

# *Atmospheric electrification in dusty, reactive gases in the solar system and beyond*

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# Atmospheric electrification in dusty, reactive gases in the solar system and beyond

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29 **Abstract:** Detailed observations of the solar system planets reveal a wide variety of local  
30 atmospheric conditions. Astronomical observations have revealed a variety of extrasolar  
31 planets none of which resembles any of the solar system planets in full. Instead, the  
32 most massive amongst the extrasolar planets, the gas giants, appear very similar to the  
33 class of (young) Brown Dwarfs which are amongst the oldest objects in the universe.  
34 Despite of this diversity, solar system planets, extrasolar planets and Brown Dwarfs  
35 have broadly similar global temperatures between 300K and 2500K. In consequence,  
36 clouds of different chemical species form in their atmospheres. While the details of  
37 these clouds differ, the fundamental physical processes are the same. Further to this,  
38 all these objects were observed to produce radio and X-ray emission. While both kinds  
39 of radiation are well studied on Earth and to a lesser extent on the solar system planets,  
40 the occurrence of emission that potentially originate from accelerated electrons on Brown  
41 Dwarfs, extrasolar planets and protoplanetary disks is not well understood yet. This paper  
42 offers an interdisciplinary view on electrification processes and their feedback on their  
43 hosting environment in meteorology, volcanology, planetology and research on extrasolar  
44 planets and planet formation.

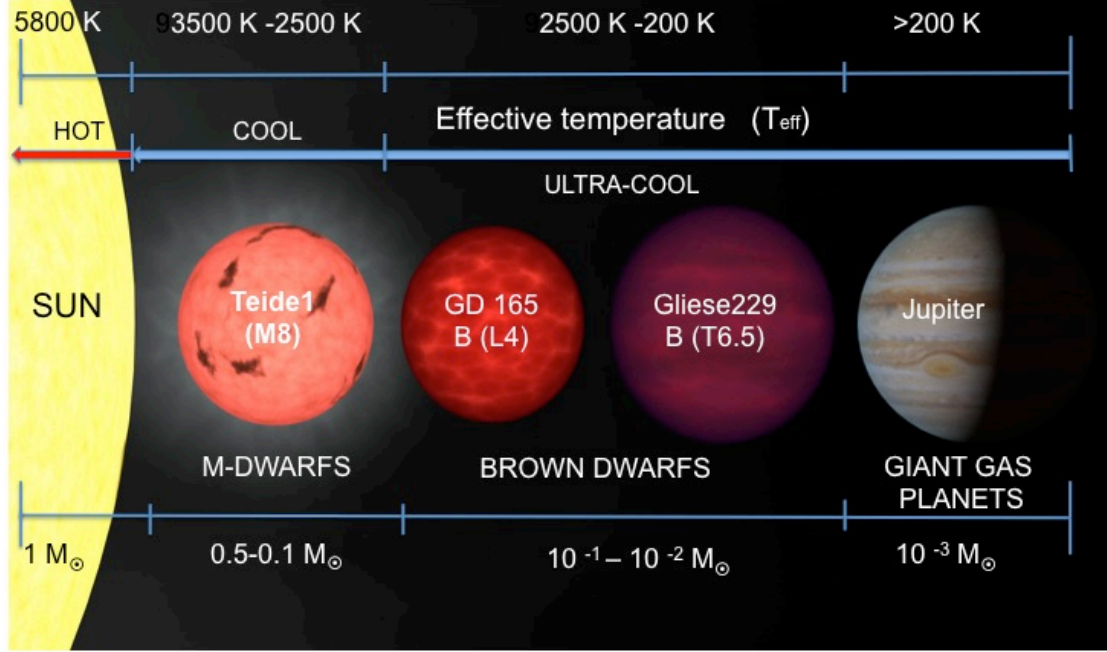


Figure 1. The large context: Planets are the coldest and smallest objects in the universe known to possess a cloud-forming and potential life protecting atmosphere. Brown Dwarfs are as cool as planets but they form like stars (like the Sun) through the collapse of a gravitational unstable interstellar cloud. Planets (like Jupiter and Earth) form as by-product of star formation in protoplanetary disks. Note that the lower temperature boundary is not yet well determined.

45

## 1. Introduction

46 The Earth and the solar system planets were the only planetary objects known until  
 47 the discovery of the first brown dwarf GD165B (Becklin & Zuckerman 1988) and the  
 48 first extrasolar planet in 1992 (orbiting the pulsar PSR1257+12, Wolszczan & Frail  
 49 (1992)). Earth, Jupiter, and Saturn are cloudy solar system planets for which atmospheric  
 50 discharges in form of lightning is confirmed observationally in radio and in optical  
 51 wavelengths. Space exploration and ground based observations have shown that lightning  
 52 is a process universal in the solar system, but also that charge and discharge processes  
 53 occur in a large diversity on solar system planets. Charging and discharging processes are  
 54 essential for our understanding of the origin of our planet and maybe even for the origin  
 55 of life: It is believed that charged dust is required to form planets and that lightning  
 56 opens chemical paths to the formation of biomolecules. The purpose of this paper is  
 57 to point out overlapping interests in electrifying media that contain liquid and solid  
 58 particles in meteorology, volcanology, solar system objects, extrasolar planets, brown  
 59 dwarfs and protoplanetary disks. We therefore provide a selective overview of atmospheric  
 60 electrification processes and related electrical phenomena based on knowledge from  
 61 solar system and Earth observations, and on lab-based research in combination with  
 62 relevant findings and development in research on extrasolar planets, brown dwarfs

and protoplanetary disks. We hope to stimulate a closer interaction between these communities.

The last few decades have taken us from a Universe with only a single planetary system known, to one with thousands, and maybe millions, of such systems. We are now entering the time when we explore theories and results derived for the solar system and for Earth in application to unknown worlds. Figure 1 places Jupiter, one of the solar system giant gas planets, into the astrophysical context: Jupiter (right) is compared to the coolest stellar objects (M-dwarfs and Brown Dwarfs). Brown Dwarfs bridge the stellar (represented by the Sun in Fig. 1) and the planetary regime as their atmospheres can be as cold as those of planets but they form like stars. The Sun (left) is surrounded by hot plasma (corona) while planets are enveloped in a cold cloud forming atmosphere some of which exhibit electrical phenomena as part of a global electric circuit. The Sun is intensively studied by satellites like SOHO<sup>1</sup> and HINODE<sup>2</sup> leading to efforts like SWIFF for space weather forecasting (Lapenta et al. 2013). Comparable high-resolution monitoring is neither feasible for solar system planets, moons or comets nor for extrasolar objects. Instead, experimental work on Earth, Earth observation, modelling and comparative studies for the solar system and extrasolar objects need to be combined; examples for Earth studied as extrasolar planet are e.g. in Kitzmann et al. (2010); B  tr  mieux & Kaltenegger (2013) and Hodos  n et al. (2016).

Figure 2 compares images, spectra (disk-integrated radiation flux), atmospheric ( $T_{\text{gas}}$ ,  $p_{\text{gas}}$ )-structures, and the local degrees of gas ionization for Earth, Saturn and two types of Brown Dwarfs (L-type (pink) – hotter, and T-type (purple) – cooler). All data for Earth are from observations, the Saturn data are derived from Cassini<sup>3</sup> spacecraft observation, the brown dwarf spectra are observed with SpeX on IRTF<sup>4</sup> (Cushing et al. 2005), and the ( $T_{\text{gas}}$ ,  $p_{\text{gas}}$ )- and the  $f_e$ -structure are results from atmosphere simulations.  $f_e$  refers to the local degree of ionisation and is defined as  $f_e = p_e/p_{\text{gas}}$  with  $p_e$  and  $p_{\text{gas}}$  the local electron and the local gas pressure, respectively. The Earth image is a photograph taken from the International Space Station. The Saturn image is a visible light image taken by the Cassini space craft, and the brown dwarf image is an artist’s impression based on atmosphere simulations. No direct image exists for any brown dwarf because the nearest brown dwarfs (the binary system Luhman 16) is 6.59 light years away from Earth. All three classes of objects have chemically and dynamically active atmospheres that form clouds and that may be undergoing local charge and discharge events. Their local atmospheric conditions differ, including the chemical composition, as result of their formation history and the irradiation received from a host star. Interdisciplinary research combining plasma physics, meteorology, volcanology, solar system exploration and astrophysics as suggested in (F  llekrug et al. 2013) is required to study weather phenomena on Earth, solar system planets and on extrasolar planetary objects also in view of upcoming space missions like CHEOPS<sup>5</sup>, PLATO<sup>6</sup> and JWST<sup>7</sup>.

<sup>1</sup> <http://sci.esa.int/soho/>

<sup>2</sup> [http://www.nasa.gov/mission\\_pages/hinode](http://www.nasa.gov/mission_pages/hinode)

<sup>3</sup> <http://sci.esa.int/cassini-huygens/>

<sup>4</sup> <http://irtfweb.ifa.hawaii.edu/spex/>

<sup>5</sup> <http://sci.esa.int/cheops/>

<sup>6</sup> <http://sci.esa.int/plato/>

<sup>7</sup> <http://jwst.nasa.gov/>

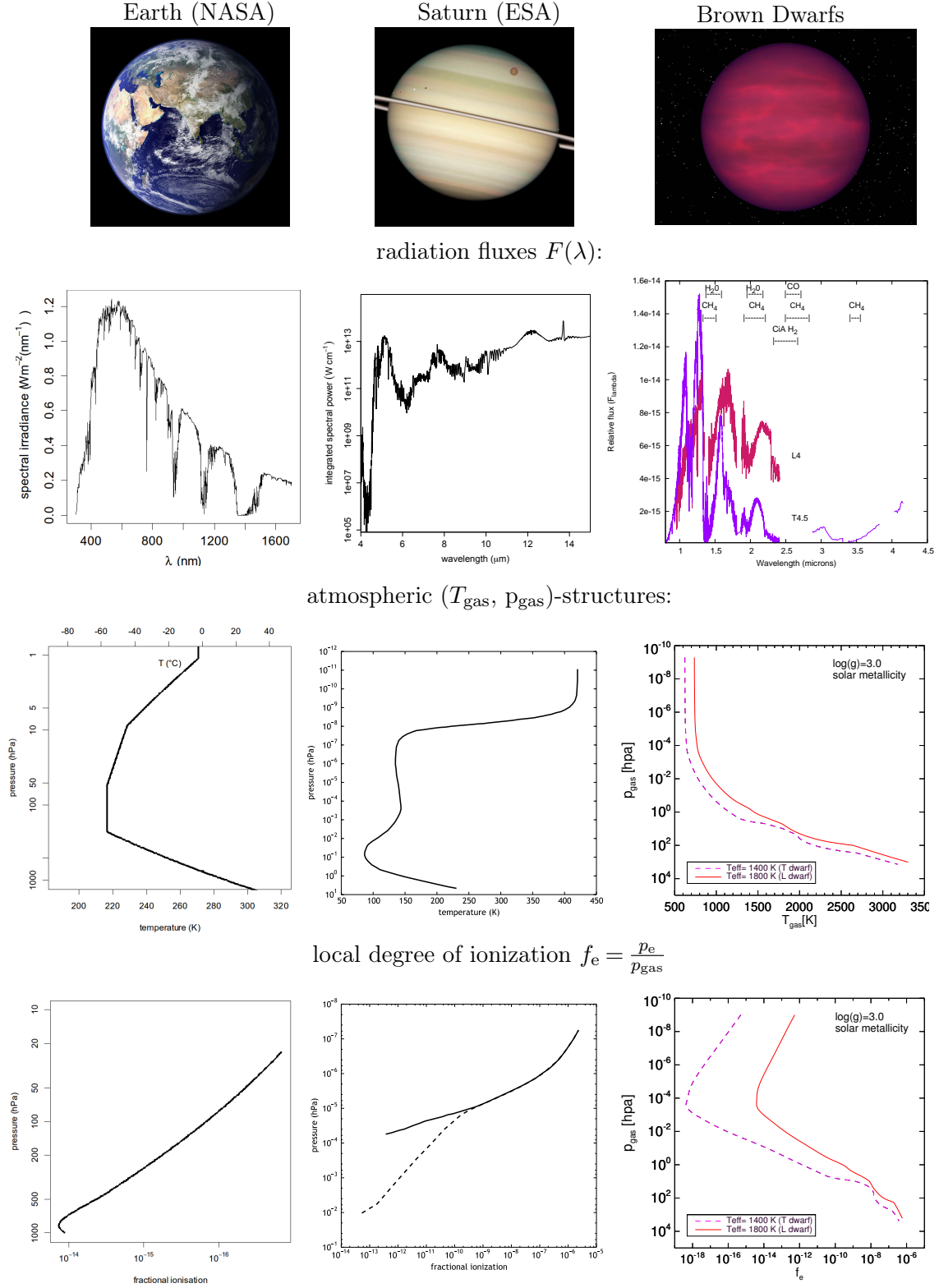


Figure 2. This figure shows the spectrum of emitted radiation,  $F(\lambda)$ , the temperature profile as a function of pressure going up into the atmosphere, ( $T_{\text{gas}}$ ,  $p_{\text{gas}}$ ), and the degree of ionisation,  $f_e$ , as a function of pressure for planet Earth, for Saturn and for two brown dwarfs. The Saturn thermodynamical data are from Moses et al. (2000), Moore et al. (2004) (solid line) and Galand et al. (2009) (dashed line) were used to derive the degree of ionization [courtesy: Alejandro Luque]. Saturn's disc-integrated spectrum is based on the latest profiles of atmospheric temperature and gaseous composition derived from analysis of Cassini Composite Infrared Spectrometer spectra (Irwin et al. 2008; Fletcher et al. 2012; courtesy: Leigh Fletcher). The brown dwarf spectra are from Cushing et al. (2005) [courtesy: Sarah Casewell], the atmosphere models from Witte et al. (2011) [courtesy: Isabel Rodrigues-Barrera].

Plasma and discharge experiments are essential in providing a controlled environment in contrast to observation of atmospheric phenomena. Such experiments can involve the three different mass components constituting an atmospheric gas: electrons, ions, and dust particles with their masses  $m_{e-} < m_{ion} < m_d$ . The mass differences result in different spatial effects like ion acoustic waves and plasma crystals. An atmospheric environment that is only partially ionized may show plasma character on only local scales compared to the global scale of the comet, moon, planet, brown dwarfs or protoplanetary disk. One potentially far reaching example for the origin of life on Earth are volcanoes (Johnson et al. 2008) which can produce significant electrostatic charging and subsequent lightning during eruption (Sect. 3d) on Earth and maybe also on Jupiter's moon Io for example. In volcanoes but also in terrestrial clouds, particles of similar mass govern the charge and discharge processes and plasmas form during violent discharge only. Understanding dust charging processes is important for space exploration because the local ionization changes as result of the variability of the solar wind hitting the moon's or an asteroid's surface. A spacecraft landing, like Philae, the Rosetta lander, has a very similar effect (Sect. 4). In situ measurements from the chemically active Earth atmosphere offer insight in charge and discharge processes, their local properties and their global changes (Sect 3a). While plasma experiments are conducted in a controlled laboratory environment, measurements inside the uncontrollable Earth's natural atmospheric environment lead to an understanding of the vertical and horizontal ionization where the relative importance of electrons, ions and dust, hence their total mass relation, changes with atmospheric height. For example, the fair weather current is carried by ions only due to the lack of free electrons between 0–60 km. Understanding the *Wilson Global circuit* (Sect. 3c) helps the understanding of the Earth weather and climate. Such observations allow an understanding of atmospheric processes on Earth that can only be gained for solar system and extrasolar bodies by intensive modelling efforts guided by observations and experiments.

Section 2 provides a short background summary on charge processes of discrete solid or liquid surfaces in atmospheric gases, the link to laboratory works and an example of related plasma technology development. Section 2 further sets the stage for this interdisciplinary paper by defining terms used in later sections.

Section 3 summarizes charging and discharging processes in the terrestrial atmosphere, including processes in the atmospheres of other solar system planets. Section 4 reviews charging processes on moon and asteroids in the presence of solar wind and space plasmas, but without substantial neutral atmospheres. Section 5 provides insight into astronomical observations that suggest that mineral-cloud forming atmospheres of brown dwarfs and extrasolar planets are also electrically active, that different ionization processes will electrically activate different parts of such atmospheres, and that similar processes are expected to act in protoplanetary disks. Section 6 concludes this paper. Each section ends with a list of future works/ open questions when suitable.

## 2. Setting the stage for interdisciplinary exchange

This section outlines the key concept of this interdisciplinary paper and it provides definitions of terms used in Sects. 3 - 5. This section links to laboratory experiments which have driven the understanding of ionised atmosphere gases that contain or form dust



particles or liquid droplets. One example of plasma technology development is included to demonstrate the impact of this paper's theme also beyond academic research. This section deals with the smallest scales where charge processes act, later sections will address topics related to successively larger-scale charge processes in the terrestrial atmosphere, on the Moon and asteroids, and also outside the solar system in extrasolar planets, brown dwarfs and protoplanetary disks.

#### (a) *Fundamental charging processes*

The key concepts in this paper depend on the accumulation and dissipation of electrical charge on discrete solid or liquid surfaces suspended in atmospheric gases. The free charge on the surfaces can arise from two primary mechanisms (in the planetary atmosphere context): processes involving (i) friction (triboelectric charging); and (ii) the transport of free charge (plasma processes). More details on processes specific to various environments like Earth atmosphere, volcanoes or extrasolar planets are provided in the respective subsections (e.g. Sects. 3a, b and d).

##### (a.1) *Classical frictional charging*

Transiently contacting surfaces can lead to charge accumulation, by producing either a surplus or a deficit of electrons compared to the neutral case. Indeed, there is evidence that fragments of polymer chains can be exchanged by colliding particles (Saunders 2008), leaving net charges on the surfaces. This process is termed triboelectric charging, and has a very long history of practical application (Galembeck et al. 2014), even if the underlying processes are still not entirely resolved. Originally, *contact electrification* was used to refer to electrostatic charge transfer resulting from contact, including contact modes such as detachment, sliding, rolling, impact, etc. The specific charge processes related to rubbing was only later termed as tribo-electrification. Such charging is an inevitable consequence of the frictional interaction between hard surfaces: electrons transfer (by some process) from one surface to the other, leading to charged surfaces. For example, dust entrained in strong, collisional flows (such as volcanic eruptions or mineral clouds in extrasolar planets, Sects. 3d and 5) will acquire charges of different polarity (negative and positive) directly from the inter-grain collisions themselves. Such macroscopic particles can include ice crystals in atmospheric clouds, where the diversity of growth rates (and consequent dynamics) of crystals influences the polarity of charge transfer, and leads to such clouds becoming charge separated by the relative drift of the charged particles (Saunders 2008). Charge accumulation and separation can lead to energetic relaxation, in the form of lightning.

##### (a.2) *Plasma charging*

There is an additional mechanism for forcing charge onto a surface, in possibly much larger quantities than can be acquired by triboelectric or contact processes: plasma charging. A plasma is a gas in which a fraction of the molecules are ionised, leading to an abundance of free charge existing as an additional 'gas' component. Though neutral overall, there is a natural scale-length over which the plasma can create large potential differences caused by charge population fluctuations: this is because free electrons are light and mobile compared to the heavier positive ions, and therefore the electrons can

temporarily escape their charged counterparts, leading to charge densities appearing for short intervals, and over restricted distances (this is explained in detail in subsequent sections below). Should an isolated solid (dust or crystal) or liquid (aerosol) surface be introduced into this plasma, these natural fluctuations in the charge distribution will cause such surfaces to acquire surplus free charge, forced onto it by the action of the plasma itself. Isolated surfaces exposed to plasma will quickly (typically on a microsecond timescale or less) charge up to reach the plasma or floating potential (Khrapak et al. 2012; Khrapak & Morfill 2008; Hutchinson & Patacchini 2007), by the action of a continuous electron current to the surface from the ambient plasma, which rapidly establishes a negative charge before the compensating positive ion current can respond. Ultimately there is a balance reached, but one that reflects the relative electron mobility over the ions. Since there is so much more free charge available in a plasma compared to triboelectric processes, then there is an enhanced capacity for dust exposed to plasma discharges to store considerable surface charge in comparison to purely collisional interactions between grains: since the plasma surface charge reflects the plasma conditions, and not just the grain chemistry and collisionality, then the plasma is an independent and effective agent for creating charged particles.

