pe}$, the Debye radius, where $v_e = v_{th,e}$ is the electron thermal velocity, and $\omega_{pe}$ is the electron plasma frequency, the oscillation frequency of electrons around equilibrium position (discovered by Langmuir (Langmuir, 1923)). The notion that the atmosphere of Earth must be electrically conducting goes back to C.F. Gauss who in expanding the Earth’s magnetic field in spherical harmonics discovered that it contained a substantial component due to outer sources which he suspected to be currents somewhere at large altitude above surface. It took however until 1902 when Oliver Heaviside (Nahin, 1990; Appleton, 1947; Watson-Watt, 1950) proposed the existence of a high-altitude conducting layer that reflects radio waves. This was confirmed in 1924-1927 by Edward V. Appleton (Appleton, 1947). The formation and nature of this layer was understood when Sydney Chapman (Chapman, 1931) realised that solar UV was capable of ionising the upper atmospheric layers around 100-130 km altitude being absorbed there. H. Kallmann (Kallmann, 1953) ultimately proved that taking into account the full solar spectrum the ionisation effectively reached down to below 80 km altitude, and with the advent of the space age it became clear that the atmospheric constituents can be ionized also by precipitating energetic particle impacts from the sun and cosmic rays down to much lower altitudes. These processes are reviewed elsewhere in this book.

Nobel prizes were awarded to most of the leading gas discharge researchers in this period. And in the early thirties several extended reviews were written on this subject, among them the famous accounts of Compton and Langmuir (Compton and Langmuir, 1930; Langmuir and Compton, 1931). After the golden twenties and thirties the physics of proper gas discharges lost its importance in fundamental physics becoming a branch of applied physics while plasma physics, its fully ionized twin, shifted into the centre of attention mainly because of two reasons, the interest in fusion research and advent of the space age. Space plasma physics became attractive for the public and politics. Still, in ionospheric physics and the interest in the mechanism of lightning the physics of gas discharges maintained to stay alive over all this period of relative draught.

In the more recent years gas discharges became much more interesting again in relation to natural transient luminous events (TLEs) that have been discovered (Franz et al., 1990; Sentman et al., 1995; Neubert, 2003) to go on in the upper atmosphere during thunderstorms such as spectacular phenomena like sprites, elves, and electric jets as well as the accumulation of evidence for lightnings and related effects on other planets, in planetary rings and even in astrophysical objects. In addition, the relation of such events to space weather has provided another impetus to their investigation. (The processes of the generation of the charges and separation which is required before discharge can set on are reviewed in this book by Yair (Yair, 2008) and are the content of Chapter 6. Some of
Figure 1. Rough model of temperature $T_n(h)$ and binary collision frequency $\nu_c(h)$ as functions of altitude above ground level for a simplified atmosphere. The light line shows the altitude dependence of the binary collisional mean free path $\lambda_{mfp}(h)$. In the mesosphere-thermosphere boundary region this becomes several decimetres. The vertical line shows the electron cyclotron frequency at around $\omega_{ce} = 4.5 \times 10^6$ Hz which is nearly constant over this range of heights. For this simple atmospheric model starting at the bottom of the mesosphere the binary collision frequency falls below the electron cyclotron frequency with increasing altitude (shaded region). Hence, at these altitudes the electron conductivity becomes a tensor.

these observations are discussed in the present book.) Because of the importance of such effects the physics of gaseous discharge is by far not yet exhausted. There is one particular aspect of it that in the future will certainly achieve more attention. This is the problem of the energetic coupling between near-Earth space and the atmosphere. More generally the question of how a planetary atmosphere couples to its space environment poses a problem that is of fundamental importance for climatology and the understanding how energy is fed into processes that are important for the planetary climate from the outside, the interplanetary and magnetospheric plasmas through the coupling of the ionosphere and the atmosphere. Sprites, elves and jets suggest that this is indeed an important problem which has just been barely realised and has not yet been investigated to the extent it deserves. There are extended recent reviews of these phenomena available (Fullekrug et al., 2006; Pasko, 2007).
1.2. Parameters