### (a.3) *Defining general terms*

After a summary of the principal mechanisms for charging surfaces in gases in Sects. a.1 and a.2, the most important vocabulary used throughout the paper is defined below to allow a better understanding of the links between the interdisciplinary topics in Sects. 3-5. Appendix 1 provides a glossary.

*Dust particles, aerosols, droplets:* An important feature in many charging processes is the presence of macroscopic particles such as dust, aerosols or droplet. These are macroscopic particles large enough to move under the influence of gravity. The particle sizes can vary by orders of magnitude. They can be liquid or solid. They can be composed of a mix of different materials that changes with temperature. *Aerosols* are suspended particles of either phase. Dust is predominant on moon and asteroids, in volcanic lightning and mineral clouds of extrasolar planets and brown dwarfs, and as building blocks for planets in protoplanetary disks. Also hydrometeors (droplets, graupel and ice particles, snowflakes ...) could fall into this category, but are considered aerosols in geoscience. Macroscopic particles as dust and aerosols can be electrically charged which de-mobilizes the charge that previously resided in the gas in form of electrons or ions. Dust, for example, will acquire a negative total charge in the absence of external influence like stellar UV radiation.

*Ionization* is the process of dissociating neutrals into charged species, due to a variety of mechanisms: electron impact ionization, Penning ionization (ionization through chemical reactions), direct dissociation by strong electric fields, UV-photo-ionization. The total electric charge is conserved during ionization, but once the charges are free they can move independently. In air (the atmospheric gas on Earth with its electronegative oxygen component) free electrons are very short lived in the absence of strong electric fields. Ionized air in the Earth troposphere and stratosphere consists of positive and negative ions. The fair weather currents on Earth are ion currents (see Sect. 3c).

*Plasma* is a gas consisting of charged particles. It is often restricted to charged particle gases where collective phenomena, like plasma oscillations, are more important than

collisional phenomena. A *plasma* is created if there is sufficient ionization of neutrals that charged particle density becomes significant. A plasma is characterized by the capacity to produce a collective self-field that is significant when compared to any imposed field (such as that produced by external electrodes, or induced by collapsing magnetic fields, or by impinging electromagnetic radiation). An electrically neutral medium is created that can respond to an external electromagnetic field, but there is no spontaneous charge separation in equilibrium on scale-lengths greater than the Debye length<sup>8</sup>. There is a significant distinction between plasmas which are collisionless, and those which are collisional<sup>9</sup>: 1) Collisionless plasmas consist mainly of positively charged ions and of electrons or negatively charged ions, depending on the electronegativity of the ionized gas. They interact through electromagnetic fields rather than through mechanical collisions. Examples are the magnetosphere and the interplanetary plasma (Sect. 4) where the assumption of ideal MHD holds. 2) In a collision dominated plasma, the motion of charged particles is dominated by collisions with neutral atoms and molecules, rather than by the direct electromagnetic interaction with other charged particles. The transiently existing plasmas in the terrestrial tropo-, strato- and mesosphere up to the E layer of the ionosphere are mostly collision dominated plasmas, except for the highly ionized and hot lightning return stroke channel.

*Charging or Charge separation* will be used for the process where macroscopic particles like dust or aerosols are charged. This can occur in particle collisions (in thundercloud electrification, dust devils in deserts, volcanic lighting) in non-ionized atmospheres or in vacuum, or by attaining charge from a plasma (e.g. in dusty plasmas) spontaneously due the different mobility of the charged species, in ambipolar diffusion, for example.

If mechanical forces (gravity, convection) that act on the charged dust particles are stronger than the electric forces, charges can be separated over a certain distance. An electric potential builds up that can discharge by lightning and the related transient luminous events.

*Electrification* is understood as the processes leading to charging of dust or other macroscopic particles obeying both polarity and charge conservation. As a result, a macroscopic electric field can build up. Sometimes used synonymously with *Charging or Charge separation*.

*Discharging* is the process where the electric potential is released by electric currents. This can happen continuously, or through a rapid transition like the rapid growth of discharge channels in lightning discharges. Emission of high energy radiation can be associated with the rapid channel growth.

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<sup>8</sup> The Debye length is the length beyond which the Coulomb force of a charge can not affect other charges. Strictly, the Debye length is the e-folding distance within which charge neutrality is not guaranteed, because thermal fluctuations can displace electrons relative to positive ions, leaving a small net charge.

<sup>9</sup> These terms refer to approximations made in the plasma kinetic gas theory where the Boltzmann equation describes the evolution of the particle distribution function  $f(\vec{x}, \vec{v}, t)$ . Neglecting the collisional source term of the Boltzmann equation leads to the *collisionless Boltzmann equation* (*Vlasov equation*) from which then the MHD equations are derived, and the electric and magnetic field strength are derived as macroscopic quantities. In a collisional plasma, the full Boltzman equation is to be solved.

(b) *Charged dust in experimental work*

Dust in plasmas has a long history - one which is even more relevant in contemporary planetary exploration. This section explores the phenomena associated with dust interacting with ionization in the ambient atmosphere to ensure non-equilibrium processes (both physics and chemistry) have a significant and enduring influence on the evolution of the atmosphere in general, including the dust itself. The discussion here ranges over the impact of charged dust imposing a long-range order in confined plasmas, through to micro-discharges arising from binary encounters between freely-floating charged aerosols, releasing low-energy free electrons into the ambient atmosphere, with all the possibilities that this entails for molecular activation by dissociative attachment and radical formation. The common theme throughout is the capacity - literally - for dust to retain the electrostatic memory of ambient discharges via free-charge acquisition, and for that discharge legacy to be reshaped and realised in potent form by harnessing hydrodynamical forces on fluid timescales, rather plasma ones. In this way, transient plasma effects can be stored, reconfigured and released on meaningful scales in such a way as to have a tangible influence on large-scale evolution of planetary atmospheres. The following sections discuss dust-plasma interactions in (i) laboratory plasma dust, where floating particulates can be a help or a hazard in plasma applications, including plasma crystals, and in (ii) the dynamic evolution of charged aerosols, where fluid deformation and evaporation can moderate the evolution of encapsulated targets.

(b.1) *The plasma laboratory: Dusty plasmas and plasma crystals*

Dusty plasmas have been studied in laboratory experiments for several decades. Langmuir et al. (1924) reported the observation of minute solid particles and aggregates in a laboratory streamer discharge and suggested the dust could play a role in ball lightning (see also Rakov & Uman 2003 for a review). ‘Dusty plasmas’ are sometimes referred to as ‘complex plasmas’ although the latter description is more wide-ranging and can include other types of constituents and features such as sheaths (Phelps & Allen 1976), quantum effects and dust. *Dusty plasma* is referred to in cases when collective behaviour of dust becomes important resulting in new types of waves and instabilities. This occurs when the Debye length and inter-particle distance are of the same order and the effects of neighbouring particles cannot be neglected, as opposed to the case when the Debye length is much less than the typical inter-particle distance (isolated charged dust).

The experimental research on dusty plasmas in laboratories has (i) been aimed at increasing fundamental understanding and (ii) also been strongly motivated by the need to control the behaviour of dust in plasmas that are used in industrial applications. Dust deposited from within the plasmas that are involved in the semiconductor component fabrication and materials processing industries can damage the components and significantly affect the productivity of these industries. In contrast to the need to mitigate the potentially harmful effects of dust in industrial plasma etching and deposition, the capability to form and control dust in plasmas is being exploited in the production of nanoparticles for the expanding nanoscience industry.

Fundamental research programmes have explored phenomena such as dust crystallisation and wave propagation within dusty laboratory plasmas where a stationary and fully ionised gas is considered. In laboratory experiments the earth’s gravitational field influences the dusty plasma behaviour and while the vast majority of experiments have

313 been carried out in laboratories on the surface of the earth, there have been some  
 314 experiments on dusty plasmas carried out in the near-weightless conditions within the  
 315 International Space Station. Whereas at sea level 2D dust crystals can be produced, the  
 316 low-gravity conditions are usually needed to produce 3D dust crystals.

317 Several types of waves, including longitudinal electron plasma waves and ion acoustic  
 318 waves (Allen & Phelps 1977), can propagate in dust-free plasmas formed from ionized  
 319 gas and containing electrons and ions as well as some neutral atoms and molecules.  
 320 Additional wave propagation modes appear if a magnetic field is applied to the plasma.  
 321 While all of these waves are damped usually as they propagate it is also possible for them  
 322 to become growing waves, or instabilities (Allen & Phelps 1977; Kuhn et al. 1981), when  
 323 appropriately excited. For example ion acoustic waves (Allen & Phelps 1977) can be  
 324 driven unstable by passing a current through the plasma, i.e they are triggered by a drift  
 325 motion of the electrons relative to the ions. In a dusty plasma the charged, massive dust  
 326 particles can produce new types of wave motion: The dust ion-acoustic wave (DIAW)  
 327 is a modified ion acoustic wave, where the ions continue to provide the inertia and the  
 328 presence of the quasi-stationary charged dust particles modifies the normal ion acoustic  
 329 wave dispersion. In contrast to the DIAW, in the dust acoustic wave (DAW) the dust  
 330 particles move and provide the inertia rather than the ions. Both the DIAW and the  
 331 DAW can be observed because their frequencies are low enough for camera systems to  
 332 resolve the images of the wave propagation.

333 Measurement of dusty plasmas in the laboratory and comparison with simulations using  
 334 particle in cell (PIC) codes allows these codes to be benchmarked against the laboratory  
 335 experimental observations. PIC code simulation of laboratory plasma experiments and  
 336 comparison with space measurements has proven successful in the case of auroral  
 337 kilometric radiation (Speirs et al. 2008; McConville et al. 2008) because of their capability  
 338 to simulate the onset and dynamics of microinstabilities in dusty plasmas. The use of  
 339 PiC codes to simulate the behaviour of dusty plasmas in space should prove equally  
 340 fruitful in obtaining detailed explanations of the formation, properties and consequences  
 341 in astrophysics (Shukla & Mamun 2002; Fortov & Morfill 2010).

#### 342 (b.2) *Delivering charges to microscopic particles*

343 The evolutionary processes governing the dynamics and stability of charged macroscopic  
 344 water droplets in a discharge plasma are part of an innovative collaborative project  
 345 on bacteria detection (Rutherford et al. 2014; Maguire et al. 2015). The technique of  
 346 using droplet evaporation as a moderator for charge deposition provides a method to  
 347 precisely deliver a known amount of charge to microscopic particles such as bacteria  
 348 cells or (cloud) condensation seeds. For that, aerosolised bacteria samples will be passed  
 349 through a discharge plasma to acquire significant electrical charge which can be measured  
 350 in the lab. If the charge-carrying aerosol evaporates, it's surface area decreases but the  
 351 aerosol retains the charge. Ultimately, if the Coulomb force overcomes the surface tension,  
 352 then the droplet expels charge to bring the retained charge back into the stability limit  
 353 (the Rayleigh limit  $Q_r(t)$ ), which is a function of its radius. Hence the droplet continues  
 354 to track the Rayleigh limit<sup>10</sup> as it evaporates. Once all the fluid has gone and the interior

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<sup>10</sup> The Rayleigh limit,  $Q_r(t)$ , gives the limiting size of the surface electric field that balances the surface tension: the latter provides the restoring force to return the droplet to it's equilibrium spherical shape, and so causes the perturbed droplet to oscillate. If the distorted outer surface of the droplet carries

355 seed particle (bacterium or grain) is revealed, the charge placed on it is known. This is  
 356 the charge consistent with the Rayleigh limit at the radius of the grain.

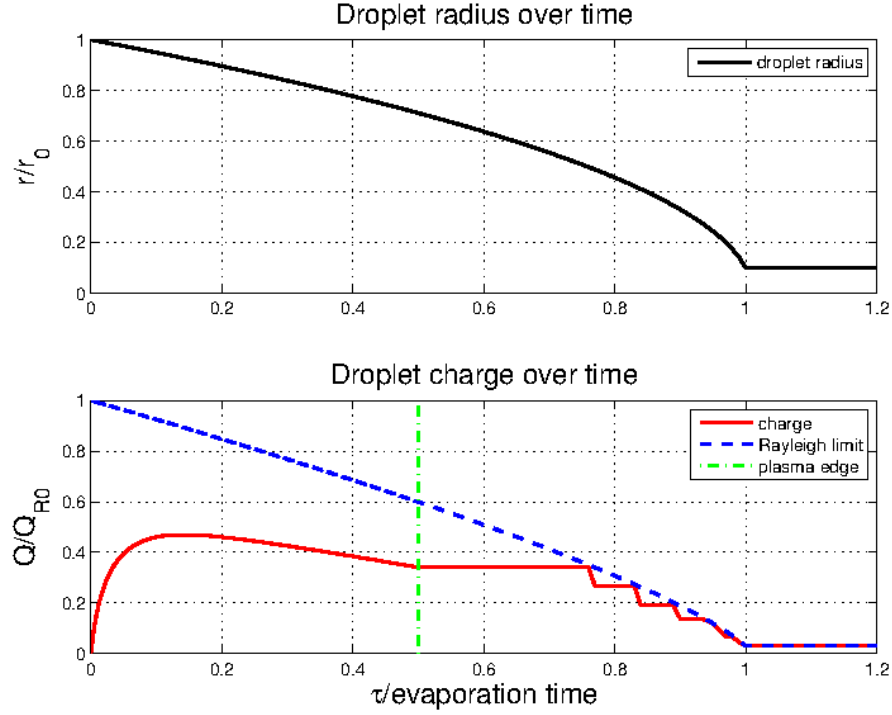


Figure 3. The figures show the evolution of a liquid droplet that acquires a surface charge as a result of travelling through a plasma discharge. The horizontal axis is time, normalised to the characteristic time required to reduce (by evaporation) the droplet radius to one tenth of its initial value. The droplet spends 50% of its evolution inside the plasma; the green dotted line shows the time at which the droplet leaves the discharge environment. **Top:** The radius evolution as the droplet evaporates. **Bottom:** The charge (red line) and Rayleigh limit (blue line) of an evaporating water droplet containing a bacteria cell that is one-tenth of the initial droplet radius. Time is normalised. Outside the plasma, the charge on the droplet remains relatively constant until the stability limit is reached, at which point the droplet emits enough charge to remain stable and enters a feedback cycle of emission and evaporation. The final charge deposited on the bacterium is closely linked to the Rayleigh limit of the minimally-encapsulating droplet (Bennet et al. 2014).

357 The charging mechanism can be described as follows (Bennet et al. 2014). Water droplets  
 358 entering a plasma will form a sheath between the droplet surface and the plasma, as a  
 359 simple consequence of the disparity in mobility between electrons and ions. Electrons  
 360 will collide more frequently with the drop surface and remain there, causing it to acquire  
 361 a negative surface charge. The charged droplet will then attract positive ions from the

---

sufficient electric charge, then the local surface field may oppose the effect of surface tension and thus prolong the restoration to equilibrium profile, i.e. reduce the oscillation frequency. If there is sufficient surface charge, then the deformation persists, and the oscillation frequency is formally zero which defines the Rayleigh limit. Exceeding the Rayleigh limit means that the droplet is unstable to perturbation, and is forced to eject charge and mass.

plasma until the electron and ion currents to the surface of the droplet reach equilibrium; at this point, the droplet is at the plasma potential.

Suppose an initially stable water droplet has acquired charge by passing through a plasma (or indeed by an alternative charging mechanism; green vertical line in Fig. 3) and is now floating freely in air, having left the plasma behind. If the the initial droplet charge is less than the initial Rayleigh limit,  $Q_{r0}$ , of the droplet, then the droplet it is stable. As evaporation proceeds outside the plasma, the droplet charge stays roughly constant, while the Rayleigh limit,  $Q_r(t)$ , evolves according to

$$Q_r(t) = \beta(t)Q_{r0}, \quad (2.1)$$

with  $Q(t=0) = \alpha Q_{r0}$ ,  $\alpha < 1$  being the initial charge on the droplet, and  $\beta(t) < 1$  for all  $t > 0$ . The initial values for the results in Fig. 3 are:  $\alpha(t=0) = 0.0025$ ,  $r_0 = r(t=0) = 10\mu\text{m}$ ,  $Q(t=0) = 10^4$  because the Rayleigh limit is  $4 \times 10^6$  e.  $\beta = 1$  at  $t = 0$ ;  $\beta$  is not shown in Fig 3. If  $Q_r(t)$  decreases far enough that  $Q_r(t) \approx Q(t)$ , then the droplet will become unstable and emit sufficient charge to restore the stability condition of  $Q_r(t) > Q(t)$ . Evaporation continues until once again the stability condition is broken and more charge is emitted back into the ambient gas. This feedback loop continues until the entire droplet has evaporated.

As the droplet evaporates, both the droplet radius  $r(t)$  and the Rayleigh limit for the charges on the droplet,  $Q_r(t)$ , decrease. If the droplet encapsulates a bacteria or dust grain, the evaporation cannot proceed beyond a minimum radius  $r_m$ . The final charge on the droplet of size  $r_m$  at a final time,  $t_f$ , is then

$$\begin{aligned} Q(t_f) &\approx \beta(t_f)Q_{r0} = Q_r(t_f) \\ &\approx 8\pi\sqrt{\gamma\epsilon_0 r_m^3}. \end{aligned} \quad (2.2)$$

The upper limit of final droplet charge depends only on the minimum radius of the particle,  $r_m$ , left behind once the droplet has evaporated, irrespective of the starting charge. This is assuming that the Rayleigh limit is encountered at some intermediate point in the evaporative evolution of the water mantle that forms the drop encapsulating a bacteria or dust grain.

This is a valuable process, since grains processed in this way carry the electrostatic legacy of the plasma environment encountered earlier in their history. Such charged particles can either act as a source of low-energy free charge injected into the atmosphere to produce non-equilibrium electron-moderated chemical evolution of the latter (for example, dissociative attachment producing radicals) or indeed a constraining electrostatic environment stable over fluid length and time scales.

### 3. Electrification and discharging in terrestrial and planetary atmospheres

When we aim to understand electrification and electric phenomena in weakly ionized atmospheres of extrasolar planets, a characterization of the phenomena on Earth and in the atmospheres of solar system planets can provide guideline and inspiration. This section therefore starts with an overview of the main electrical processes in the terrestrial atmosphere up to the ionosphere, the fair weather currents and the thunderstorms

399 with transient luminous events and terrestrial gamma-ray flashes. Then we continue  
 400 with lightning phenomena in volcanic ash plumes and review a few processes in the  
 401 atmospheres of other solar system planets. For more details see Rakov & Uman (2003);  
 402 Leblanc et al. (2008) and Dwyer & Uman (2014); Betz et al. (2009); Füllekrug et al.  
 403 (2006); Ebert & Sentman (2008).

404 Ionization and electric currents in the terrestrial atmosphere are driven by two main  
 405 mechanisms: a) The atmosphere is very weakly ionized by external sources like Cosmic  
 406 Rays and radioactivity (Sect. 3a). The resulting conductivity supports the fair weather  
 407 currents that relax electric potentials in atmospheric regions far from thunderstorms. b)  
 408 Thunderclouds play a particular role in separating electric charges and in building up  
 409 large electric potentials (Sect. 3b). Cloud particles first exchange charge during collisions,  
 410 and are then separated due to mechanical forces (such as gravity and convection) larger  
 411 than the attractive electric forces between particles of opposite polarity. For this reason,  
 412 meteorologists use lightning flashes as indicators for strong turbulent convection in the  
 413 atmosphere. When these electric potentials suddenly discharge, a variety of ionized  
 414 and conducting channels is formed through localized ionization processes (collisional,  
 415 thermally driven or photon impact). In the first stage of a discharge, these ionization  
 416 reactions are driven by strong electric fields and local field enhancement and are  
 417 dominated by the impact of fast electrons on neutral atoms or molecules, while at later  
 418 stages Ohmic heating and thermal equilibration create temperature driven ionization  
 419 reactions.

#### 420 *(a) Ionization of the terrestrial atmosphere outside thunderstorm regions*

421 In common with other solar system atmospheres (Harrison et al. 2008), the earth's  
 422 lower atmosphere outside thunderstorm regions is made electrically conductive by  
 423 the ionising action of high energy particles generated within the heliosphere (e.g.  
 424 solar energetic particles, SEPs) and beyond (e.g. galactic cosmic rays, GCRs). A  
 425 consequence of the terrestrial atmosphere's small but finite conductivity ( $\approx 10^{-14} \text{ S m}^{-1}$   
 426 in surface air, see also Fig. 6) is that current flow can occur through the atmosphere,  
 427 between disturbed weather and fair weather regions. Similar circumstances occur in  
 428 other atmospheres, depending on the existence of charge separation processes and the  
 429 atmospheric conductivity.

430 Ion production in the earth's lower atmosphere (i.e. the troposphere and stratosphere)  
 431 results from a combination of terrestrial and extra-terrestrial sources. Near the planet's  
 432 continental surfaces, the effects of natural radioactivity contained within the soil and  
 433 rocks, or released in the form of radioactive gases such as radon, provide the dominant  
 434 source of ion production. At heights from 3 to 5 km above the continents (i.e. above  
 435 the boundary layer where eddy diffusion of radon isotopes occurs which depend on  
 436 orography), or over the oceans, extra-terrestrial sources, principally GCR, dominate the  
 437 ion production, while SEPs and UV irradiation dominate the ionisation in the ionosphere,  
 438 but typically do not have sufficient energy to reach the troposphere.

439 **Balloon-borne measurements:** Vertical soundings of the ion production rate in the  
 440 troposphere and stratosphere (i.e. to about 35km) can be made using balloon-carried



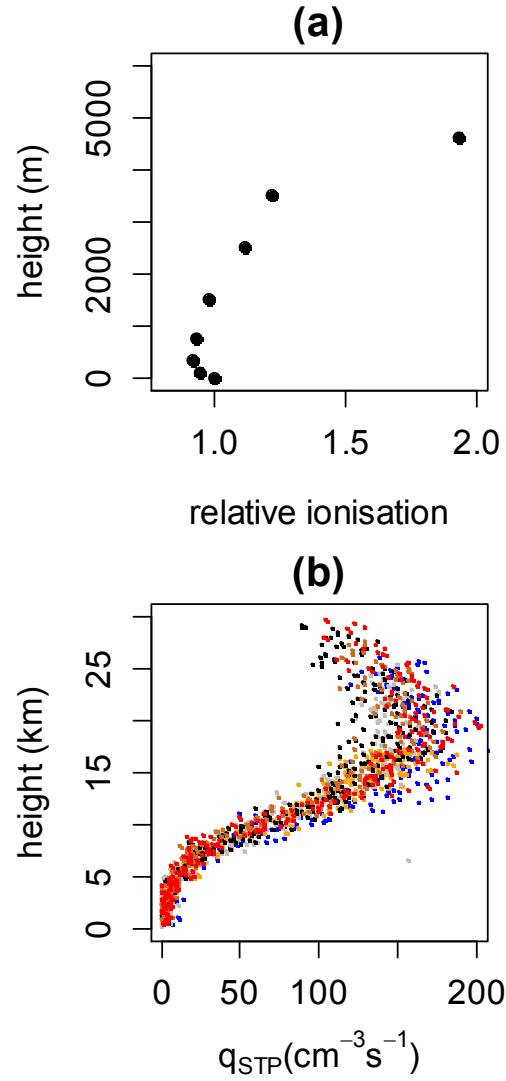


Figure 4. Vertical profile of the ionisation rate in the terrestrial atmosphere, as (a) originally obtained by Hess (7th August 1912), with ionisation at each height shown relative to the measured surface ionisation and, (b) from a series of balloon flights (colours used to identify individual flights) made from Reading, UK during 2013.  $q_{\text{STP}}$  is the ion production rate per unit volume, for air at standard temperature and pressure (STP).

instruments<sup>11</sup>. Historically this was the original airborne platform through which the existence of the cosmic source of ionisation was confirmed, in a manned balloon flight made by Victor Hess on 7th August 1912 (Hess 1912). This flight carried ionisation chambers and fibre electrometers, in which the rate of decay of the charged fibre was recorded visually and the ion production rate inferred (Pfofzer 1972). Hess found that the ion production rate initially diminished with height, but then began to increase (Fig. 4 (a)). This subsequent increase indicated that ionisation was originating from above. Figure 4 (b) shows a profile of the ion production rate per unit volume at standard temperature and pressure,  $q_{\text{STP}}$ , made using a modern balloon-carried Geiger counter (or Geigersonde) launched from a mid-latitude site (details are given in Harrison et al. 2014). This shows the same increase in ionisation observed by Hess at the lower altitudes, but the modern balloons extend the measurements to greater altitudes. A characteristic feature is the maximum in ionisation at about 20km, first observed Regener & Pfofzer (1935). The presence of the Regener-Pfofzer maximum results from a balance between the energy of the incoming particles, and the density of the atmosphere.

A long series of regular Geigersonde measurements has been made by the Lebedev Institute in Moscow, using a variety of sites including Moscow, Murmansk and Mirny (Antarctica). The value of this stable long-term measurement series is considerable, as, by taking advantage of the different geomagnetic latitudes of the sites concerned, it allows features of the cosmic ray ionisation to be established. Cosmic rays follow the geomagnetic field lines, and the lower energy particles are able to enter at higher latitudes (which is expressed as a lower geomagnetic rigidity). The high energy CR particles survive for longer in the Earth atmosphere, while the low energy CR particles are completely absorbed soon after they enter the atmosphere. Figure 5 shows a long times series of Geigersonde measurements made at the Regener-Pfofzer maximum, from sites with different rigidity (Stozhkov et al. 2013). The 11 year (Schwabe) cycle in solar activity is clearly present through the inverse response in GCRs, and, at the high latitude sites, the exceptional nature of the cosmic ray maximum in 2010/11 associated with the deep solar minimum, is particularly apparent.

**Atmospheric conductivity:** Cosmic ray ionisation in the terrestrial atmosphere sustains a steady source of cluster ions, which provide the finite conductivity of air. The total conductivity,  $\sigma_t$ , is given by

$$\sigma_t = e(\mu_+ n_+ + \mu_- n_-) \quad (3.1)$$

where  $\mu_{\pm}$  represents the mean mobility of positive or negative ions present,  $n_{\pm}$  the associated bipolar ion number concentrations and  $e$  is the elementary charge. Ions are removed by attachment to aerosol particles and water droplets, reducing the conductivity in these regions. Both the mobility and concentration vary with atmospheric properties and composition. The mobility of ions depends on the environmental temperature and pressure and the ion concentration is strongly affected by attachment to aerosol particles and water droplets, reducing the conductivity accordingly where the aerosol is abundant. This means that, in the earth's environment, where aerosols are generated

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<sup>11</sup> The atmosphere above this altitude is sometimes called ignorsphere, because above balloon and below satellite altitudes it is very difficult to explore. In particular, the density of free electrons in the lower ionosphere can now be measured only indirectly through the pattern of electromagnetic radiation that is emitted by lightning strokes and reflected by the ionosphere (Lay et al. 2010; Shao et al. 2013).

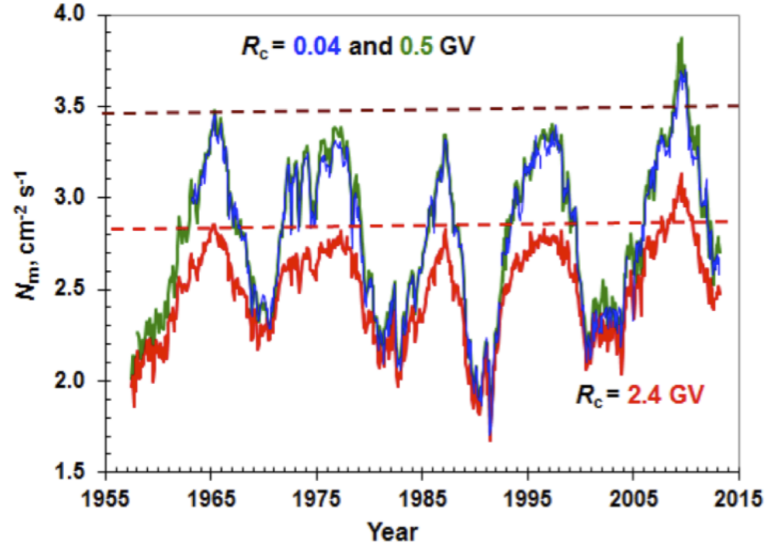


Figure 5. Time series of monthly averages of cosmic ray fluxes,  $N_m$  [ $\text{cm}^{-2}\text{s}^{-1}$ ], measured at the height of the Regner-Pfotzer maximum. Curves show measurements made at northern polar latitude (geomagnetic rigidity  $R_c = 0.6$  GV, green curve), southern polar latitude in Antarctica ( $R_c = 0.04$  GV, blue curve) and at the mid-latitude location of Moscow ( $R_c = 2.4$  GV, red curve). The CR flux increase since 2010 can be seen from the comparison provided by the dashed lines, which mark the cosmic ray levels in 1965 (from Stozhkov et al. 2013).

both naturally and through human activities, the local air conductivity can show an anthropogenic influence (Harrison 2006; Silva et al. 2014), allowing early indirect conductivity measurements to provide an insight into historical air pollution (Harrison 2006; Aplin 2012). Together with variations in the source rate,  $q_{\text{STP}}$ , these lead to a variation in the conductivity with height (e.g. Harrison & Carslaw 2003). In the heights of the lower ionosphere, where photo-ionisation also contributes appreciably, the conductivity becomes substantially larger than the lower atmosphere. Figure 6 shows a vertical profile of the air's conductivity, and a calculation of the relaxation timescale, defined by  $\epsilon_0/\sigma_t$ . This is the e-folding timescale for the discharge of an isolated particle in a conductive medium. This provides an indication of how active (in terms of the rate of charge separation) a charging process needs to be at different heights in the atmosphere. In comparison with lower troposphere air with a typical conductivity of  $\approx 10^{-14} \text{ S m}^{-1}$  as reviewed by Rycroft et al. (2008), the planetary surface has a greater electrical conductivity, of at least  $10^{-8} \text{ S m}^{-1}$ . This means the air represents a low conductivity region sandwiched between upper and lower boundaries having much greater conductivity.

(b) *Thundercloud electrification, lightning and transient luminous events*

**Ionic conductivity and ionic plasmas in the terrestrial atmosphere:** Most electric phenomena in the terrestrial atmosphere are carried by ions and aerosols; only in the strong transient electric fields of an evolving discharge or in the ionosphere are more

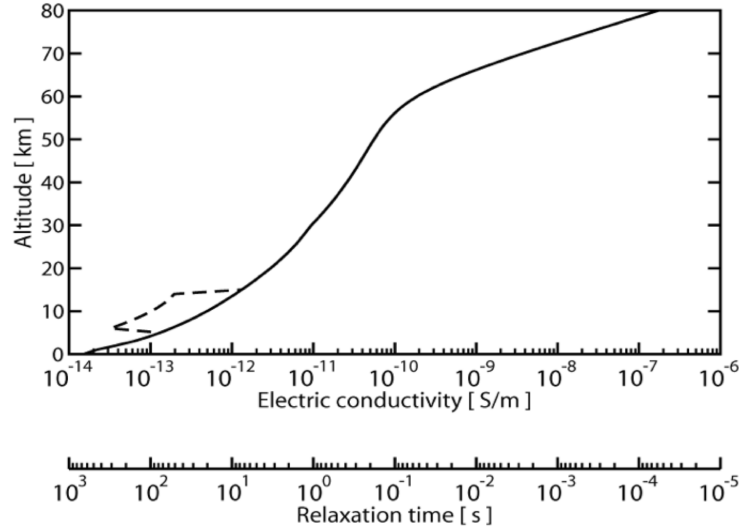


Figure 6. Vertical variation in electrical conductivity,  $\sigma_t$ , of the terrestrial atmosphere, as represented in the model of Rycroft et al. (2007). The dashed line indicates the change of conductivity due to clouds. The equivalent electrical relaxation time is found from  $\epsilon_0/\sigma_t$ , where  $\epsilon_0$  is the permittivity of free space.

501 electrons free and not attached to electronegative atoms, molecules or larger compounds  
 502 consisting, e.g., of water molecules clustering around ions, other aerosols, up to droplets  
 503 from micro- to millimeter size. Cosmic rays and radioactivity are external sources of  
 504 ionization (Sect. 3a); they first create electron ion pairs, then the electrons rapidly attach  
 505 to electronegative molecules (mostly to oxygen) leaving the positive and negative ions in  
 506 the atmosphere behind which carry the fair weather currents (Sect. 3c).

507 **The electric field in thunderclouds** builds up in two stages. In the first stage  
 508 macroscopic particles are electrically charged, and in the second stage particles of different  
 509 polarity are separated by gravitation or other (mechanical) forces; in order to separate  
 510 particles with different polarities, these forces need to be stronger than the electric  
 511 attraction between charges of different polarity, since otherwise the electric forces would  
 512 counteract the growth of the electric field. The possible charging mechanisms at work  
 513 within normal terrestrial thunderclouds are reviewed, e.g., by Jayaratne et al. (1983) and  
 514 Saunders (2008). An important conclusion of these reviews is that charge is efficiently  
 515 separated between particles only in direct collisions.

516 Liquid droplets cannot experience collisions or fracture as charging process as they would  
 517 typically merge on contact, hence they do not charge easily. However, frozen particles  
 518 can collide and exchange charge. Therefore, terrestrial water clouds get electrified mostly  
 519 in regions below the freezing temperature (Mason 1953), more precisely at temperatures  
 520 between 0 and  $-40^\circ\text{C}$ . The dominant charging mechanism is thought to occur when  
 521 graupel and ice particles collide. Saunders (2008) reviews the evidence from Krehbiel's

cloud measurements in 1986 "that ice crystals rebounding from riming graupel<sup>12</sup> in the presence of super-cooled water is a requirement of the charge transfer process". This observation is consistent with lab measurements of Saunders et al. that during collision essentially "fast growing ice surfaces charge positively, and conversely, sublimating (graupel) surfaces charge negatively". However, further dependencies on growth velocities etc. need to be taken into account. The particle collisions are mediated by gravity acting on large particles and by turbulent convection within the cloud. Gravity will also move the heavy positively charged graupel particles downward while the light positive ice crystals move upward with the convective flow of the cloud air, creating charge centers and electric fields within the cloud. This particular charging mechanism is based on the intrinsic polarization of water molecules. Macroscopic particles of different material can charge quite efficiently, too, and create electric fields and discharges. Both volcanic ash plumes, so-called dust devils in terrestrial deserts and various granular media in the lab support discharges, as is discussed further in Sect. 3d. The understanding of charging processes in volcanic ash plumes might inspire further progress on the long standing question of charging normal thunderclouds (Yair 2008). Such normal water clouds mixed with dust have recently been observed to exhibit particularly strong and exceptional discharges (Füllekrug et al. 2013).

Due to the attachment of ions to water droplets, electric charges in clouds are particularly immobile. The conductivity in the remaining gas phase is therefore low before lightning activity starts. This low conductivity (hence low degree of ionization, see also Fig. 2) supports a high electric field up to the moment of discharging.

**The stages of lightning:** Lightning is the sudden release of the electric potential energy through the fast growth of a disperse network of ionized channels. On average,  $44 \pm 5$  lightning flashes (intracloud and cloud-to-ground combined) occur around the globe every second (Christian et al. 2003). Moreover, according to OTD (Optical Transient Detector) measurements, lightning occurs mainly over land areas with an average land/ocean ratio of approximately 10:1 (Christian et al. 2003). The visible growing channels are called lightning leaders; their path is prepared by streamer coronae. While streamers are space charge driven ionization fronts, leaders maintain their internal conductivity by increased temperature, molecular excitations and ionization reactions in the discharge channel. If a conducting channel connects cloud and ground, the return stroke carries the largest current and is visible and audible as the lightning stroke; but intra- and intercloud lightning are much more likely. The stages of lightning have been described in many articles, with varying emphasis on phenomena or physical mechanisms. A few recent ones are by Bazelyan & Raizer (2000); Cooray (2003); Rakov & Uman (2003); Betz et al. (2009); Dwyer & Uman (2014); Cooray (2015).

A long standing question is how lightning can be initiated because the observed electric fields are below the classical break-down field (where electron impact ionization overcomes electron attachment to oxygen in the Earth atmosphere; e.g. Treumann et al. 2008; Helling et al. 2013), and free electrons are not available anywhere in the atmosphere. Gurevich et al. (1992) suggested that cosmic particle showers could supply free electrons, and that relativistic run-away electron avalanches could develop in an electric field below

<sup>12</sup> Riming graupel is a graupel particle coated with water droplets that froze immediately when they collided with the ice surface of the graupel. The surface structure of graupel deviates from a perfect crystalline structure (e.g. von Blohn et al. 2009).

the classical breakdown value. Gurevich & Karashtin (2013) recently suggested that the interplay of a cloud particle with Cosmic Rays could start the discharge. A quantitative analysis confirming this scenario is presented by Dubinova et al. (2015).

Lightning occurs not only between cloud and ground, but also within and between clouds. Also the 'bolt from the blue' is a phenomenon where a lightning strike seems to appear out of a blue sky next to a thundercloud. These strikes are an indication that lightning leaders can leave the cloud also at its upper edge or in the sideward direction and then turn downwards.

**Transient Luminous Events:** The full scale discharge activity associated with terrestrial water clouds became known in the scientific literature only after 1989 when the first Transient Luminous Events were described (for article collections, see Füllekrug et al. (2006); Ebert & Sentman (2008)). Basically, electric potential stored in a cloud can also discharge in the upward direction as a jet up into the stratosphere or as a gigantic jet that extends into the mesosphere. The primary lightning can drive secondary discharges, namely elves, halos and sprites in the E layer of the ionosphere, and in the night time mesosphere (where the D layer of the ionosphere is located during day time)<sup>13</sup>. Elves and halos are responses of the lower edge of the ionospheric E layer to the electromagnetic pulse and the quasi-static potential of the parent lightning stroke, while sprites propagate downward from the ionosphere into the mesosphere (so-called column sprites) and sometimes back up again (carrot sprites; Stenbaek-Nielsen & McHarg 2008, Luque & Ebert 2009). Due to similarity relations between discharges at different atmospheric densities (Pasko 2007; Ebert et al. 2010), tens of kilometers long sprite discharge channels in the thin upper atmosphere are physically similar to cm size streamer discharges at normal temperature and pressure - up to corrections due to different electron attachment and detachment reactions that can explain long-delayed sprites (Luque & Gordillo-Vázquez 2012). Sprites are pure streamer discharges (Liu & Pasko 2004b,a), and therefore are less complex than lightning strokes with their streamer, leader and return stroke stages, evolving on very different scales of space, time and energy. Due to the efforts of many authors in the past 20 years, the models for streamer discharges are now becoming more quantitative, so that we now approach the quantitative understanding of sprite discharges through detailed modelling and experimental efforts (Nijdam et al. 2014).

**Gamma-Ray Flashes and other high energy emissions from thunderstorms:** In 1994, the BATSE<sup>14</sup> satellite detected gamma radiation from earth, and it was recognized that this radiation came from thunderstorms (Fishman et al. 1994; Fishman & Meegan 1995). Later also beams of electrons (Dwyer et al. 2008) and even positrons (Briggs et al. 2011) were discovered from satellites. The Fermi Gamma-Ray Space Telescope detected a clear positron annihilation signal over Egypt from a thunderstorm over Zambia where the two events were connected in space and time through a geomagnetic fields line (that electrons and positrons follow sufficiently high in the ionosphere where collisions with air molecules is negligible; Briggs et al. 2011). High

<sup>13</sup> The electron density at these altitudes is an important parameter for discharge modeling. Only recently a method was developed to determine it partially and indirectly (Lay et al. 2010; Shao et al. 2013).

<sup>14</sup> <http://gammaray.nsstc.nasa.gov/batse/>

energy X-rays were also detected from lightning leaders approaching ground and from long sparks in the laboratory, see, e.g. Kochkin et al. (2012). We refer to the review by Dwyer & Uman (2014). It is clear that electrons are accelerated into the run-away regime within the electric fields inside and above the thunderstorm, where they continuously gain more energy from the field than they can lose in collisions with neutral air molecules. These collisions with molecules result in X- or gamma ray emission (Bremsstrahlung). The gamma-rays are ionizing radiation and generate electron positron pairs, or liberate neutrons or protons in photonuclear reactions (Babich et al. 2014).

There are two basic mechanisms discussed in the literature for the primary electron acceleration: either Galactic Cosmic Rays with sufficient energy to penetrate deep into the atmosphere and to generate relativistic run-away electrons avalanches (RREAs) in the electric fields inside the thundercloud, or the acceleration of low energy free electrons into the high-energy run-away regime at the tip of a lightning leader where electric fields are very high. The review by Dwyer & Uman (2014) favors the RREA mechanism, in agreement with the previous model development by the first author. The alternative is the runaway of thermal electrons at the leader tip suggested by Xu et al. (2012). Such detailed models depend on the model parameters for the background cloud field and its geometry, on the altitude of the lightning leader, but also on the collision cross-sections at the required energies that are not reliably available.