The electric discharge is the final step of a whole sequence of processes going on in a gas that is subject to ionisation and internal gas dynamics. Most of these processes have been or will in subsequent sections in this book be described for Earth and other planets surrounded by an atmosphere or some equivalent to it. At the end of all these processes stands an electric field of strength $E$ that is maintained in some way over sufficiently long time, and positive and negative electrical charge layers that are separated from each other by a distance $L$. This electric field can be maintained only up to a certain strength $E \leq E_{\text{crit}}$ which when exceeded causes violent breakdown of the field. Processes of build-up of the electric field are related to the various processes of ionisation and fill a considerable space in this book. Here we restrict ourselves to a very basic and by no means complete discussion of the breakdown processes. Several aspects of these will be given in great detail in the last Chapter 7 of this book.

The atmosphere is considered to be collisional with collision frequency $\nu_c$ determined mainly by collisions between electrons and the various neutral components of the atmosphere. A more sophisticated theory must take into account the composition of the atmosphere including aerosols, various excitation and ionisation processes as for instance cosmic ray ionisation or frictional ionisation and so on, the presence of a magnetic field, the horizontal and vertical dynamics of the atmosphere, its water content, temperature distribution, and its altitudinal inhomogeneity. All these factors (including those we are not aware of here) enter the real discharge process, and some of them are considered in great detail elsewhere in this book as in the article of Roussel-Dupré et al. (Roussel-Dupré et al., 2008). Here we merely mention them as not easy to treat complications of a realistic atmospheric discharge process encountered for instance in a lightning discharge or the recently discovered high-altitude discharges in sprites, blue jets, giant jets, and elves.

In the simplest model of a resistive atmosphere the collisions are treated classically (and we will not deviate from this in the present introductory paper). This implies that $\sigma_c \approx 5 \times 10^{-19} \text{ m}^{-2}$ is the constant classical two-body collisional cross section. In addition the neutral gas density obeys the barometric law $n_n(h) = n_0 \exp[-m_n g(h) h / k_B T_n(h)]$, where the index $n$ means neutrals, $h$ is the height above sea level, $n_0$ density at ground level, $g(h)$ the gravitational acceleration at altitude $h$, $m$ mass, $T(h)$ temperature at $h$, and $k_B$ Boltzmann’s constant. Note that in contrast in a fully ionized plasma the cross section is the Rutherford or (when averaged over the thermal distribution function) the Spitzer-Braginskii cross section which strongly depends on density and particle speed thus implying a completely different physics. Since in the upper layers of the atmosphere and in particular in the ionosphere the gas is partially ionized with a substantial admixture of electrons and ions the really relevant cross section will be a mixture of classical and Spitzer cross sections. In the neutral atmosphere on the other hand several other effects have to be considered which are related to the excitation cross sections of the different gas molecules, the molecular nature of the gas and the composition of the atmosphere at different altitudes as well as the different ionisation energies. Moreover, the eventual presence of an electric field and the background convective wind motions of the gas as well the effects of the external radiation change the conditions. All such effects are ignored here but for realistic cases should be taken into account in their relative importance.

With the above notations the collision frequency becomes

$$\nu_c(h) = \nu_0 \exp \left[ -\frac{m_n g(h) h}{k_B T_n(h)} \right] \sqrt{\frac{T_n(0)}{T_n(h)}}, \quad \nu_0 \equiv n_0 \sigma_c \sqrt{\frac{2 k_B T_0}{m_n}}$$

(1)
The temperature and density of air at ground level are roughly $T_0 \approx 300$ K and $n_0 \approx 2 \times 10^{20}$ m$^{-3}$. The latter value depends on what is assumed for the composition of air. In the above formula the height dependence of the gravitational acceleration $g(h) \approx g(0)(1 - 2h/R_E)$ can be safely ignored since in the altitude range from 0 to 100 km the variation of the ratio of height to Earth radius $R_E$ is $\lesssim 1\%$. The temperature (see Figure 1) in this altitude range changes by a factor of $T_0(h)/T_0 \leq 3$. Thus its change is important only in the exponential factor. At zero level we have $\nu_0 \approx 3 \times 10^9$ Hz.