Füllekrug et al. (2013) reported on the observation of two consecutive positive lightning discharges where the first positive lightning discharge initiates sprite streamers which discharge the lightning electromagnetic field above the thundercloud. This was seen as a pulsed discharge event followed by a high-energy electron beam. A small number of stratospheric, charged aerosols was likely present as result of a Sahara dust storm and forest fires in Spain providing a collimating electric field geometry that accelerated the electrons. This is the first simultaneous detection of radio signatures from electrons accelerated to thermal and relativistic energies above thunderclouds.

### (c) *The Wilson Global Circuit*

The vertical structure of conductivity in the atmosphere, with the upper and lower conducting regions each able to sustain a local potential, allows a vertical potential difference to exist between the two regions. Investigations using balloon measurements from the late 1800s showed a variation in potential with atmospheric height (Nicoll 2012), with the upper conducting region being about 250kV positive with respect to the lower conducting region. The finite conductivity of the intermediate atmosphere between these charged regions allows a vertical current to flow. This current was observed directly by CTR Wilson (Wilson 1906) in fair weather conditions with no local charge separation. CTR Wilson concluded that the current flow was likely to be sustained by charge separation in distant disturbed weather regions. Evidence supporting this is that the diurnal variation in Universal Time (UT) near-surface electric field, measured under fair weather conditions, is independent of where it is measured globally, and shows strong similarities with the diurnal variation in active global thunderstorm area (Whipple & Scrace 1936). This diurnal variation in surface atmospheric electric field is known as the Carnegie curve, after the sailing vessel on which the original defining measurements were made (Harrison 2013).

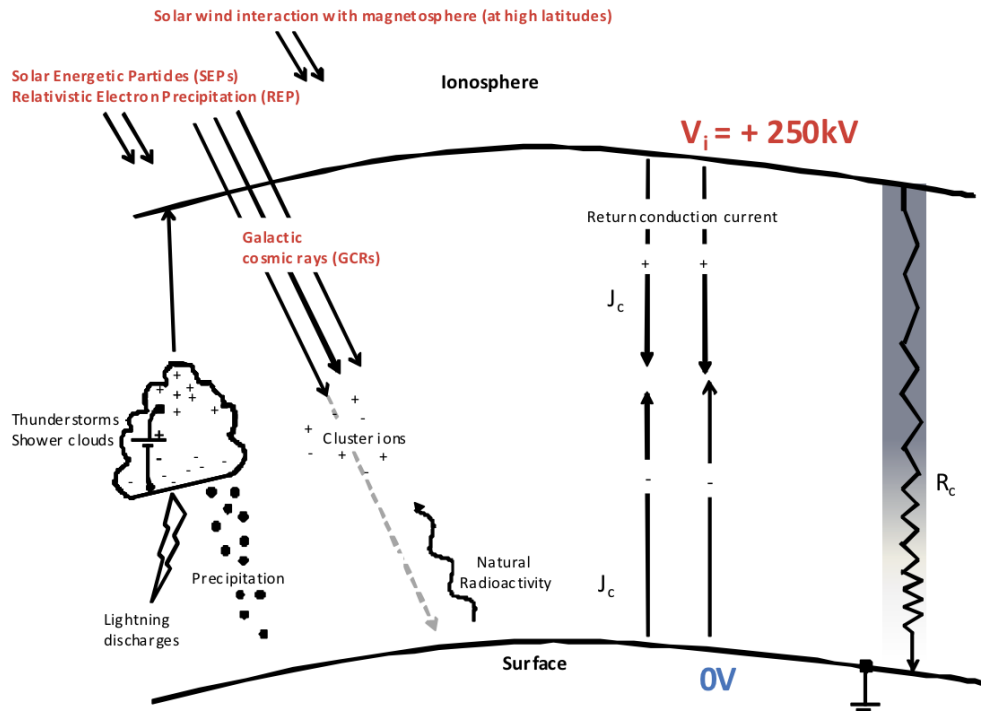


Figure 7. Schematic depiction of the role of ionization from Solar Energetic Particles (SEP), Relativistic Electron Precipitation (REP) and Galactic Cosmic Rays (GCR), in facilitating the current flow within the global atmospheric electric circuit. Natural sources of radioactivity include isotopes within the soil and the release of radon (from Nicoll (2014)).

650 The conceptual model that described the electrical transport across the planet between  
 651 disturbed weather and fair weather zones - the global atmospheric electric circuit (Wilson  
 652 1921, 1929) - has provided a fruitful description for investigation of terrestrial atmospheric  
 653 electrification, which may offer useful insights for other atmospheres (Aplin et al. 2008).  
 654 Although the original reasoning used to identify the global circuit was based on current  
 655 flow considerations, the wide range of timescales of the contributing processes leads to  
 656 a distinction being made conventionally between the AC and DC global circuit (Rycroft  
 657 & Harrison 2012).

658 **The AC global circuit:** The upper and lower conducting regions of the terrestrial  
 659 atmosphere form a simple waveguide, in which electromagnetic waves can propagate,  
 660 as originally predicted by Schumann (Schumann 1952). Lightning provides a source  
 661 of such electromagnetic radiation to excite waves in this cavity oscillator, and natural  
 662 resonances with a fundamental mode at about 8Hz as predicted were first observed at  
 663 the earth's surface in the 1960s (Balser & Wagner 1960; Rycroft 1965). These natural  
 664 resonances in the earth-ionosphere cavity (Q resonator) constitute the AC global electric  
 665 circuit. Somewhat surprisingly, resonances at 8, 14, 20 Hz are also observed on satellites  
 666 at altitudes of several hundred km, above the ionosphere (Simões et al. 2011; Dudkin  
 667 et al. 2014). Although the electric field measured is much smaller at a satellite platform



668 compared with ground based measurements (three orders of magnitude smaller for the  
 669 first Schumann peak), the fact that it is detectable at all offers the possibility for fly-by  
 670 measurements at other planetary bodies.

671 **The DC global circuit:** Figure 7 summarizes the DC current flow in the Wilson  
 672 global circuit. Charge separation in disturbed weather regions leads to current flow within  
 673 the ionosphere, fair weather regions and the planetary surface. The vertical conduction  
 674 current density,  $J_c$ , in fair weather regions is  $\sim 2 \text{ pA m}^{-2}$ , where the resistance of a unit  
 675 area column of atmosphere,  $R_c$ , is about 100 to 300  $\text{P}\Omega\text{m}^2$  (Rycroft et al. 2000). If  
 676 horizontal layers of cloud or particles are present, the electrical conductivity is reduced  
 677 because of the removal of the ions providing the conductivity by the particles. Hence,  
 678 for a passive particle layer, this means that the layer also defines a region of reduced  
 679 conductivity. If a current passes vertically through the passive particle layer (PPL),  
 680 charging will result at the step change in conductivity at the upper and lower layer  
 681 boundaries. The charging can be derived by assuming no horizontal divergence of the  
 682 current (as is observed, Gringel et al. 1986), and assuming Ohm's Law and Gauss' Law  
 683 in one dimension. For a conductivity  $\sigma_t(z)$  varying with height  $z$ , the charge per unit  
 684 volume  $\rho_e$  is given by

$$\rho_e = \epsilon_0 J_c \frac{d}{dz} \left( \frac{1}{\sigma_t(z)} \right) \quad (3.2)$$

685 where  $J_c$  is the vertical current density and  $\epsilon_0$  is the permittivity of free space. Figure 8  
 686 shows calculations of the charging for a PPL of prescribed concentration and size. This  
 687 leads to a reduction in the concentration of positive and negative ions in the same region.  
 688 The gradients in conductivity at the PPL boundaries allow the charge density to be  
 689 derived, either in terms of the mean charge calculated across the particles, or as a particle  
 690 charge distribution (Fig. 8). The charging expected at the PPL edges is clearly evident  
 691 and similar charging effects have been observed at the boundaries of layer clouds in the  
 692 terrestrial atmosphere (Nicoll & Harrison 2010).

693 **Conditions for global circuits:** The existence of global circuits in planetary  
 694 atmospheres has been suggested through possible analogies with the earth system,  
 695 in which current flows between charge-separating and non-charge-separating (or "fair  
 696 weather") regions, through the enhanced conductivity zones provided by the planetary  
 697 surface and the upper atmosphere (Aplin 2006, 2013). Entirely different electrical  
 698 processes may be involved, such as in the global circuit suggested for Mars (Fillingim  
 699 1986; Farrell & Desch 2001) which is driven by dust, or be associated with volcanic dust  
 700 electrification (Houghton et al. 2013). The basic electrical requirements for a planetary  
 701 global circuit have been discussed by Aplin et al. (2008), which are

- 702 • upper and lower conductive regions
- 703 • charge-separating processes
- 704 • current flow

705 Implied necessary conditions are (1) a sufficiently strong gravitational field to retain a  
 706 gaseous atmosphere, and (2) proximity to energetic sources of radiation (e.g. a host star  
 707 or a binary companion) which can form ionized layers in the atmosphere ultraviolet and

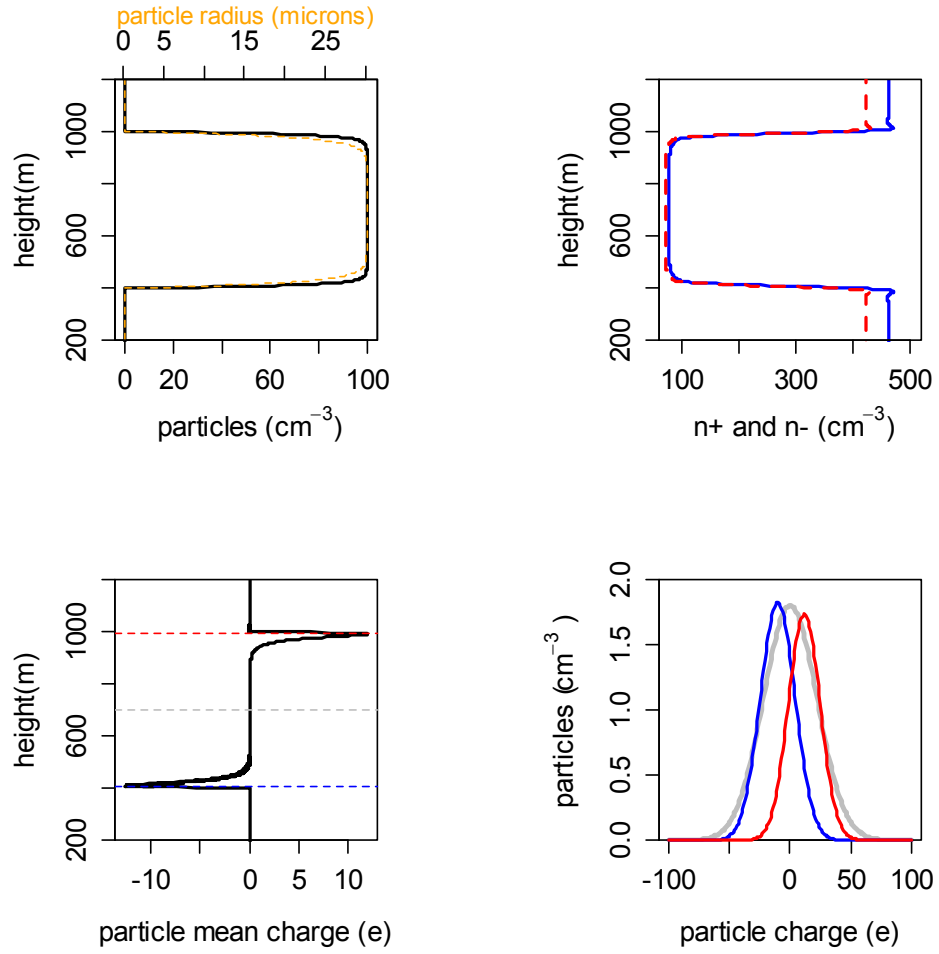


Figure 8. Simulated effect of a horizontal layer of particles through which a current flows. The panel show profile of: (upper left panel) prescribed particle size and concentrations, (upper right panel) number concentrations of positive ( $n_+$ , dashed red line) and negative ( $n_-$ , solid blue line) small ions, (lower left panel) mean charge on particles and (lower right panel) particle charge distribution evaluated at the three positions marked on the lower left panel with dashed lines. (Assumptions: ion production rate  $10 \text{ ions cm}^{-3}\text{s}^{-1}$ , vertical conduction current density  $2 \text{ pA m}^{-2}$ .)

Table 1. Possible detection methods for the key requirements of a global circuit in a planetary atmosphere.

<i>Requirements:</i>	<b>Charge generation</b>		<b>Lower conductive surface or region</b>	<b>Upper conductive region</b>
	Electrical discharges	Precipitation		
<b>Schumann resonances</b>	✓		✓	✓
<b>Radar</b>		✓	✓	
<b>Broadband radio emission</b>	✓			
<b>Optical</b>	✓			

X-ray regions of the spectrum to create an ionosphere. Table 1 summarizes the possible approaches which might be used to detect these necessary requirements.

Of these requirements, providing evidence in a planetary atmosphere of current flow is a particularly key aspect. In the terrestrial atmosphere, current flow was originally established using a surface electrode with an appreciable collecting area (Wilson 1906). Use of similar surface mounted electrodes is unlikely to be practical in space missions, hence other approaches suitable to the single burst of measurements made by descent probes entering an atmosphere need consideration. If horizontal layers of cloud or particles are present in an atmosphere, which are passive electrically, (i.e. not able to generate electrification internally), Eq. 3.2 indicates that seeking charging at the edges of particle layers provides an opportunity for the existence of vertical current flow. PPL edge charging can, in principle, be determined using a descent probe able to measure charge and detect the presence of particles, for example using the combination of electrical (Nicoll 2013) and optical (Harrison & Nicoll 2014) detectors used in the terrestrial atmosphere. Through deploying such sensing technology on a suitable platform, vertical current flow in a planetary atmosphere in the solar system may be inferred without the need for surface measurements.

In summary, the bigger picture here concerns the relationship between physical processes external to an atmosphere and active processes within it. Future work in this area therefore needs to consider:

- The range of charge separation processes which can occur in different planetary environments and the controlling influences on current flow, which may be internal or external in origin. Charge separation occurs between the same material (e.g. the dust electrification on Mars), different phases of the same substance (e.g. water-ice-hail interactions on Earth), or between different substances and phases.
- In the last set of circumstances, account of the local atmospheric chemistry and its influence on charging will be needed. Some consideration should be given to the nature of the charge separation, and whether simple electrical analogies in terms of constant current or voltage sources are appropriate.
- In terms of the current flow, there may be significant external influences, including the triggering of lightning-like discharges by external variations (e.g. Owens et al, 2014). For some planetary body configurations, there may also be direct tidal effects on the conductive regions in the atmosphere or other coupled interactions such as those between Saturn’s magnetosphere and Titan.

(d) *Electrical charging in volcanic plumes & Volcanic Lightning Experiments*

**Electrical charging in volcanic plumes:** Volcanoes generate some of the most violent forces in nature, and are not only present on Earth but on several of the planets and moons in our solar system, e.g. on Venus and Io (Shalygin et al. 2015), or more generally, volcanism can occur on rocky planetary objects with a hot core. The set of presently known extrasolar planets contains also planets (e.g. 55 Cancri e, Demory et al. 2011) that may be classified as volcanic due to their proximity to their host star and their high bulk density that indicates a rocky bulk composition. On Earth, volcanic lightning is often present during eruptions (see Harrison & Mather 2006; McNutt & Williams 2010 for reviews), providing strong evidence for the electrical charging of volcanic ash as well as demonstrating that charge separation sufficiently large to initiate breakdown within the volcanic plume environment. Numerous mechanisms have been suggested by which volcanic ash in Earth-based volcanoes can become electrified including fractoemission (James et al. 2000), contact or triboelectrification (Houghton et al. 2013), and thunderstorm-style ice-contact charging ('dirty thunderstorm' mechanism; Williams & McNutt 2005), each of which may occur at different altitudes throughout the plume (Fig. 9). Understanding the relative importance of these mechanisms in generating volcanic lightning during an eruption is required in order to explain observations of volcanic lightning and why some eruptions produce lightning and not others. On Earth, volcanic lightning provides the ability to detect explosive volcanic plumes remotely, as well as estimates of the minimum plume height to be made in the absence of other observational methods such as radar and lidar (Bennett et al. 2010). Electrostatic forces may also play an important role in modulating the dry fallout of ash from volcanic plumes, potentially important for modelling of ash transport downwind of volcanic eruptions (Harrison et al. 2010), although much future research is required in this area.

Away from Earth, active volcanism exists on several bodies in our solar system. Volcanic eruptions on Venus are typically associated with fluid lava flows - there is no evidence of the explosive ash eruptions that occur frequently on Earth which are often associated with active volcanic lightning. Conversely, Io, one of Jupiter's many moons often exhibits signs of explosive eruptions. Io's eruptive columns reach to hundreds of km altitude in contrast to Earth based plumes which may reach up to up to 40km in rare circumstances (Oppenheimer 2003). The existence of volcanoes on other bodies in the solar system (e.g. Venus, Airey et al. 2015) suggests the possibility of charging mechanisms associated with such volcanic activity, which may or may not be similar to those on Earth. This leads to the possibility that studying volcanic lightning on Earth may provide insight into dust charging processes in environments where mineral dust is common such as in the atmospheres of brown dwarfs or extrasolar planets as detailed in Sect. 5.

**Volcanic Lightning Experiments:** Explosive volcanic eruptions are commonly associated with intense electrical activity and lightning. A number of techniques have been used to study the electrical activity of volcanic plumes including close range VHF lightning mapping arrays (e.g. Thomas et al. 2007; Behnke et al. 2013), long range VLF lightning observations (e.g. Bennett et al. 2010) and optical lightning detection using high speed cameras (Cimarelli et al. 2014). Direct measurement of the electric field near the vent, where the electrical activity in the volcanic plume is first observed is difficult, but a handful of studies exist including those by Anderson et al. (1965); Gilbert et al. (1991); James et al. (1998); Miura et al. (2002). Lab based experiments

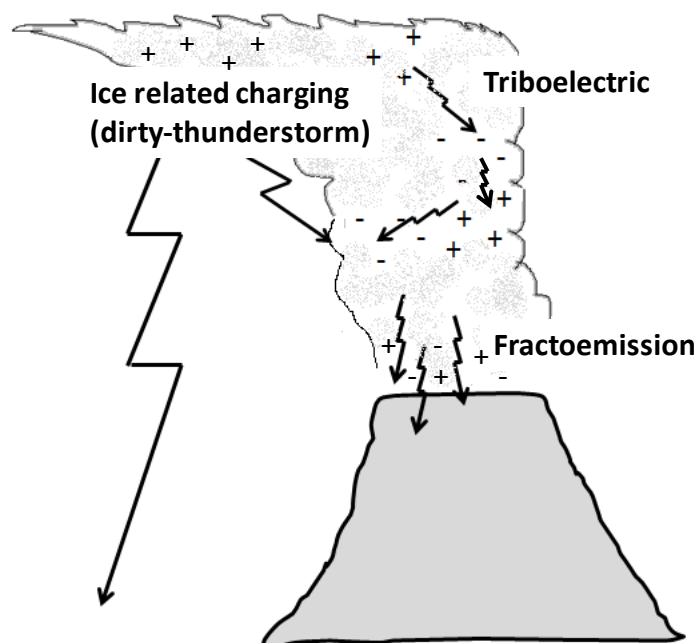


Figure 9. Sketch of volcanic charge generation mechanisms thought to be active in volcanoes on Earth. Fractoemission, caused by the fragmentation of magma, is thought to occur close to the vent, whereas triboelectric charging (frictional contact charging) can occur throughout the plume, wherever particles are present. The dirty thunderstorm mechanism requires ice particles in the plume and is only likely to be important for plumes which reach altitudes with temperature that allow freezing to occur.

are also essential to studying volcanic charge generation mechanisms in a controlled environment, and can allow different charge mechanisms to be examined individually. Laboratory experiments by Büttner et al. (2000) and James et al. (2000) have studied the fractoemission mechanism, whereby James et al. generated silicate particles by fracture during collisions between pumice samples. During the experiments there was evidence of ion release during the fracture process. Triboelectrification processes have also been studied in the lab using both silica beads (Forward et al. 2009a) and volcanic ash (Houghton et al. 2013), where it has been demonstrated that the particle size distribution has important effect on the magnitude of the charge generated.

Cimarelli et al. (2014) have achieved an analog of volcanic lightning in the laboratory during rapid decompression (shock-tube) experiments of gas-particle (both natural volcanic ash and glass beads) mixtures under controlled conditions. Experiments show that more discharges are generated for finer starting material and that there is no correlation between the number of discharges and the sample chemistry (Taddeucci et al. 2011). The experiments highlight that clustering of particles trapped in the turbulent eddies of the jet provides an efficient mechanism for both charge generation (tribocharging) and lightning discharge as observed in volcanic plumes. Clusters form and break-up by densification and rarefaction of the particle-laden jet. A cluster's lifetime is regulated by the turbulence time scale and its modification during the evolution of

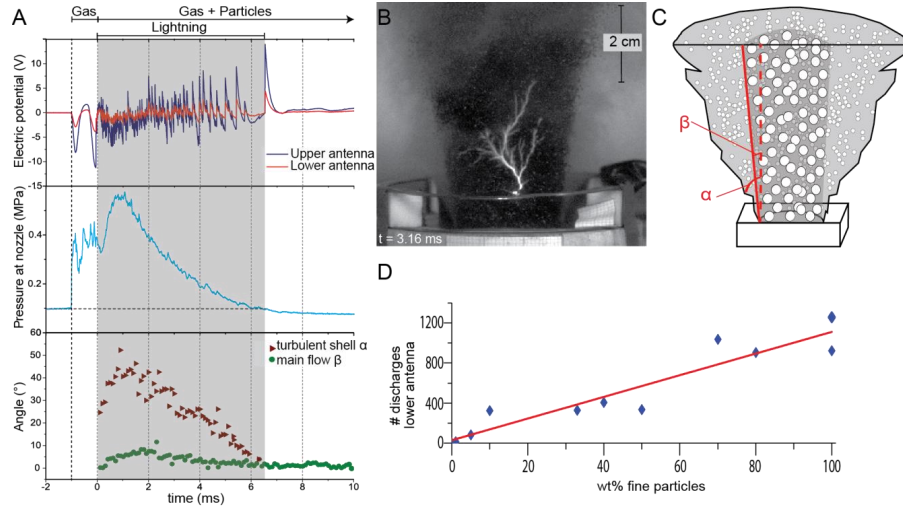


Figure 10. Results of a rapid decompression experiment with volcanic ash ( $250\ \mu\text{m}$ ). **Panel A:** Electric potential recorded by the antennas, pressure at the nozzle and angle of the core of the flow ( $\beta$ ) and the surrounding turbulent shell ( $\alpha$ ) with respect to the vertical. Shaded area indicates the time window of lightning occurrence. **Panel B:** Rest-frame of the high-speed videos showing the particle-laden jet is well-constrained and surrounded by the turbulent sheath of finer ash and lightning flashes are recorded. **Panel C:** Schematic section of the jet showing the main flow core (coarser particles; dark grey shadow), the turbulent shell (finer particles; light grey shadow) and the respective opening angles ( $\beta$  and  $\alpha$ ) to the vertical. **Panel D:** Number of discharges  $> 0.2$  V recorded at the lower antenna in experiments with bimodal glass beads (500 and 50 m) as a function of the wt.% of finer particles.

the jet flow. Cluster generation and disruption provide the necessary conditions for electrification of particles by collision, local condensation of electrical charges and its consequent separation, thus creating the electric potential gradient necessary to generate lightning discharges. Clustering can be particularly effective in the presence of prevalently fine ash-laden jets exiting volcanic conduits<sup>15</sup> thus facilitating ash aggregation in the plume (Taddeucci et al. 2011). Further charging by the formation of hydrometeors (i.e. water droplets or ice particles) in the upper regions of the plume (Van Eaton et al. 2012) could provide additional mechanisms of plume electrification, although the presence of ice particles in the plume (from low latitude volcanoes where surface temperatures are high and plume heights low (Aizawa et al. 2010)) can be ruled out in many monitored eruptions that produced electrical discharges, thus confirming the primary role of particle self-charging in the generation of volcanic lightning. The experiments show the direct relation between the number of lightning discharges and the abundance of fine particles in the plume as observed in the case of 2010 Eyjafjallajökull eruption in Iceland, as well as in many other ash-rich eruptions or explosive episodes, independently from their eruption magnitude and magmatic composition. Improved lightning monitoring at active volcanoes may provide first-hand information not only on the location of the eruption but more importantly on the presence and amount of fine ash ejected during an eruption, which is a fundamental input in ash-dispersion forecast models. Multiparametric observations of volcanic plumes are therefore needed to fully understand

<sup>15</sup> The volcano conduit is the pipe that carries magma from the magma chamber, up through the crust and through the volcano itself until it reaches the surface.

the favourable conditions for volcanic lightning generation and to correctly interpret electrification and discharge phenomena to understand plume properties. Newly designed shock-tube experiments open new perspectives in the investigation of self-charging mechanism of particles that are relevant for atmospheric phenomena on Earth (such as dust storms and mesocyclones) and other planetary bodies, as well as industrial processes involving granular materials.

#### (e) *Kinetic gas-chemistry during discharges in solar-system planet atmospheres*

Atmospheric discharges have been detected in all gaseous giants of our Solar System (Yair 2012) and are therefore likely to be present in extrasolar planets as suggested in (Helling et al., 2011; Aplin, 2013; Helling et al., 2013; Bailey et al., 2014). Transient Luminous Events (TLEs) occur in the Earth atmosphere (see Sect. 3b) where they influence the local gas composition, and with that, potential observational features.

A number of models to study in detail the non-equilibrium kinetic chemistry of TLEs have been developed (Gordillo-Vázquez 2008; Gordillo-Vázquez & Donkó 2009; Gordillo-Vázquez & Luque 2010; Parra-Rojas et al. 2013, 2015). These studies have allowed the optical signatures and spectra of TLE optical emissions (from the UV to the NIR) to be quantified as should be seen from ground, balloons, planes and from space (e.g. Gordillo-Vázquez et al. 2012) illustrating good agreement with available observed spectra.

Kinetic gas-chemistry models have been developed to calculate the TLE-induced changes in the electrical conductivity (Gordillo-Vázquez & Luque 2010) of the Earth upper atmosphere showing good agreement with available measurements. The importance of some key kinetic mechanisms (electron detachment from  $O^-$ ) has been shown to explain the inception of delayed sprites (Luque & Gordillo-Vázquez 2012). The impact of lightning on the lower ionosphere of Saturn and the possible generation of halos and sprites has been modelled by Dubrovin et al. (2014). This allowed to study the coupling between atmospheric layers in Saturn and Jupiter due to lightning-generated electromagnetic pulses and to predict different possible optical emissions from elve-like events triggered by lightning in the giant planets (Luque et al. 2014). The extension of such an approach to extrasolar atmospheres requires a dedicated kinetic gas-chemistry network which is able to handle a considerably wider range of chemical compositions and temperatures than for the solar system planets (see, e.g. the STAND2015 network from Rimmer & Helling 2015).

#### (f) *Future Studies*

On Earth the quasi-static and the radiation components of the lightning electric field have comparable effects on the secondary TLE-discharges in the upper atmosphere. However, in planets with larger typical distances, the radiation field can be stronger than the quasi-static field (Luque et al. 2014). The radiation field is responsible for ring-shaped expanding emissions of light at the lower edge of the ionosphere. It is therefore speculated that giant TLEs may exist in giant planets. This new area of research has introduced many open questions, such as:

- Can lightning-related TLEs occur on Saturn and Jupiter? What kind of TLE could be observable, what would be the required sensitivity and appropriate wavelength

- range? Could the optical flash emission on Saturn and Jupiter originate from other discharge processes than conventional lightning discharges?
- Can lightning-related TLEs take place in the upper layer of the Venusian atmosphere? How would lightning influence the chemical composition and electrical properties of the Venusian upper atmosphere?
  - No direct optical lightning observation is available for the atmospheres of Neptune and Uranus, only indirect radio detection possibly associated to electric discharge events. What could be the lightning mechanisms in Neptune and Uranus?
  - What would be the possible atmospheric optical and chemical signatures in the case that lightning activity exists in extrasolar planets and brown dwarfs atmospheres?

#### 4. Electrification on the Moon and on asteroids

Charged dust grains and dusty plasmas are known to constitute the near-surface environment of airless bodies such as the Moon, asteroids, comets, Saturn's rings and many planetary moons. Our solar system, being exposed to a variety of plasma conditions and solar activity, provides a natural laboratory to study dust charging and dynamics. Charging of neutral dust particles occurs when dust grains are exposed to space plasma, for example, through interactions with the solar wind. These plasma interactions are believed to be the reason for many of the observations reported in the literature (e.g. spokes in Saturn's B ring and dust streams ejected from Jupiter Horányi et al. (2004)).

In dusty plasmas, dust particles have the ability to alter the properties of various plasma waves and instabilities (e.g. D'Angelo 1993; Kopnin et al. 2009; Rao 1993, 1995). In some cases the presence of dust can affect the instability (e.g. Sen et al. 2010), whereas in other cases the presence of dust can drive new unstable modes (Rao & Shukla 1990). Both high and low frequency modes can be excited. High frequency modes are excited because the dust can modify the relative drift between the plasma species (electrons and ions) or simply reduce the electron density. Low frequency modes (both electrostatic and electromagnetic) occur when the dust dynamics are considered. One of the interesting modes is dust-ion acoustic instability which is driven by the relative drift between the dust and the plasma (Rao 1993). An example of such a scenario exists in Saturn's E-ring where the plasma co-rotates with the planet while the dust follows Keplerian orbits. Rosenberg (1993) has shown that the relative speed between the dust and the plasma to drive the instability is of the order of the ion thermal speed. By introducing the magnetic field new modes called dust-magneto-acoustic waves are excited according to the theory (e.g. Rao 1995) which is the generalisation of the electrostatic dust-ion acoustic wave, first reported by Shukla & Silin (1992).

Beyond the macroscopic behaviour of dusty plasmas, understanding dust charging in the space environment is important for several reasons. The variable exposure of the moon to solar wind, UV radiation, terrestrial magnetospheric plasmas, and meteoroid impacts results in a time-dependent, complex plasma environment. The charging, possible subsequent mobilization, and transport of fine lunar dust have remained a controversial issue since the Apollo era, and have been suggested to lead to the formation of a dusty exosphere, extending tens to hundreds of kilometres above the surface. Recent



international interest and potential return to the moon in the near future has been declared by major space agencies around the world (NASA, ESA, JAXA, Russia, China). The success of these missions depends largely on the ability to understand and predict the effects of dust on the lunar environment in order to prepare crews and equipment to withstand such a harsh environment. Whilst NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) (launched on 6th Sept. 2013) is the first dedicated mission to make measurements of lunar dust composition, other missions are planned. For example, there are dust detectors on the Russian lander mission to the moon's South pole (Luna Glob, 2016) and a joint Russian-Indian (Lunar-Resurs) mission in 2017/18.

Asteroids and comets are similarly complex environments, of interest because they are formed from material originating from the time when the Solar System was formed. Precise isotope ratio measurements give insights into the formation of our planetary system. Carbonaceous compounds from some primitive asteroid, that have not been affected by weathering other than in interplanetary space, could have contributed to the origins of life through delivery of organic compounds to Earth. There is therefore substantial scientific interest in measuring the surface material of asteroids and comets. Examples of successful missions include NASA Deep Impact and Stardust (see review by Ververka & et al. 2013) and the European Rosetta mission's Philae lander touched down on the comet 67P/Churyumov-Gerasimenko in November 2014 (e.g. Todd et al. 2007). The mass spectrometry needed to understand the rocky particles on the surface of asteroids (regolith: dust, soil, broken rock, and other related materials and is present on Earth, the Moon, Mars, some asteroids, and other terrestrial planets and moons) is too sophisticated for comparatively simple spacecraft-borne instrumentation, and this has motivated several sample return missions aiming to return regolith to Earth for more detailed analysis. The Japanese Hayabusa mission collected a sample from asteroid Itokawa in 2005, NASA's Osiris-Rex mission visits asteroid Bennu in 2016, and a European mission, Marco Polo-R was also recently studied in detail (Michel et al. 2014).

#### (a) Charge effects on the Moon

In its orbit, the moon is exposed to the incoming solar wind when it is not in the Earth's magnetosheath where most of the plasma interacts with the moon surface, forming a wake region behind the lunar obstacle. The exposed (sunlit) surface is charged positively to about +5V due to high photoelectron current but on the shadow side, the inability of ions to fill in the plasma void results in regions with energetic electrons, which will subsequently charge the surface negatively to few hundred volts in normal conditions or up to few thousand volts in extreme cases. The charging from galactic cosmic rays is negligible in comparison to the effects of the solar wind. Like the Moon, asteroids have dusty plasma environments, with similar charging mechanisms such as from space plasmas or the solar UV flux (Lee 1996).

At midpoint between the sunlit and the night side of the moon, the solar wind passes through almost parallel to the surface. At much lower negative potential compared to the night side, this lunar terminator region has been found to be the source of 'streamers' or 'horizon glow' as observed by astronauts during the Apollo mission. It is found that the glow is produced by the scattering of sunlight by dust particles originating from the surface, a result to be confirmed by LADEE. It is thought that the dust on the lunar surface is charged by the Sun's UV radiation and that other processes can

contribute, such as solar wind plasma, secondary electron emission and triboelectric charging. The repulsive electric field between the dust and the surface causes the dust to levitate from the surface. Similar mechanisms are expected to act on asteroids. Although dust charging and levitation have been extensively discussed (e.g Whipple 1981; Goertz 1989), these processes are not yet fully understood for the complex lunar surface where both the topology and orbital configurations of the moon add to the complexity. Recent development of 3D dusty plasma code based on Space Plasma Interaction Software (SPIS) (Anuar et al. 2013; Hess et al. 2014) has provided a useful tool to simulate many possible scenarios on lunar surface such as lunar surface charging, shadowing phenomena and dust levitation. Figure 11 presents time-sequence simulations of the release of dust outside the rim of a lunar crater. At the terminator (top panels) the presence of strong negative electric fields repels dust particles, preventing them from reaching the basin of the crater. On the dayside (bottom panels) dust is attracted towards the middle of the crater basin due to the basin having a lower surface potential than the rim surface.

In the lunar environment a controversial and an open question is the high altitude component of the lunar dust: what is the maximum height that dust can be observed? The topology and the orbit of the moon itself pose interesting questions such as:

- What is the charge density distribution on the surface as a function of local time and how does it change along the orbit as the Moon enters the earth’s magnetosphere?
- What is the plasma density distribution above the moon surface, and how does it change with height and time as a result of interaction with dust particles?
- What is the configuration of the local small-scale electric fields? How do the vertical and horizontal components of the surface electric fields evolve during the passage of the lit - dark boundary, and along the lunar orbit?
- How do magnetic anomalies alter the surface electric fields and plasma?

#### *(b) Charge effects on asteroids*

In the case of an asteroid, there are possible electrostatic effects on, firstly, surface material, and, secondly, through the electrostatic effects of a spacecraft visiting an asteroid, which could influence the outcomes of sample return missions. Asteroids become charged by cosmic rays, the solar wind and photoelectron emission. For asteroids in the solar system, the charging effects of cosmic rays are negligible in comparison to the solar wind’s effect, on the nightside, and photoelectron charging on the dayside. The most direct mechanism for charging effects on asteroids views electrostatic processes as one type of “space weathering” which is a broad term for surface modification of these bodies. Space weathering is relevant for asteroid sample return missions since it refers to processes that could physically and chemically modify the sample from its “pristine” state, thought to be representative of the early Solar System. As photoelectric levitation of dust particles on the surfaces of asteroids is expected to occur, charging effects could modulate the size distribution, by redistribution of regolith, for example, through “ponding” in craters. Modification of the size distribution could also have more complex effects for the asteroid’s density and orbital evolution (Aplin et al. 2014).

Recent models (Aplin et al, 2014) considered the electrostatic implications of a spacecraft visiting an asteroid, and found that photoelectric shadowing from the spacecraft itself was substantial. This shadowing will generate electric fields in the sampling region, a hitherto

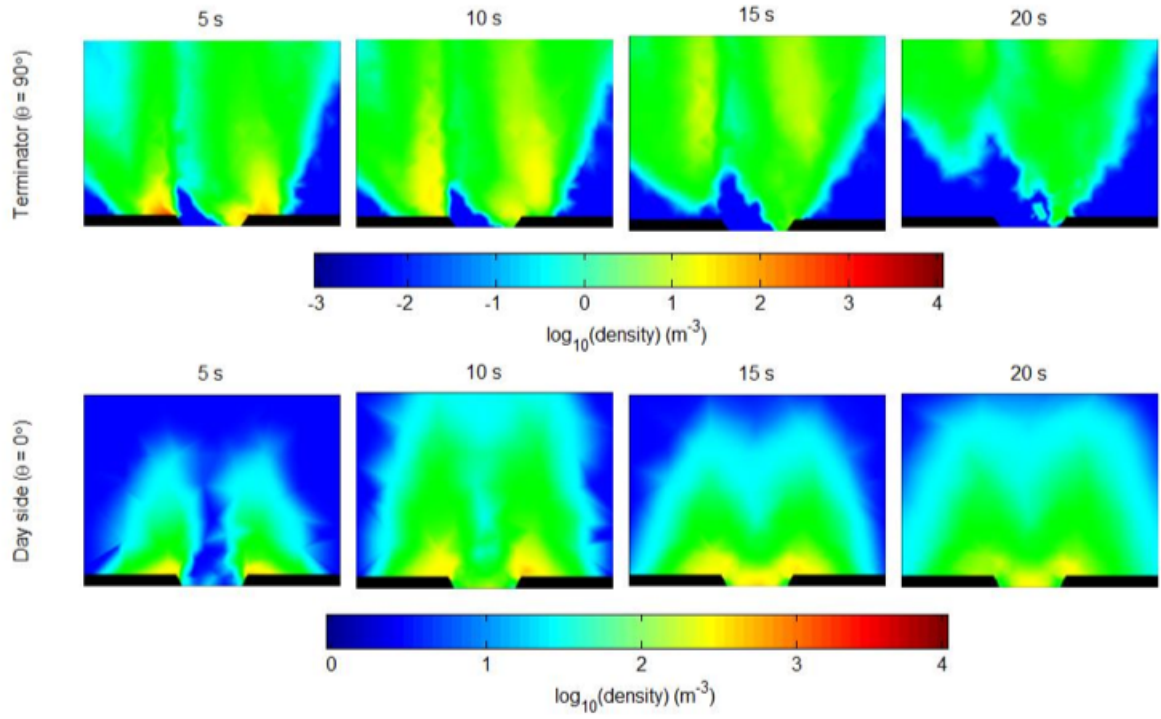


Figure 11. Time-sequence simulations of the release of dust outside the rim of a lunar crater For two regions: terminator (top panels) and dayside (bottom panels). The crater of 5m diameter is modelled as a opening in the bottom of the panels which represents the surface of the moon. The x and y axes represent the lunar surface and the height of the simulation which are 45m and 60m respectively.

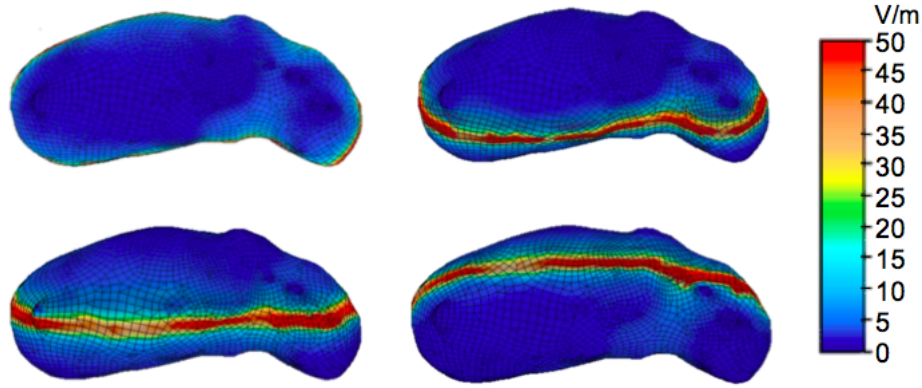


Figure 12. Four viewing angles of 3D electrostatic modelling of the surface electric field for the asteroid Itokawa (after Aplin et al. 2011). The highest electric fields exist at the terminator region. Effects of surface topography on the electric field can also be seen.

neglected process that could modify the sample to be collected. Aplin et al. (2014) demonstrated that simple isolated electrodes mounted on a spacecraft could measure the screening from the spacecraft, and, with careful choice of position, these electrodes could also measure the minimally disturbed electrical environment. Figure 12 shows modelled electric fields at the surface of the asteroid Itokawa. The dayside is assumed to be at +5V, and the nightside at -1000V (Aplin et al. 2011) resulting in high electric fields at the terminator. Further work is needed to consider other electrostatic effects of a sample return mission, for example the mechanical lofting of particles from spacecraft touchdown, which would become charged. Triboelectric (frictional charging) effects could also be significant. Although both Martian analogue and lunar material tribo-charge efficiently (e.g. Aplin et al. 2012; Forward et al. 2009b), triboelectric effects have not been considered in the asteroidal (like in Fig. 12) or lunar environment. Triboelectric charging could occur both from collisional processes between lofted regolith, and potentially more significantly for human exploration and sample return, from interactions between spacecraft and the environment, such as sampling mechanisms or rovers.