Figure 1 summarises the vertical profile of the temperature and binary collision frequency in a simplified way with the collision frequency calculated for an oxygen mass dominated atmosphere. Since the Earth is magnetized the collision frequency is in principle a tensor giving rise to a tensorial electrical conductivity $\sigma = (\sigma_\parallel, \sigma_P, \sigma_H)$, where $\sigma_P$ is the conductivity perpendicular to $b \equiv B / B$, the unit vector parallel to Earth’s magnetic field $B$, and $\sigma_H$ is the Hall conductivity perpendicular to both, the electric and magnetic fields. The expressions for the components of $\sigma$ are $\sigma_\parallel = e^2 n_e/m_e \nu_e = \epsilon_0 \omega_{pe}^2 / \nu_e$ parallel to $b$, and

$$\sigma_P = \frac{\nu_e^2}{\nu_e^2 + \omega_{pe}^2} \sigma_\parallel, \quad \sigma_H = -\frac{\nu_e \omega_{pe}}{\nu_e^2 + \omega_{pe}^2} \sigma_\parallel$$

(2)

where $\omega_{pe} = eB/m_e$ and $\omega_{pe} = e\sqrt{n/e_0m_e}$ are the electron cyclotron and plasma frequencies, respectively, and $\epsilon_0$ is the dielectric constant of free space. Below the mesosphere these expressions simplify to $\sigma_P = \sigma_\parallel, \sigma_H \approx -\omega_{pe} / \nu_e$. Hence the atmosphere is practically isotropic with nearly zero Hall conductivity at these altitudes. However, as Figure 1 suggests, this changes at higher altitudes in the mesosphere. Here the collision frequency drops below the electron cyclotron frequency (the vertical line in the figure) which has a weak altitude dependence only according to the weak variation of Earth’s magnetic field $B \approx B_0(1 - 3h/R_E)$ with height in the narrow altitude range of the atmosphere. Upward of the mesosphere the full conductivity tensor comes into play, which might have consequences for the development of electric discharges at these high altitudes which are the altitudes where intense sprites, jets and elves have been observed. The electrons in this region are not collisionless, however, as the electron density at altitudes which are the altitudes where intense sprites, jets and elves have been observed.

In framing the more detailed papers collected in Chapter ?? on the most interesting special cases of atmospheric discharges in the upper atmosphere and their effects on ULF wave propagation we will in the following briefly review the types of electrical discharges that may be relevant under gaseous atmospheric conditions. We explicitly exclude here other important discharges as those in charged dust and sand storms which are considered explicitly elsewhere in this volume (Renno and Kok, 2008) but become important in the atmospheres of some of the planets (Melnik and Parrot, 1998; Farrell et al., 1999).

2. Types of discharges

In order to ignite an electric discharge in an otherwise neutral gas like the atmosphere, electrons have to be set free by some process. Subsequently an electric field must be present that can accelerate electrons to energies far above ionisation energy fast enough...
in order to cause an avalanche of newly generated electrons by collisional (or other kinds of) ionisation. For this to happen the electric field must be strong which implies that by some external force the initially present negatively and positively charged layers must become separated over a sufficiently large distance $L$. Processes capable of providing such initial charges are discussed elsewhere in this book. One of the basic processes is the weak ionisation of the atmosphere produced by the continuous inflow of energetic cosmic rays into the atmosphere and the cascades of nuclear fission products and particles which are produced by them. Charge layer separation is a complicated process closely related to the physics of clouds and their internal dynamics. The reader is referred to the respective sections of this book for information.