There is clearly much work to be done in understanding the mechanisms involved in dust charging and their effects. For the asteroid case, dust needs to be included in the simulations as well as more realistic representations of the spacecraft geometry, so that shadowing effects can be studied more carefully.

## 5. Charge processes in Extrasolar atmospheric environments

Charge processes and their effects occur in many astrophysical environments. This section focuses on extrasolar objects where charge and discharge processes introduce feedback cycles similar to those discussed previously. This section summarises a field of research on cool extrasolar objects which starts to emerge as the result of recent progress in X-ray and radio observations of brown dwarfs. Brown dwarfs are objects with mass intermediate between stars and planets (Fig. 1; for a review see Helling & Casewell 2014). Since they are

not sufficiently massive for hydrogen burning in their core, they cool during their entire life time. Brown dwarf atmospheres therefore evolve from the state of a warm stellar atmosphere into an atmosphere as cool as the atmospheres of solar system planets. The oldest brown dwarfs are amongst the oldest objects in our Universe. Very-low mass stars and brown dwarfs are collectively known as ultracool dwarfs.

Charge processes are important also in star and during planet formation in protoplanetary disks. Ionisation processes are suggested to help the first steps of planet formation as demonstrated by microgravity coagulation experiments at the International Space Station (Konopka et al. 2005; see also Sect. 3d), and to allow the star to continue to accrete mass through the propolanetary disk.

Planets and stars do have magnetic fields. The magnetic field strength and geometry differ for different stars (Donati & Landstreet 2009) which has implications for e.g. the size of a planetary magnetopause or the high-energy radiation impact into a planetary atmospheres (Vidotto et al. 2014; See et al. 2014). Stellar magnetism changes with mass and rotation (as indicator for age for some stars) of the objects (Donati et al. 2008; Morin et al. 2008, 2010; Vidotto et al. 2014) introducing an additional complexity in the astrophysical context of atmospheric electrification. Brown dwarfs can have magnetic field strengths of 1000G ( $= 0.1$  T).

This section first summarises recent multi-wavelength observation of brown dwarfs as the best detectable ultra-cool and planet-like objects (Sect. 5a). Section 5b addresses ionisation mechanisms in ultra-cool atmospheres, and Sect. 5c summarised recent ideas for ionising protoplanetary disks through which stars grow and planets form.

#### (a) Multi-wavelength observations of activity on ultracool dwarfs

Below the mid-M spectral type stars ( $T_{\text{eff}} < 3200\text{K}$ ; for definition see Appendix 1), a strongly declining  $\text{H}\alpha$  emission indicates a weakening of chromospheric activity<sup>16</sup> (Gizis et al. 2000; Kirkpatrick et al. 2000; Liebert et al. 2003; Reiners & Basri 2008; Williams et al. 2014). X-ray observations support this finding: Whilst X-ray detections are common for late-M spectral types ( $T_{\text{eff}} > 3400\text{K}$ ), the X-ray luminosity declines steeply for L-type brown dwarfs ( $T_{\text{eff}} < 2000\text{K}$ ; Williams et al. 2014). By contrast, brown dwarfs are very bright radio emitters, but no correlation between X-ray and radio emission exist as it is established for stars and solar events (Güdel-Benz relation, Benz & Güdel 1994). Since the discovery of the first radio emitting brown dwarf by Berger et al. (2001), numerous surveys have detected radio emission at GHz frequencies in nearly 200 objects (Berger 2002, 2006; Berger et al. 2010; Hallinan et al. 2006, 2007, 2008; McLean et al. 2012), including emission in the coolest brown dwarfs with spectral types as late as T6.5 (Route & Wolszczan 2012). In 12 of these objects, the radio emission is highly polarised, coherent and pulses on the rotation period of the dwarf. These properties suggest that the source of the radio emission is the electron cyclotron maser instability (CMI; Wu & Lee 1979). The electron cyclotron maser mechanism has been shown to be responsible for the auroral kilometric radiation on Earth (see, Trakhtengerts & Rycroft 2008; Speirs et al. 2008; Vorgul et al. 2011). Figure 13 shows a light curve of a M-dwarf (TVLM 513-46546)

<sup>16</sup> Chromospheric activity in form of  $\text{H}\alpha$ , X-ray or Ca II K&K line emission results from the interaction of the stellar radiation field with a hot plasma above the atmosphere of a stellar object. The hot plasma that forms the chromosphere is the result of magnetic wave dissipation into thin gases and/or the deposition of excess radiation energy.

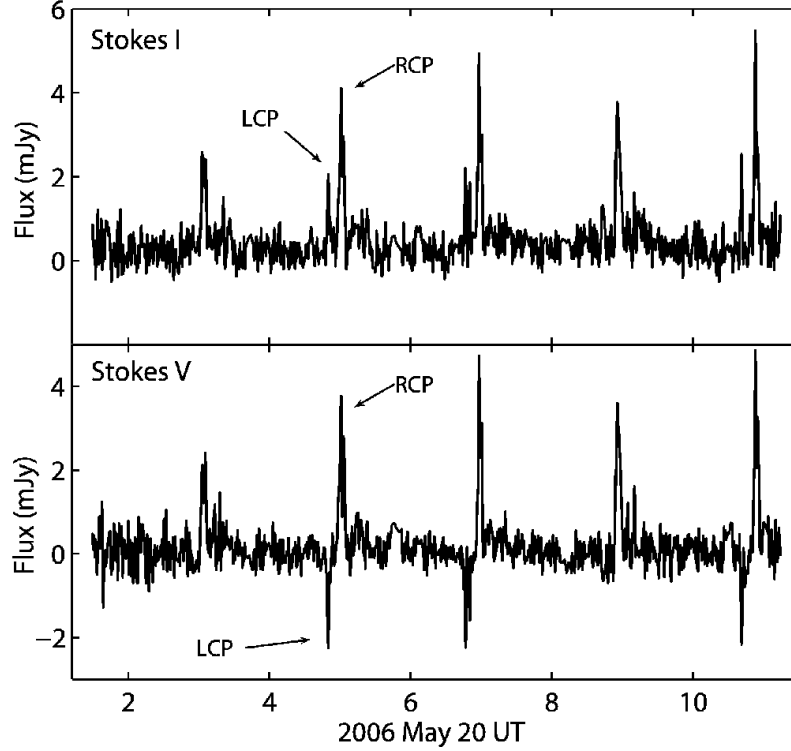


Figure 13. Light curves of the total intensity (Stokes I) and the circularly polarized (Stokes V) radio emission detected at 8.44 GHz from TVLM 513-46546, an M9.5 dwarf, taken from Hallinan et al. (2007). Right circular polarization is represented by positive values, and left circular polarization is represented by negative values in the Stokes V light curve. Bursts of both 100% right circularly polarized emission (an example is high-lighted as 'RCP') and 100% left circularly polarized emission (an example is highlighted as LCP) are detected with a periodicity of 1.96 hr.

1069 of spectral type M9.5 which shows clear and periodically repeating emission peaks at  
1070 8.44GHz.

1071 In the solar system, planets have been extensively shown to be closely associated with  
1072 auroral emission, caused when electrons moving along the magnetic field lines impact the  
1073 atmosphere. Nichols et al. (2012) show that a model designed to explain Jupiter's aurora  
1074 (Cowley & Bunce 2001) is able to explain the observed radio fluxes in the ultracool dwarf  
1075 'pulsars'<sup>17</sup> of order  $\text{MW Hz}^{-1}$ . It could therefore be possible that the radio emissions of  
1076 some ultracool dwarfs are powered by auroral currents. If this is true, there are profound  
1077 implications for the importance of ionisation processes on ultracool dwarfs. The current  
1078 system described by Nichols et al. (2012) requires, however, both a seed ionisation in the  
1079 atmosphere, and a plasma in the magnetosphere to operate. In turn, the impact of auroral  
1080 electrons on the atmospheres is likely to be dramatic; whilst Jupiter's aurora increase

<sup>17</sup> Classically, a pulsar (a pulsating radio star) is a neutron star that is highly magnetized and rapidly rotating. The emitted radiation can only be observed when the beam is pointing towards Earth. The term 'ultracool dwarf pulsar' borrows this idea of beamed, lighthouse like radiation.

the atmospheric conductivity by a factor of 1000 (e.g. Strobel & Atreya 1983; Millward et al. 2002), the radio power of ultracool pulsars is 10,000 times that of Jupiter. Jupiter's seed plasma is largely driven by the solar wind and the volcanically active Jupiter moon Io. Brown dwarfs will not have such external plasma sources, unless they are part of a binary system with mass transfer.

It is likely that these aurora are linked to optical variability seen in the ultracool dwarf pulsars. This association is suggested by the fact that five of the six ultracool dwarf pulsars that have been observed at optical wavelengths show periodic variability on the same period as the radio emission. For comparison  $\sim 5\%$  of randomly chosen ultracool dwarfs show periodic variability. Whilst the exact mechanism producing this optical variability is not yet clear, multi-colour observations of one ultracool dwarf pulsar has ruled out starspots as the cause (Littlefair et al. 2008).

**Near-IR Signature of Chromospheric Activity in Brown Dwarfs:** Recent near-IR observations with the AKARI satellite can only be explained under the assumption that a chromosphere comparable to the solar chromosphere is present. Theoretical studies of brown dwarf atmospheres predict that such low temperature atmospheres are dominated by molecules and dust, and that they can be well modelled by simple radiative equilibrium assuming thermodynamic equilibrium. However, AKARI observations in the near-infrared wavelength range suggest that also chromospheric activity plays an important role for the atmospheric structure in particular for early-type brown dwarfs (Sorahana et al. 2014). Deviations between theoretical model spectra and observed

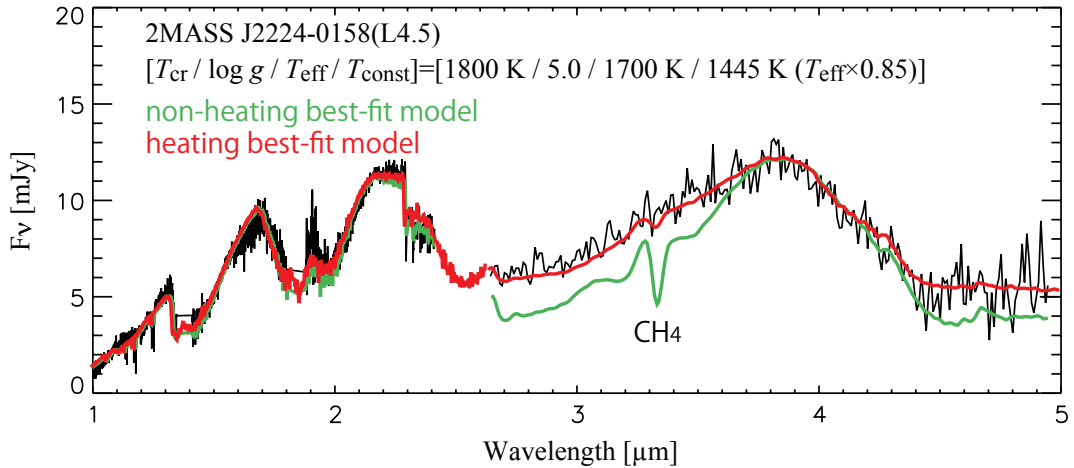


Figure 14. Comparison of the model spectrum (red and green smooth lines) with the observed spectrum for the L4.5 brown dwarf 2MASS J22240158 (thin black spiky line), which is well explained by the heating model atmosphere (red line) taking into account the heating in the upper atmospheres.

spectra around 3.0 and 4.5  $\mu\text{m}$ , which is sensitive to the upper atmospheric structure of brown dwarfs, suggest an additional heating source in the upper atmosphere. The comparison of the model spectrum with the observed spectrum for a L4.5 type brown dwarf with moderate  $\text{H}\alpha$  emission, 2MASS J2224-0158, is shown in Fig. 14 as an

example. Sorahana et al. (2014) construct a simple model that includes heating due to chromospheric activity which results in a dramatic change of the chemical structure of the atmosphere. The resulting model spectra of early-type brown dwarfs with chromospheric heating considerably improves the match with the observed spectra. This result suggests that chromospheric activity is essential to understand the near-infrared spectra of brown dwarfs, and that MHD processes can heat the upper atmosphere. A similar conclusion was reached by Schmidt et al. (2015) who photometrically examine a sample of 11820 M7-L8 dwarfs. Rodriguez-Barrera et al. (2015) have used a grid of model atmosphere simulations to demonstrate that it is reasonable to expect the formation of an ionosphere and, therefore, also a chromosphere in ultra-cool atmospheres such as on brown dwarfs.

**Irradiated brown dwarf atmospheres:** Only a handful of systems are known where a brown dwarf is heated by a hot companion. These brown dwarfs have close orbits of a few days, and they transit their host star, giving a measure of the brown dwarf's radius, which is inflated by the energy input from its star. White dwarf - brown dwarf

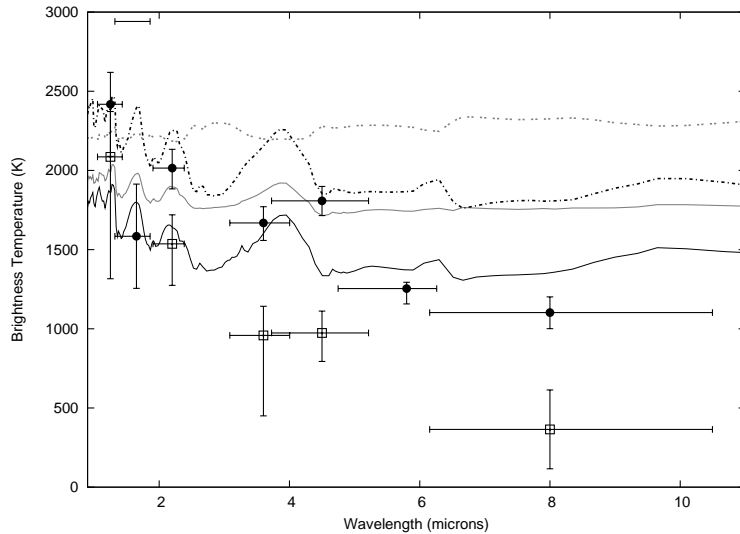


Figure 15. Brightness temperatures for WD0137-349 on the irradiated (circles) and unirradiated (open boxes) sides of the brown dwarf. The errorbars on the X scale represent the widths of the filters used. Solid lines are models that use full circulation and energy transport from the heated to non-heated side of the brown dwarf. Dotted lines show the zero circulation models. The grey lines are models containing TiO and black lines for the non-TiO model. The models represent the flux on the the dayside only. The H and  $[5.8]\mu\text{m}$  temperatures for the unirradiated side are upper limits only (diamonds), derived from the white dwarf's flux (Casewell et al. 2015).

binaries provide a case where the brown dwarfs are not outshone by their companions, and therefore an opportunity to study irradiated brown dwarfs. In five of these systems, WD0137-349B (Maxted et al. 2006), NLTT5306 (Steele et al. 2013), SDSS141126+200911 (Beuermann et al. 2013), WD0837+185 (Casewell et al. 2012) and GD1400B (Farihi et al. 2004) the brown dwarf is known to have survived a phase of common envelope



1125 evolution.<sup>18</sup> WD0137-349 is the best studied system. It is photometrically variable in  
 1126 all wavelengths from the  $V$  band though to  $8.0\ \mu\text{m}$ . These variations are on the orbital  
 1127 period of the system and peak at  $4.5\ \mu\text{m}$ . Converting the dayside and nightside flux to  
 1128 brightness temperature (peak blackbody temperature with that flux at that wavelength)  
 1129 shows a temperature difference between the two hemispheres of  $\sim 500\ \text{K}$ , and a possible  
 1130 temperature inversion in the atmosphere. Casewell et al. (2015) compare the observed  
 1131 photometry fluxes (i.e. radiative fluxes measured in a certain wavelength interval) to  
 1132 models of irradiated brown dwarfs and show that the data are best fit by models  
 1133 that incorporate full energy circulation around the brown dwarf, but do *not* contain  
 1134 a temperature inversion. However, at  $2\ \mu\text{m}$  ( $K$  band) and at  $4.5\ \mu\text{m}$ , the flux of the  
 1135 brown dwarf is still much brighter than the model. Casewell et al. (2015) suggest that  
 1136 UV irradiation can cause photochemical reactions in the upper brown dwarf's atmosphere  
 1137 that produce large hydrocarbon molecules causing the brown dwarf to be brighter at  $2\ \mu\text{m}$   
 1138 and  $4.5\ \mu\text{m}$  as were demonstrated for CR impact by Rimmer et al. (2014).

#### 1139 (b) Ionisation processes in ultra-cool atmospheres

1140 Brown dwarf and planets atmospheres are spectroscopically characterised by a rich  
 1141 ensemble of molecules (e.g. SiO, TiO, VO, CO, H<sub>2</sub>O, FeH) which lead to the conclusion  
 1142 that such atmospheres are too cool for thermal ionisation to significantly influence the  
 1143 local chemistry or energy content. But brown dwarfs and extrasolar planets exist in a  
 1144 larger diversity and, hence, are exposed to very different environments: The cosmic ray  
 1145 flux will be different in an interstellar environment than in the solar system (compare  
 1146 Sect. 3). The chemical composition of the gas in atmospheres outside the solar system  
 1147 causes the formation of mineral clouds where the cloud particles are composed of a mix  
 1148 of silicates, iron and metal-oxides (Helling 2003, 2009; Helling & Rietmeijer 2009), very  
 1149 similar to volcano ash. Extrasolar mineral clouds are much larger than terrestrial clouds  
 1150 due to the larger extension of the atmospheres of brown dwarfs and giant gas planets.  
 1151 Also such clouds are susceptible to charge and discharge processes through cosmic rays  
 1152 (Rimmer & Helling 2013) and turbulence-enhanced dust-dust collisions (Helling et al.  
 1153 2011). The study of the break-down condition in non-solar system atmospheres suggest  
 1154 that different intra-cloud discharge processes dominate at different heights inside mineral  
 1155 clouds: local coronal (point discharges) and small-scale sparks at the bottom region of  
 1156 the cloud where the gas density is high, and flow discharges and large-scale sparks near,  
 1157 and maybe above, the cloud top (Helling et al. 2013). Bailey et al. (2014) apply scaling  
 1158 laws to demonstrate that discharge will propagate farther in brown dwarf atmospheres  
 1159 than in atmospheres of giant gas planets.

1160 Brown dwarfs can be irradiated by a binary-companion (Maxted et al. 2006; Casewell  
 1161 et al. 2013, Sect. 5a) resulting in similar global circulation patterns as demonstrated for  
 1162 irradiated giant gas planets (e.g. Knutson et al. 2007; Dobbs-Dixon & Agol 2013). If  
 1163 such a wind of sufficient high speed hits a sufficiently pre-ionised gas, Alfvén ionisation  
 1164 can produce bubbles of gas with a degree of ionisation of  $\sim 1$  (Stark et al. 2013). The  
 1165 surrounding atmosphere remains in its low degree of ionisation leading to an atmosphere  
 1166 with a time-dependent and spatially intermittent degree of ionisation. A sufficient degree

<sup>18</sup> The phase of common envelope evolution in the binary star evolution involves the brown dwarf being engulfed by, and immersed in, the expanding atmosphere of the white dwarf progenitor as it evolves away from the main sequence. These systems are very close, and tidally locked resulting in one side of the brown dwarf continually being heated by its companion.

of ionisation is the precondition to understand the magnetic coupled atmospheric gas responsible for radio emission in brown dwarfs (Sect. 5a), and from magnetically driven mass loss of extrasolar planetary atmospheres (Tanaka et al. 2014). Other mechanisms for planets to lose mass are related to their host star’s radiation field (Murray-Clay et al. 2009).