2.1. Townsend spark discharge

Once sufficiently much charge has accumulated to form a charge layer and oppositely charged layers have become separated from each other a macroscopic electric field is built up. As long as this field is weaker than some threshold field, discharges go on only slowly due to recombination and may be balanced by newly created ionisation. However, when the electric field exceeds a certain threshold, a violent discharge process will set in causing break-through and the electric field will be cut short. In laboratory gas discharge physics one distinguishes a number of discharges. Two of them, which are accompanied by light emission, are shown in Figure 2. To the left is the typical arc discharge between cathode and anode, to the right is a typical glow discharge observed in a glass tube. In addition there are dark or Townsend discharges which, as the name tells, are not accompanied by visible light emission. In atmospheric physics of most interest are discharges of the kind which lead to break down of electric field potentials and these are of the kind of arc discharges when, for instance, lightning arcs are generated. In addition one distinguishes non-stationary discharges in connection with spark discharges. In Townsend dark discharges the current flow is rather weak and current densities are low, and the voltage remains constant over the time of the discharge. When the current strength increase the Townsend discharge makes the transition to glow discharge. Now the energy of the flowing electrons is large enough to collisionally excite atom to emit light from infrared up to ultraviolet. Arc discharge acquires large current densities, strong electric fields, and may emit light up to deep into the ultraviolet and weak x-rays. These processes have been described in many places and are common knowledge that is found in textbooks as e.g. in the recent one of Raizer (Raizer, 1997) or an earlier one by Lieberman and Lichtenberg (Lieberman and Lichtenberg, 1994).
2.2. ELECTRON AVALANCHE

For the purposes of atmospheric discharges the formation of current carrying electron avalanches is of most importance as shown in Figure 3. The continuous slow discharges of electric fields produced by the persistent inflow of cosmic rays into the atmosphere is of interest only in providing a seed population of electrons for the ignition of an avalanching discharge. In an avalanche the electron number increases exponentially since \( \frac{dn_e}{dt} = \alpha_i n_e \) and the production of electrons is proportional to the existing electron number with proportionality factor the Townsend ionisation rate coefficient \( \alpha_i \). This relation has the solution \( n_e(t) = n_e(0) \exp\left[ \int_0^t dt' \alpha_i(t') \right] \). The exponential factor is the temporal multiplication rate of the avalanche. In fact this corresponds as well to the spatial multiplication rate over the evolution distance of the avalanche.

Avalanches have a typical structure with a negative head consisting of the fast electrons and an extended positively charged tail containing the slow freshly produced ions who tend to retard the advancement of electrons but are kept back by the external electric field that accelerates them into opposite direction. It is clear that in such a process the electric field must become strong enough in order to overcome recombination collisions and accelerate electrons in one mean free path length (see Figure 1) up to ionisation energies. The latter are of the order of a eV, for hydrogen typically \( E_{ion} \simeq 13.6 \) eV. The accelerated electrons must be able to both run away and ionise. From this reasoning follows a simple condition for the necessary strength of the external field \( E \) in order to be able to ignite a gaseous electric discharge

\[
|E| \gtrsim E_{crit} \equiv 2 (E_{ion}/e)/\lambda_{mfp}
\] (3)

At 10 km altitude this field is quite large amounting to \( (2-3) \times 10^6 \) V m\(^{-1}\) but decreases with altitude deep into the mesosphere by roughly four orders of magnitude to become there only a few 100 V m\(^{-1}\). Hence in the higher atmosphere considerably smaller electric field strengths are required in order to ignite an electric discharge. The problem therefore consists less in exceeding the threshold at these altitudes than in generating charged layers with an electric field between them. But once this can be achieved at lower altitudes a breakthrough at higher altitudes may become easier to achieve. In this respect it is noteworthy that sprites and jets have been observed to be closely related to the low altitude thunderstorm discharges starting from the top of the thunderstorm clouds. Hence, the high threshold electric field must in fact be exceeded at low altitudes of a few km already. This poses a serious problem a solution of which has been proposed only in the two past decades (Gurevich et al., 1992; Roussel-Dupré et al., 1994; Roussel-Dupré and Gurevich, 1996; Lehtinen et al., 1997; Babich et al., 1998; Gurevich et al., 2001). These authors realised and proved by kinetic simulations that a proper kinetic description of the avalanching process must take into account not only the generation of secondary electrons but also the production of run-away electrons which have energies high enough. This causes what these authors call “runaway breakdown” (RBD). The idea in this mechanism is that a small number of seed electrons initially reaching high energy in the electric field exchange the ordinary collisional cross section for ionisation with the Rutherford-Coulomb cross section when passing though the interior of the neutral molecules. The latter cross section is inversely proportional to the square of the particle energy. it thus decreases with energy which allows for energetic particles to run away in the field and obeying a power law distribution function \( f(E) \propto E^{-1.1} \) at energies below some threshold energy which is determined by radiation losses. In fact, it has been shown (Gurevich et al., 2001) that the power is a function of the ratio of the electric to breakdown-threshold electric fields. The presence of runaway electrons considerably decreases the threshold
field strength thus making it much easier for breakthrough to occur at low atmospheric
altitudes at higher pressure and density. The threshold electric field as function of altitude
\( h \) becomes proportional to the density
\[
|E| \gtrsim E_{\text{crit,RBD}} \equiv 0.2 \left[ \frac{n_n(h)}{n_0} \right] = 0.2 \exp \left[ -\frac{m_negh}{k_BT_n(h)} \right] 10^6 \text{V m}^{-1}
\]
(4)
This value is one order of magnitude less than the above value. In addition it decreases
about exponentially with altitude in the same way as the neutral density, and at higher al-
titudes becomes very low indeed. Due to the runaway electron effect the above introduced
Townsend coefficient becomes a function of the ratio of electric to critical electric field
\[ \alpha_{\text{RBD}} \approx 0.07 \left( \frac{E}{E_{\text{crit,RBD}}} \right)^2 \]
(5)
showing the pronounced nonlinearity of the process or avalanche formation. The numerical
factor has been determined from fitting numerical simulations.