An important input for understanding ionisation processes is the global atmospheric structure and results from radiative-hydrodynamic simulations are therefore discussed in more detail below.

**Large-scale modelling of globally circulating extrasolar atmospheres:** A prominent sub-class of extrasolar planets are the short-period gaseous planets. They are (and due to observational constraints will remain) the best characterized of all extrasolar planets. The short periods ( $\sim 3$  days), gaseous nature, and largely circular orbits suggest that the rotation rate of these planets is tidally locked to their orbital period. The result is a stationary day-night heating pattern across the surface. The proximity to their host stars means that the hot daysides will be highly irradiated, reaching temperatures of several thousand degrees.

The large longitudinal temperature gradient between the day and night hemispheres drives atmospheric dynamics that transports heat from day to night sides. The efficiency of this advective transport is a subject of extensive multi-dimensional radiative hydrodynamical studies. Phase-curve observations, consisting of infrared measurements of the planetary flux throughout the entire orbit, do suggest that the night-side of the planet is somewhat cooler than the day (e.g. Knutson et al. 2007). However, the night-side temperatures are still on the order of a thousand degrees, much larger than one would expect simply from the internal cooling of the planet. This suggests that the atmosphere is actually fairly good at transporting energy across the entire planetary surface.

The winds driven by the extreme temperatures on short period planets are unlike any seen in any solar systems. The coupling between the (slow) planetary rotation and the temperature differential results in the development of a broad, supersonic, super-rotating equatorial jets (Tsai et al. 2014). Gas velocities at pressure levels of 0.1 bars in the well-known HD189733b can reach 5km/s (e.g. Dobbs-Dixon & Agol 2013).

Thus, longitudinal transport and mixing, in contrast to vertical convection/turbulence as is important in Jupiter, plays a much larger role. The complexity of the atmospheric dynamics requires coupling together a dynamical model (solving the fluid equations) to a radiative model (involving the detailed opacities). Currently, models utilize molecular opacities, primarily due to species such as CO, H<sub>2</sub>O, and CH<sub>4</sub>. However, transit observations (Pont et al. 2013; Sing et al. 2014) taken for different wavelength bands suggest a cloud coverage throughout the atmosphere. While in hindsight based on observations of brown dwarfs or our gas giant planets this is not surprising, it makes the coupled problem significantly more complex. As the efficiency of energy transport by the gas flow depends on both the fluid velocity and the cooling timescale the growth of cloud layers and the associated change in opacity will modify radiative timescale and may have important consequence for energy re-distribution. Conversely, the changes in the dynamics will alter the growth efficiency of clouds. Unfortunately, as with clouds on Earth, it is not at all clear if this will result in a net cooling or heating of various regions. The precision with which the local atmospheric properties, like gas temperature,

cloud properties, gas composition, is modeled are crucial and efforts are ongoing in the community by, for example, improving the treatment of the equation of state that cover a temperature range of 250K...6000K and a gas pressure range of 10 $\mu$ bar to 10Mbar. The equation of state provides the abundances of opacity species (ions, atoms, molecules, cloud particles) that influence the local temperature through radiative transfer effects. Theoretical calculations now suggest that clouds should be very prevalent throughout these atmospheres (Lee et al. 2015).

MHD simulations allow first insights into magnetic coupling effects despite containing much less information about atmospheric processes than radiative-hydrodynamic circulation models. Such MHD simulations have also been inspired by studies of protoplanetary disks (site of planet formation) and solar physics (e.g. Rogers & Showman 2014). Tanaka et al. (2014), for example, have used an open magnetic flux-tube model in their ideal MHD simulation to demonstrate that under this conditions the planet could form a wind driven by Alfvén waves. Murray-Clay et al. (2009) present an extensive study of UV and X-ray driven mass loss from irradiated extrasolar giant gas planets.

#### (c) Discharges in protoplanetary disks

**Discharge in magneto-hydrodynamically turbulent gases:** Magneto-hydrodynamical turbulence is suggested as a mechanism to sustain the ionisation in a cool atmospheric gas. The energy dissipated from MHD turbulence is to ionise the gas. If this energy is large enough, a positive feedback loop develops where this local ionisation serves as driving mechanisms for magneto-hydrodynamical turbulence. Magneto-hydrodynamical turbulent motion in weakly ionized media continuously creates local electric field even in comoving frame of the media. If the electric field is larger than the critical electric field for electron avalanche, discharge occurs in such a weakly ionized media. This idea has been proposed for the turbulence driven by magneto-rotational instability in protoplanetary disks by Inutsuka & Sano (2005) who found that energetic electrons in a Druyvesteyn distribution may produce impact ionization in particular conditions of the dusty gaseous disks:

The atmospheres of gaseous planets and brown dwarfs are non-uniform in chemical composition for various reasons (formation of dust grains and their sedimentation, temperature stratification, occasional accretion of planetesimals etc., see Sect. 5b). The convection of those objects can be “double diffusive convection” where the structure is destabilized by the diffusion of an elemental abundance gradient.

Recent numerical simulations show that the double diffusive convection evolves into a multi-layer structure where double diffusive convection is confined into thin layers and usual convection occupies most of the volumes, which results in very small energy flux in the radial direction (e.g. Rosenblum et al. 2011b,a). The effect of magnetic field can be important in the thin layers, since magnetic tension force is inversely proportional to the length scale of the eddy. If the ionization degree is kept high enough in the thin layers, the magnetic field possibly lowers the convective energy flux even further, and hence, slows down the gravitational contraction of those objects. Therefore, any processes that may increase the ionization degree is important in the theory of long-term evolution of very cool brown dwarfs and gaseous planets. A simple energetics argument based on the order of magnitude calculations shows that the energy required for keeping the ionization degree sufficiently high (magnetic Reynolds number  $>1$ ) is substantially small

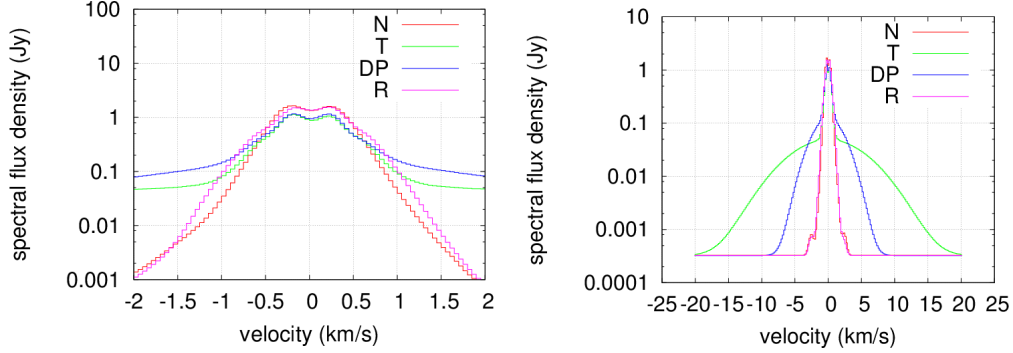


Figure 16.  $\text{HCO}^+$  (3-2) line profiles [Jy] at 267.56GHz (1.1205 mm) without (left) and with (right) lighting. Lighting is here understood in analogy to Earth lighting as a large-scale discharge process. Different line styles (N, T, DP, R) indicate different break-down models. The disk inclination of 7deg at a distance of 56 pc is similar to TW Hya. A minimum-mass solar nebula was applied and a lighting region 25AU . . . 50 AU was considered. The line flux considerably increases if lighting occurs. The ALMA sensitivity limit is 0.01Jy for this line.

1257 ( $< 10^{-4}$ ) compared to the available energy as a turbulent convective motion. The critical  
 1258 electric field for impact ionization in the astrophysical dusty plasma is calculated in  
 1259 detail as a function of gas density in Okuzumi & Inutsuka (2014) who also show that  
 1260 the resultant Ohm's law is highly non-linear and requires a new method to handle the  
 1261 magneto-hydrodynamics in particular regime. To determine the viability of the proposed  
 1262 process theoretically, magneto-hydrodynamics numerical simulations incorporating the  
 1263 micro-physics of electron impact ionization are required (e.g Muranushi et al. 2012,  
 1264 2013).

1265 **Observation of Lightning in Protoplanetary Disks by Ion Lines:** Lightning, a  
 1266 large-scale discharge process in analogy to Earth-lightning, in protoplanetary disks has  
 1267 been studied as a candidate mechanism for chondrule formation, it provides a unique  
 1268 window to probe the electromagnetic state of the protoplanetary disks. Evidence for  
 1269 strong (500-1000G (0.05-0.1T; Wasilewski & Dickinson 2000), transient magnetic fields  
 1270 is found in meteorites. As a consequence, multiple lightning models have been proposed  
 1271 for protoplanetary disks (Gibbard et al. 1997; Weidenschilling 1997; Desch & Cuzzi  
 1272 2000; Muranushi 2010). Muranushi (2010) calculate the charge distribution of dust in a  
 1273 protoplanetary disk where a magneto-resonance instability produces an electromagnetic  
 1274 field. If the electric field potential is large enough for an ensemble of insulated but charged  
 1275 dust particle, a field break-down will occur similar to the field-breakdown in dust clouds of  
 1276 brown dwarfs and extrasolar planets (Helling et al. 2013). Different break-down models  
 1277 (Townsend, Druyversteijn-Penning, Runaway) can be tested which lead to different  
 1278 values for the break-down field influencing the shape of the line profile (Fig. 16, N - no  
 1279 field).

1280 The electric field accelerates the free electrons that ionize the surrounding gas but also  
 1281 the positively-charged ion species to the energy comparable to the electrons. Because  
 1282 the ionization energy is a universal constant for each individual species, each ion will  
 1283 move with a characteristic, constant velocity in the lighting zone that is larger than the

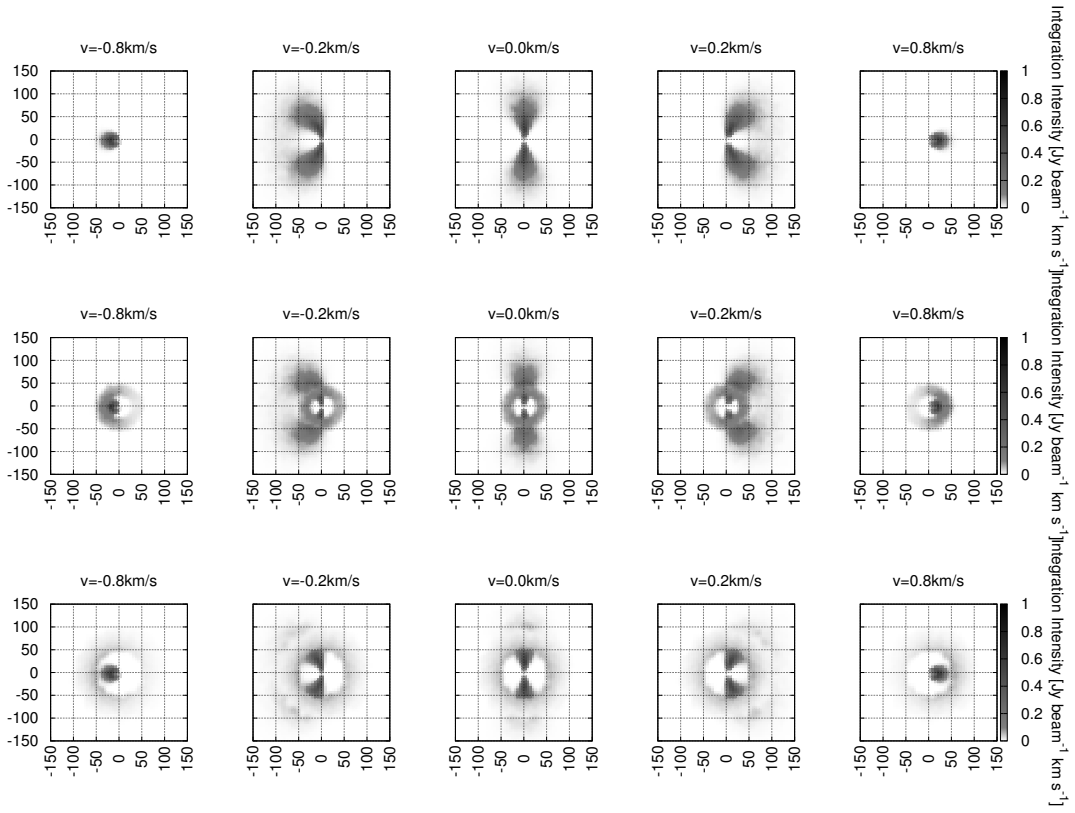


Figure 17. Simulated integrated emissions maps [ $\text{Jy beam}^{-1} \text{ km s}^{-1}$ ] for the  $\text{HCO}^+$  line at 267.56 GHz (1.1205 mm) without (top) and with (middle and bottom row, classic Townsend breakdown model) lighting. The lighting is considered to occur in a region of 25 AU...50 AU for the middle row, and of 50 AU...100 AU for the bottom row. These ALMA channel maps were simulated for 10 mJy per beam of  $0''.65 \times 0''.44$ .  $\text{HCO}^+$  appears in a larger fraction of a protoplanetary disk through the effect of lighting.

1284 thermal gas velocity. This will be unique observational feature to detect and distinguish  
1285 breakdown models in protoplanetary disks.

1286 In this model, it is assumed that the fractional abundances of  $\text{HCO}^+$  relative to  $\text{H}_2$  is  
1287  $9 \cdot 10^{-9}$ . The value is taken from  $r=100\text{au}$ ,  $z=3h$  from the XR+UV disk chemistry model  
1288 of Walsh et al. (2012). The underlying assumption is that  $\text{HCO}^+$  has been gradually  
1289 produced by XR+UV, and although the  $\text{HCO}^+$  molecules may experience a sudden  
1290 accelerated by the lightning electric fields, this does not contribute to the change of the  
1291 number density of  $\text{HCO}^+$  in the present model.

1292 Velocity distribution of the ion species (e.g.  $\text{HCO}^+$ ,  $\text{DCO}^+$  and  $\text{N}_2\text{H}^+$ ) can now be derived  
1293 and the line profiles simulated (Fig. 16 for  $\text{HCO}^+$ ). The two-dimensional position-velocity  
1294 images with lightning assumed to occur in a certain disk region (middle, bottom) is  
1295 shown as simulated ALMA<sup>19</sup> channel maps in Fig. 17. The change in the line profiles  
1296 depending on the presence of a large-scale discharge is demonstrated in Fig. 16. We found  
1297 lightning features of 10-100mJy appear in line profile. Using ALMA, full-disk lightning  
1298 will produce  $100\sigma$  signals at 56pc (TW Hya, Fig. 17) and  $20\sigma$  signals at 140pc (Orion  
1299 nebula; see Muranushi et al. 2015).

#### 1300 (d) Future studies

1301 Combining the expertise available on solar system and terrestrial atmosphere research  
1302 and electrical phenomena therein will help answering some of the following question, but  
1303 might also be inspired by these questions:

- 1304 • In how far can terrestrial and solar system lightning statistics guide our expectation  
1305 for extrasolar environments like on extrasolar planets, brown dwarfs and in  
1306 protoplanetary disks?
- 1307 • How are brown dwarf (and extrasolar planet) atmospheres affected by the  
1308 irradiation of their companion (or host star)?
- 1309 • Going beyond the Solar System, clouds are present in brown dwarf and  
1310 exoplanetary atmospheres. What kind or which combination of atmospheric  
1311 electricity phenomena could explain the required levels of ionized atmosphere to  
1312 provide an explanation for the continuous radio emissions, the 656 nm and X-ray  
1313 emissions?
- 1314 • What would be the possible atmospheric optical and chemical signatures in the  
1315 case that lightning activity exists in exoplanetary and brown dwarfs atmospheres?

## 1316 6. Conclusion

1317 Electrification processes and electrical phenomena are ubiquitous: dust charging and  
1318 discharging is linked to electric gas breakdown in planetary atmospheres inside and  
1319 beyond the solar system where it is involved in global circuits and the occurrence of  
1320 plasma processes. Charge processes play a major role in modifying the ambient chemical

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<sup>19</sup> Atacama Large Millimeter Array, [www.almaobservatory.org](http://www.almaobservatory.org)

1321 composition and the transport properties of neutral gas also in protoplanetary disks where  
 1322 planets form. Charged relativistic grains are suggested as potential primary particles  
 1323 for ultrahigh energy Cosmic Rays (Hoang et al. 2014). The following set of challenges  
 1324 has emerged as common for the themes of this paper which have been guided by the  
 1325 workshop 'Electrification in dusty atmospheres inside and outside the solar system' held  
 1326 in September 2014<sup>20</sup>:

- 1327 (a) An increased population of ion, free electron and radicals lowers the chemical  
 1328 potential for gas-species reactions, leading to potentially observable spectroscopic  
 1329 fingerprints, and
- 1330 (b) also increases the thermal and electrical conductivity of the gas to a certain  
 1331 threshold, enabling more energetic phenomena such as lightning to take place or  
 1332 accretion to proceed during star- and planet formation.n
- 1333 (c) The presence of free charge may be transient (as in lightning) but the electrostatic  
 1334 influence can endure: Charging of dust and aerosols can influence electrostatic  
 1335 character of the ambient atmosphere on longer length and time scales to produce  
 1336 small non-thermal populations of energetic particles.
- 1337 (d) Finite enhanced electrical conductivity can allow magnetic relaxation, and access  
 1338 to stored magnetic energy as a general source of excitation which is unavailable to  
 1339 neutral gases.
- 1340 (e) Non-thermal electrons may facilitate chemical reactions in ways that are  
 1341 classically (i.e. gas-thermodynamically) unlikely: For example, dissociative electron  
 1342 attachment can produce oxygen radicals at little energetic cost, leading to oxidative  
 1343 reactions proceeding at a rate inconsistent with ambient temperatures, or the  
 1344 formation for complex carbohydrates.
- 1345 (f) Charged dust may evolve differently compared to neutral dust: Long-range  
 1346 organization produced by electrostatic effects could produce coherent dust  
 1347 dynamics that would not be possible if only fluid mechanics dominates. surface  
 1348 charging, leading to elongated growth (non-zero eccentricity: polarization of light  
 1349 is observable), or destruction of part of the grain population by Coulomb explosion.

1350 These themes lead to the need of

- 1351 • Further research in dust charging mechanisms in the context of volcano lightning,  
 1352 atmospheres of Brown Dwarfs and exoplanets, and protoplanetary disks.
- 1353 • New instruments in future space missions to test new findings about electrical  
 1354 activity in Solar System Planets. Result would provide models that could mimic  
 1355 electrical activity in Brown Dwarfs and exoplanets.
- 1356 • Further research about the role of dust in electrical discharges in the upper  
 1357 atmosphere of the Earth.
- 1358 • New key insights in charge mechanisms of the Moon and asteroid fine dust grains by  
 1359 interacting with the solar wind and UV flux. This contributes to the fundamental  
 1360 knowledge of the Moon electric environment and will be very useful for further man  
 1361 missions to the Moon and unmanned missions to the asteroids.

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<sup>20</sup> <http://leap1.sciencesconf.org/>

- 3D simulations of extrasolar atmospheres including chemical and electrical feedback of clouds in a magnetised gas.

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## Glossary

**AC:** alternating current

**asteroid:** small rocky bodies of inner solar system, ranging in size from 10m to 900m in diameter

**aurora:** large diffuse light-emitting structures in the lower ionosphere ( $> 90$  km) generated when energetic particles displaced from the ionosphere collide with ground state neutral species and excite them. The excited species (oxygen atoms and nitrogen molecules) emit light when returning to ground state

**carbonaceous compound:** material rich in Carbon; in an astrophysical context, such compounds usually are associated with primitive solar system remnants

**conduit, volcano conduit:** the pipe that carries magma from the magma chamber, up through the crust and through the volcano itself until it reaches the surface.

**chondrule:** molten or partially molten droplets that appear as spherical, solid inclusions of different chemical composition than the matrix of their parent asteroid. They represent one of the oldest solid materials within the solar system.

**cosmic rays:** Ionized nuclei and electrons that are distinguished by their high energies. The ionized nuclei have energies ranging from  $10^6$  eV to greater than  $10^{20}$  eV and comprise 99% of cosmic rays. They originating either from the Sun or outside the Solar System likely from Super Novae or Gamma Ray Bursts.

**cyclotron maser instability:** the mechanism whereby a population of relativistic electrons drift along an ambient magnetic fields, producing coherent radiation that reflects the magnetic field strength.