3. Secondary effects

The avalanches produced in these spark discharges in the atmosphere have a number of
secondary effects. Sparks are bright, emitting light due to the excitation of both atoms
and ions which emit in various lines of the electromagnetic spectrum. Moreover, space
charges that are built up over macroscopic vertical and also horizontal length scales by
the dynamics of the neutral atmosphere due to dragging the charges also act back on
the dynamics, braking it due to the electrostatic forces that develop when the charges
become sufficiently large. Finally, the ionisation of the atmosphere considerably affects
the atmospheric chemistry. Other effects that can be expected are the generation of VLF,
ELF and ULF waves which both have been observed to occur during and in the wake
of thunderstorms and probably also coincide with sprites, jets and elves (see the papers
by Simoes, Bosinger and Mika in Chapter 7 of the present book). The mechanisms gen-
erating these emissions and variation which include compressional as well as magnetic
variations have not yet been understood. They might be related to several disturbances of
the atmosphere during breakdown.

3.1. Waves

The simplest one is the mechanical distortion of the atmosphere during noisy discharges
which causes thunder and mechanical oscillations of the atmosphere. During such distur-
bances the ionic component of the atmosphere also undergoes similar distortions which
may result in low frequency sonic waves of speed \( c_{\text{is}} \approx \sqrt{m_e/m_i}v_e \approx 40 \text{ km s}^{-1} \), where
\( v_e \) is the thermal velocity of electrons. It is usually believed that these waves are strongly
damped due to the high collision frequency at low altitudes (see Figure 1). At higher than
mesopause altitudes this argument does not hold anymore also because Landau damp-
ing will not be strong as the ions are very cold there while electrons have eV energies.
Ion sound turbulence therefore should accompany any discharge at those altitudes. At
low altitudes we must compare the mean free path of electrons with the Debye length
\( \lambda_D = v_e/\omega_{pe} \), where the plasma frequency \( \omega_{pe} \approx 60\sqrt{n_e} \text{ kHz} \), and the electron density
is measured in cm\(^{-3}\). The electron density produced in a discharge is some fraction \( \zeta \) of
\( n_n \). At 10 km altitude \( n_e \approx 2 \times 10^{10} \sqrt{\zeta} \) yielding \( \lambda_D \approx 5 \times 10^{-5} \zeta^{-1/2} \text{ m} \). Hence, for \( \zeta \)
the order of percent at this altitude the Debye length is larger or comparable to the mean
free path, increasing with increasing altitude as the root of $\zeta$. Depending on the altitude dependence of $\zeta$ the mean free path might exceed the Debye length or not. When the Debye length is shorter the plasma properties dominate and ion sound excitation cannot be ruled out. Ion sound waves will be radiated from the avalanche region in this case. Generation of VLF waves in the whistler mode requires magnetized electrons which seems to be natural at altitudes above the mesopause. From lightning spherics in the troposphere it is well known that this also occurs at much lower altitudes.

The excitation of whistlers seems quite natural as they have been observed at ionospheric and magnetospheric altitudes already on the earliest spacecraft armed with antennas for wave detection. Their correlation with spherics was clearly demonstrated there. Detection of wave phenomena at atmospheric altitudes in relation to atmospheric discharges as reported in the present book became possible however only more recently due to observations on ground and low altitude spacecraft like Demeter. The latter observations, in particular, suggest a close similarity between phenomena in the auroral region at higher altitudes and those in atmospheric discharges (Parrot et al., 2008) for which there is still no explanation available and which might force us to change our view with respect to the physics of atmospheric discharges. Such phenomena might be closely connected with the basically unresolved problem of how electron beams that are generated at lightning altitudes can propagate upward in the atmosphere up to the lower boundary of the ionosphere. A simple answer might be that a collimated weakly relativistic electron beam due to its high momentum and its much higher temperature than the surrounding atmosphere exerts sufficiently high pressure on the surrounding gas to expel it from its channel of propagation. If this is the case it represents a hot, collisionless, strongly magnetized electron plasma beam which is capable of generating electron holes on the way of the...
Buneman instability (a strong current instability in plasmas). Such holes act as sources of whistler waves which propagate on the resonance cone and have been observed in aurorae. There is a large amount of further effects such intense beams may cause as for instance heating of the local atmosphere and emission of radio waves. Currently the physics of such phenomena in the atmosphere remains to be widely unexplored.

3.2. RADIATION

Several types of radiation have been observed in relation to atmospheric electric discharges, natural and artificially triggered (Dwyer et al., 2003) lightnings in addition to the above mentioned spherics and the whistlers propagating in the upper ionosphere and magnetosphere caused by them. The latter are in fact plasma waves and cannot leave the plasma. However, discharges have been seen accompanied by radiation in the optical, radio waves, and even in UV and X rays up to the Gamma ray energy range and, recently and most surprisingly, even in the ELF and ULF wave ranges (Bosinger et al., 2008; Mika et al., 2008). Moreover, spacecraft observations of other planets (Jupiter, Saturn) seem to show indications of short time radio emissions in connection with lightnings on those planets (Fischer et al., 2008).

Referring to the above discussion of the general physics of breakdowns the least surprising forms of radiation emitted from such breakdown discharges are optical, UV, X ray and even Gamma ray emissions. An early prediction (Wilson, 1925; Wilson, 1956) based on the Townsend mechanism that lightnings should be accompanied by the generation of energetic electrons and possibly even emission of X-rays has been basically confirmed by the more recent BATSE experiment aboard the Compton Gamma Ray Observatory (Fishman et al., 1994) and by the Alexis spacecraft observations both made from space (Blakeslee et al., 1989; Holden et al., 1995). The Gamma radiation is caused by the energetic electron component generated in the runaway phase of the discharge when avalanches of electrons are formed. The radiation mechanism has been investigated theoretically (Roussel-Dupré and Gurevich, 1996; Gurevich et al., 2000; Gurevich et al., 2002). Since very high energy electrons are required to generate these Gamma ray bursts the observations completely falsify Wilson’s mechanism while they are in excellent agreement with the RBD mechanism, providing a strong argument in favour of runaway breakdown and lowering of the avalanching threshold. The Gamma rays observed are not caused in nuclear interaction, and no Gamma lines have been detected yet. They form the high energy tail of the energetic X ray emission resulting from free-free radiation of the most energetic runaway electrons. The absence of lines is an indication for the existence of an upper threshold of the accelerating electric field.

The emitted radio radiation can hardly be in the synchrotron range as this requires much higher than available emission measures, i.e. large volumes which are occupied by energetic electrons in addition to strong magnetic fields. Therefore the only imaginable mechanisms must be based on plasma mechanisms like the head-on interaction of beam generated Langmuir (L) waves due to a process $L + L' \rightarrow T$ (where $T$ is the transverse radio wave). How can they be realised in the collision dominated lower atmosphere?

Existence of L waves requires that the beam region be largely evacuated from neutral gas. Generated by a fast weakly relativistic beam they propagate in the direction of the beam. The backward moving $L'$ wave could however be generated by backscattering of $L$ at the slow cold ion component according to the process $L + i \rightarrow L' + i^*$. where $i$ is the ion involved, $L'$ the backscattered Langmuir wave the wave vector direction of which is inverted, and $i^*$ is the excited ion (which may emit light due to excitation). Similarly it is possible that L waves interact with the ion sound waves mentioned above according
to a reaction \( L + \text{IS} \rightarrow T \) (here IS stands for the low frequency ion sound wave). In the former case the emitted radio wave has frequency close to twice the plasma frequency \( \omega \simeq 2\omega_{pe} \). In the second case the emission frequency is near the plasma frequency itself since the IS wave has very low frequency only. Another mechanism may be due to excitation of electron-acoustic waves EA of frequency close to a fraction of the electron plasma frequency. The reaction equation is \( L + \text{EA} \rightarrow T \), and the frequency is above but close to \( \omega \gtrsim \omega_{pe} \), typically \(< 1.5\omega_{pe}\). All these mechanisms require the existence of plasma, hot plasma electrons and only a very small and negligible admixture of neutrals. How this can be achieved remains unclear unless pressure balance between the hot beam and the surrounding atmosphere evacuates the propagation channel of the beam as has been speculated above.

The last possible mechanism of radio emission, the electron cyclotron maser, is extraordinarily efficient (Treumann, 2006). It requires a strong field aligned electric potential, parallel current flow and a strong magnetic field in addition to a negligible component of cold electrons and neutrals. It also requires some pitch angle scattering of the electron distribution such that the electrons have a substantial perpendicular to the magnetic field velocity component (gyrating magnetized electrons). This could again be realized if the channel of electronic current flow can be evacuated from neutral atmospheric gas. In this case the maser mechanism generates intense radiation at and around the local electron cyclotron frequency \( \omega_{ce} \), which in the atmosphere is in the MHz range. The bandwidth of the emitted radiation depends on the electron beam temperature and can be very narrow up to a substantial part of the electron cyclotron frequency.

The generation of electron cyclotron maser radiation should be accompanied by other local and observable effects like the generation of electron holes via the Buneman instability. In the auroral region such holes are always present whenever electron beams flow along the magnetic field (Carlson et al., 1998; Ergun et al., 1998) closing the auroral current circuit (Elphic et al., 1998) at much higher than atmospheric altitudes above 4000 km. These holes also serve as sources for intense localised whistler packets, so-called saucer emissions (Ergun et al., 2001; Newman et al., 2002; Ergun et al., 2003) similar to those which have been reported from DEMETER observations and are discussed elsewhere in this book (Parrot et al., 2008). The observation of saucers during lightnings could be taken as indication of the presence of such electron holes in the region of strong vertical electric fields and therefore support the claim that such fields generate electron beams, cause plasmas, evacuate the lightning channel, and even cause radiation.

Most mysterious is the emission of radio waves, ULF waves and ELF Schumann resonances. The excitation of very low frequency electromagnetic radiation in the ELF and ULF range cannot be easily understood by either of these mechanisms. What mechanism can shake the magnetic field lines at such low frequencies? Energetic bursts of electron beams propagate basically parallel to the electric field across the atmosphere. Such beams can cause some side effects. For instance, the relativistic increase in the beam-electron mass at high energies combined with the large number of electrons in the energetic tail of the distribution may provide sufficient inertia to generate Alfvén waves by the electron firehose instability in mid-latitudes. This might become possible because of the very high pressure anisotropy of the strongly collimated beams with parallel temperature \( T_\parallel \gg T_\perp \), remembering that the perpendicular temperature is just of the order of the ionisation energy and the energetic beams have energies up to Gamma ray energy and consist of magnetized electrons which propagate parallel to the magnetic field. If such Alfvén waves could be generated in an electron channel in a discharge the question still remains of how those waves can transform into radio emission at such low frequencies that Schumann
resonances with free space wavelength in the $10^4$ km range can be resonantly excited in the atmospheric-ionospheric wave guide? So far no viable transformation mechanism is known.

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