**DC:** direct current

**Debye length:** the scale-length associated with the violation of charge neutrality in a plasma, due to thermal fluctuations causing charge separation

**double diffusive convection:** a form of convection (i.e. hydrodynamic bulk motion) that is driven by two distinct gradients in fluid composition arising from two different species abundances.

**Druyvesteyn distribution:** a driven-equilibrium distribution function that takes into account the presence of large-scale electric fields in a plasma, as well as interactions with



- 1406 neutrals
- 1407 **effective temperature,  $T_{\text{eff}}$  [K]** is a measure for the total radiation flux emitted at all  
 1408 wavelength  $\lambda$  [Å] ( $T_{\text{eff}} = F_{\text{tot}}/\sigma$  with  $F_{\text{tot}} = \int F_{\lambda} d\lambda$ ;  $F_{\lambda}$  [erg/s/cm<sup>2</sup>/Å] – radiative flux;  $\sigma$   
 1409 [erg cm<sup>-2</sup>s<sup>-1</sup>K<sup>-4</sup>] – Stefan-Boltzmann constant)
- 1410 **electrical conductivity**: a material property that characterises the ease with which  
 1411 electricity can be passed through it
- 1412 **extrasolar**: outside or beyond the Solar System
- 1413 **fair weather current**: atmospheric current of ions present during undisturbed weather  
 1414 condition
- 1415 **floating potential**: the electric potential (or voltage) that spontaneously arises on a  
 1416 surface immersed in a plasma, due to the difference in mobility between electrons and  
 1417 heavier ions
- 1418 **fractoemission**: the emission of particles (charged, neutral and photons) during and  
 1419 after fracturing of surfaces
- 1420 **Geiger counter**: an instrument for measuring ionizing radiation, detects alpha particles,  
 1421 beta particles and gamma rays using the ionization produced in a Geiger-Müller tube
- 1422 **Hydrometeors**: water droplets or ice particles
- 1423 **ion acoustic wave**: a sound wave carried by the motion of plasma ions, as opposed to  
 1424 the electrons
- 1425 **isotope ratio**: means of quantifying the relative abundance of isotopes (which are  
 1426 elements which have nuclei that differ in the number of neutrons, but which are otherwise  
 1427 chemically identical).
- 1428 **jet**: directed and confined stream of fluid or gas
- 1429 **Jy**: Janskys (symbol: Jy) are the unit for the observed spectral flux density: 1 Jy =  
 1430 10<sup>26</sup> W m<sup>2</sup> Hz<sup>-1</sup>. The unit is named after Karl G. Jansky, an US radio astronomer. His  
 1431 discovery of the radio waves emitted by the Milkyway initiated radio astronomy as new  
 1432 research field.
- 1433 **M-dwarfs**: the lowest mass (0.075-0.5M<sub>Sun</sub>), main sequence stars; most common type of  
 1434 stars in the milky way
- 1435 **magma**: fluid mixture of molten and semi-molten rock and volatiles produced by  
 1436 volcanism
- 1437 **magnetic Reynolds number**: a dimensionless number equal to the ratio of advective  
 1438 to diffusive effects, where the latter are characteristic of the magnetic field. Hence a large  
 1439 magnetic Reynolds number ( $\gg 1$ ) means that the magnetic field plays a dominant role  
 1440 in the fluid evolution as diffusion is unimportant and the magnetic field is advected with  
 1441 the fluid flow.
- 1442 **M (spectral type)**: Stars are grouped into spectral classes which link to their effective  
 1443 temperature, luminosity, evolutionary state. The spectral class M indicates the coolest  
 1444 stars on the main sequence where hydrogen burning assures the most stable phase in a  
 1445 star's life. Brown dwarfs are cooler than M-dwarfs and were classified as L, T and Y with  
 1446 Y being the coolest and most planet like.
- 1447 **mesocyclone**: a rapidly rotating column of air, typically a few miles in diameter, readily  
 1448 identified by its characteristic radar signal and consistent with storm conditions
- 1449 **mobility**: the drift speed of a charged particle produced when subjected to a steady  
 1450 electric field
- 1451 **near-IR**: electromagnetic radiation in the wavelength range 800nm to 5 microns
- 1452 **Ohm's law**: relates the electrical current flowing between two points to the potential  
 1453 difference between those same points
- 1454 **plasma void**: a finite region in a dusty plasma which is dust-free

1455 protoplanetary disk: a region of dust and rocks orbiting a young star from which planets  
1456 could be formed

1457 **regolith**: layer of unconsolidated dust and fragmented rock that covers a terrestrial  
1458 planet

1459 **shock tube**: a device designed to create shocks (i.e. sharp density and pressure  
1460 discontinuities) in gases, usually in order to produce ionization fronts

1461 **sounding**: a method to measure local temperature, humidity, wind etc. in the Earth  
1462 atmosphere by means of radio sonds, laser beams (optical) or sound waves

1463 **sprite**: a large (50 km high and 10-20 km wide) electrical discharge that occurs above  
1464 thunderclouds at altitudes around 50-85 km with a diffuse region (above 70-75 km)  
1465 and a filamentary (streamer-like) region (below 70-75 km) [values are given for Earth]

1466 **stratosphere**: major layer of the Earth's atmosphere, lying above the troposphere (0-11  
1467 km) and below the mesosphere (50-90 km)

1468 **thunderstorm**: storm characterised by the presence of lightning

1469 **triboelectrification**: the process whereby two surfaces can acquire or lose charges by  
1470 mutual collision

1471 **troposphere**: lowest layer of the earth's atmosphere, lying between 0 and 11km, in which  
1472 most of the weather phenomena occur

1473 **turbulence**: chaotic flow in which the pressure and gas velocity change rapidly in space  
1474 and time

1475 **volcanic ash**: fragments of rock created during a volcanic eruption, usually 2mm or less  
1476 in diameter

1477 **volcanic conduit**: passage or tube created by the flow of magma in a volcano

1478 **volcanic plume**: the gas and ash cloud ejected into the atmosphere by a volcanic  
1479 eruption

## References

1480

- 1481 Airey M. W., Mather T. A., Pyle D. M., Glaze L. S., Ghail R. C., Wilson C. F., 2015,  
1482 PSS, 113, 33
- 1483 Aizawa K., Yokoo A., Kanda W., Ogawa Y., Iguchi M., 2010, GRL, 37, 17301
- 1484 Allen J. E., Phelps A. D. R., 1977, Reports on Progress in Physics, 40, 1305
- 1485 Anderson R., Bjornsson S., Blanchard D. C., Gathman S., Hughes J., Jonasson S., Moore  
1486 C. B., Survilas H. J., Vonnegut B., 1965, Science, 148, 1179
- 1487 Anuar A. K., Honary F., Hapgood M., Roussel J.-F., 2013, Journal of Geophysical  
1488 Research (Space Physics), 118, 6723
- 1489 Aplin K. L., 2006, Surveys in Geophysics, 27, 63
- 1490 Aplin K. L., 2012, Atmospheric Environment, 50, 373
- 1491 Aplin K. L., 2013, Electrifying Atmospheres: Charging, Ionisation and Lightning in the  
1492 Solar System and Beyond
- 1493 Aplin K. L., Bowles N. E., Urbak E., Keane D., Sawyer E. C., 2011, Journal of Physics  
1494 Conference Series, 301, 012008
- 1495 Aplin K. L., Goodman T., Herpoldt K. L., Davis C. J., 2012, PSS, 69, 100
- 1496 Aplin K. L., Harrison R. G., Rycroft M. J., 2008, SSRev, 137, 11
- 1497 Aplin K. L., Macfaden A. J., Bowles N. E., 2014, PSS, 99, 103
- 1498 Babich L. P., Bochkov E. I., Kutsyk I. M., Rassoul H. K., 2014, PHYSICAL REVIEW  
1499 D, 89
- 1500 Bailey R. L., Helling Ch., Hodosán G., Bilger C., Stark C. R., 2014, ApJ, 784, 43
- 1501 Balser M., Wagner C. A., 1960, Nature, 188, 638
- 1502 Bazelyan E. M., Raizer Y. P., 2000, Lightning Physics and Lightning Protection
- 1503 Becklin E. E., Zuckerman B., 1988, Nature, 336, 656
- 1504 Behnke S. A., Thomas R. J., McNutt S. R., Schneider D. J., Krehbiel P. R., Rison W.,  
1505 Edens H. E., 2013, Journal of Volcanology and Geothermal Research, 259, 214
- 1506 Bennet E. D., Mahony C. M., Askari S., Potts H. E., Everest P., Rutherford D., McDowell  
1507 D. A., Mariotti D., Maguire P., Diver D. A., 2014, Submitted to New J. Physics
- 1508 Bennett A. J., Odams P., Edwards D., Arason P., 2010, Environmental Research Letters,  
1509 5, 044013
- 1510 Benz A. O., Güdel M., 1994, A&A, 285, 621
- 1511 Berger E., 2002, ApJ, 572, 503
- 1512 Berger E., 2006, ApJ, 648, 629
- 1513 Berger E., Ball S., Becker K. M., Clarke M., Frail D. A., Fukuda T. A., Hoffman I. M.,  
1514 Mellon R., Momjian E., Murphy N. W., Teng S. H., Woodruff T., Zauderer B. A.,  
1515 Zavala R. T., 2001, Nature, 410, 338

- 1516 Berger E., Basri G., Fleming T. A., Giampapa M. S., Gizis J. E., Liebert J., Martín E.,  
1517 Phan-Bao N., Rutledge R. E., 2010, *ApJ*, 709, 332
- 1518 Bétrémieux Y., Kaltenegger L., 2013, *ApJL*, 772, L31
- 1519 Betz H. D., Schumann U., Laroche P., 2009, *Lightning: Principles, Instruments and*  
1520 *Applications*
- 1521 Briggs M. S., Connaughton V., Wilson-Hodge C., Preece R. D., Fishman G. J., Kippen  
1522 R. M., Bhat P. N., Paciesas W. S., Chaplin V. L., Meegan C. A., von Kienlin A.,  
1523 Greiner J., Dwyer J. R., Smith D. M., 2011, *Geophysical Research Letters*, 38
- 1524 Büttner R., Zimanowski B., Röder H., 2000, *JGR*, 105, 2819
- 1525 Casewell S. L., Burleigh M. R., Lawrie K. A., Maxted P. F. L., Dobbie P. D., Napiwotzki  
1526 R., 2013, *Mem. Societa Astronomica Italiana*, 84, 1022
- 1527 Casewell S. L., Lawrie K. A., Maxted P. F. L., Marley M. S., Fortney J. J., Rimmer  
1528 P. B., Littlefair S. P., Wynn G., Burleigh M. R., Helling Ch., 2015, *MNRAS*, 447
- 1529 Christian H. J., Blakeslee R. J., Boccippio D. J., Boeck W. L., Buechler D. E., Driscoll  
1530 K. T., Goodman S. J., Hall J. M., Koshak W. J., Mach D. M., Stewart M. F., 2003,  
1531 *Journal of Geophysical Research (Atmospheres)*, 108, 4005
- 1532 Cimarelli C., Alatorre-Ibargüengoitia M., Kueppers U., Scheu B., Dingwell D. B., 2014,  
1533 in *EGU General Assembly Conference Abstracts Vol. 16 of EGU General Assembly*  
1534 *Conference Abstracts, Experimental generation of volcanic lightning*. p. 9004
- 1535 Cooray V., 2003, *The Lightning Flash*
- 1536 Cooray V., 2015, *An introduction to Lightning*
- 1537 Cowley S. W. H., Bunce E. J., 2001, *PSS*, 49, 1067
- 1538 Cushing M. C., Rayner J. T., Vacca W. D., 2005, *ApJ*, 623, 1115
- 1539 D'Angelo N., 1993, *PSS*, 41, 469
- 1540 Demory B.-O., Gillon M., Deming D., Valencia D., Seager S., Benneke B., Lovis C.,  
1541 Cubillos P., Harrington J., Stevenson K. B., Mayor M., Pepe F., Queloz D., Ségransan  
1542 D., Udry S., 2011, *A&A*, 533, A114
- 1543 Desch S., Cuzzi J., 2000, *Icarus*, 143, 87
- 1544 Dobbs-Dixon I., Agol E., 2013, *MNRAS*, 435, 3159
- 1545 Donati J.-F., Landstreet J. D., 2009, *ARA&A*, 47, 333
- 1546 Donati J.-F., Morin J., Petit P., Delfosse X., Forveille T., Aurière M., Cabanac R.,  
1547 Dintrans B., Fares R., Gastine T., Jardine M. M., Lignières F., Paletou F., Ramirez  
1548 Velez J. C., Théado S., 2008, *MNRAS*, 390, 545
- 1549 Dubinova A., Rutjes C., Ebert U., Buitink S., Scholten O., Trinh G. T. N., 2015, *Physical*  
1550 *Review Letters*, 115, 015002
- 1551 Dubrovin D., Luque A., Gordillo-Vazquez F. J., Yair Y., Parra-Rojas F. C., Ebert U.,  
1552 Price C., 2014, *Icarus*, 241, 313

- 1553 Dudkin D., Pilipenko V., Korepanov V., Klimov S., Holzworth R., 2014, Journal of  
1554 Atmospheric and Solar-Terrestrial Physics, 117, 81
- 1555 Dwyer J. R., Grefenstette B. W., Smith D. M., 2008, GRL, 35, 2815
- 1556 Dwyer J. R., Uman M. A., 2014, Physics Reports, 534, 147
- 1557 Ebert U., Nijdam S., Li C., Luque A., Briels T., van Veldhuizen E., 2010, Journal Of  
1558 Geophysical Research-Space Physics, 115
- 1559 Ebert U., Sentman D. D., 2008, Journal of Physics D Applied Physics, 41, 230301
- 1560 Farrell W. M., Desch M. D., 2001, JGR, 106, 7591
- 1561 Fillingim M., 1986, Global electric circuit of Mars
- 1562 Fishman G. J., Bhat P. N., Mallozzi R., Horack J. M., Koshut T., Kouveliotou C.,  
1563 Pendleton G. N., Meegan C. A., Wilson R. B., Paciesas W. S., Goodman S. J., Christian  
1564 H. J., 1994, Science, 264, 1313
- 1565 Fishman G. J., Meegan C. A., 1995, ARA&A, 33, 415
- 1566 Fletcher L. N., Hesman B. E., Achterberg R. K., Irwin P. G. J., Bjoraker G., Gorius N.,  
1567 Hurley J., Sinclair J., Orton G. S., Legarreta J., García-Melendo E., Sánchez-Lavega  
1568 A., Read P. L., Simon-Miller A. A., Flasar F. M., 2012, Icarus, 221, 560
- 1569 Fortov V. E., Morfill G. E., 2010, Complex and Dusty Plasmas: From Laboratory to  
1570 Space. CRC Press/Taylor & Francis
- 1571 Forward K. M., Lacks D. J., Sankaran R. M., 2009a, Physical Review Letters, 102, 028001
- 1572 Forward K. M., Lacks D. J., Sankaran R. M., 2009b, Journal of Geophysical Research  
1573 (Space Physics), 114, 10109
- 1574 Füllekrug M., Diver D., Pinçon J.-L., Phelps A. D. R., Bourdon A., Helling Ch., Blanc  
1575 E., Honary F., Harrison R. G., Sauvaud J.-A., Renard J.-B., Lester M., Rycroft M.,  
1576 Kosch M., Horne R. B., Soula S., Gaffet S., 2013, Surveys in Geophysics, 34, 1
- 1577 Füllekrug M., Kolmasova I., Santolik O., Farges T., Bór J., Bennett A., Parrot M., Rison  
1578 W., Zanotti F., et al. 2013, Environmental Research Letters, 8, 035027
- 1579 Füllekrug M., Mareev E. A., Rycroft M. J., 2006, Sprites, Elves and Intense Lightning  
1580 Discharges
- 1581 Galand M., Moore L., Charnay B., Mueller-Wodarg I., Mendillo M., 2009, Journal of  
1582 Geophysical Research (Space Physics), 114, 6313
- 1583 Galembeck F., Burgo T. A. L., Balestrin L. B. S., Gouveia R. F., Silva C. A., Galembeck  
1584 A., 2014, RSC Adv., 4, 64280
- 1585 Gibbard S., Levy E., Morfill G., 1997, Icarus, 130, 517
- 1586 Gilbert J. S., Lane S. J., Sparks R. S. J., Koyaguchi T., 1991, Nature, 349, 598
- 1587 Gizis J. E., Monet D. G., Reid I. N., Kirkpatrick J. D., Liebert J., Williams R. J., 2000,  
1588 AJ, 120, 1085
- 1589 Goertz C. K., 1989, Reviews of Geophysics, 27, 271
- 1590 Gordillo-Vázquez F. J., 2008, Journal of Physics D Applied Physics, 41, 234016

- 1591 Gordillo-Vázquez F. J., Donkó Z., 2009, *Plasma Sources Science Technology*, 18, 034021
- 1592 Gordillo-Vázquez F. J., Luque A., 2010, *GRL*, 37, 16809
- 1593 Gordillo-Vázquez F. J., Luque A., Simek M., 2012, *Journal of Geophysical Research*  
1594 (*Space Physics*), 117, 5329
- 1595 Gringel W., J.M. R., D.J. H., 1986, *Electrical structure from 0 to 30km*
- 1596 Gurevich A., Milikh G., Roussel-Dupre R., 1992, *Physics Letters A*, 165, 463
- 1597 Gurevich A. V., Karashtin A. N., 2013, *Physical Review Letters*, 110
- 1598 Hallinan G., Antonova A., Doyle J. G., Bourke S., Briske W. F., Golden A., 2006, *ApJ*,  
1599 653, 690
- 1600 Hallinan G., Antonova A., Doyle J. G., Bourke S., Lane C., Golden A., 2008, *ApJ*, 684,  
1601 644
- 1602 Hallinan G., Bourke S., Lane C., Antonova A., Zavala R. T., Briske W. F., Boyle R. P.,  
1603 Vrba F. J., Doyle J. G., Golden A., 2007, *ApJL*, 663, L25
- 1604 Harrison R. G., 2006, *Atmospheric Environment*, 40, 3327
- 1605 Harrison R. G., 2013, *Surveys in Geophysics*, 34, 209
- 1606 Harrison R. G., Aplin K. L., Leblanc F., Yair Y., 2008, *SSRev*, 137, 5
- 1607 Harrison R. G., Carslaw K. S., 2003, *Reviews of Geophysics*, 41, 1012
- 1608 Harrison R. G., Mather T. A., 2006, *AGU Fall Meeting Abstracts*, p. A286
- 1609 Harrison R. G., Nicoll K. A., 2014, *Review of Scientific Instruments*, 85, 066104
- 1610 Harrison R. G., Nicoll K. A., Aplin K. L., 2014, *Journal of Atmospheric and Solar-*  
1611 *Terrestrial Physics*, 119, 203
- 1612 Harrison R. G., Nicoll K. A., Ulanowski Z., Mather T. A., 2010, *Environmental Research*  
1613 *Letters*, 5, 024004
- 1614 Helling Ch., 2003, in Schielicke R. E., ed., *Reviews in Modern Astronomy Vol. 16*  
1615 *of Reviews in Modern Astronomy, Circuit of Dust in Substellar Objects (With 10*  
1616 *Figures)*. p. 115
- 1617 Helling Ch., 2009, in Stempels E., ed., *15th Cambridge Workshop on Cool Stars, Stellar*  
1618 *Systems, and the Sun Vol. 1094 of American Institute of Physics Conference Series,*  
1619 *Cloud formation in substellar atmospheres.* pp 162–171
- 1620 Helling Ch., Casewell S., 2014, *A&A Review*, 22, 80
- 1621 Helling Ch., Jardine M., Mokler F., 2011, *ApJ*, 737, 38
- 1622 Helling Ch., Jardine M., Stark C., Diver D., 2013, *ApJ*, 767, 136
- 1623 Helling Ch., Rietmeijer F. J. M., 2009, *International Journal of Astrobiology*, 8, 3
- 1624 Hess S. L. G., Sarrailh P., Mateo-Velez J. C., Jeanty-Ruard B., Cipriani F., Forest  
1625 J., Hilgers A., Honary F., Thiebault B., Marple S. R., Rodgers D., 2014, *IEEE*  
1626 *Transactions on Plasma Science*, p. submitted
- 1627 Hess V. F., 1912, *Phys. Zeitschr.*, 13, 1084

- 1628 Hoang T., Lazarian A., Schlickeiser R., 2014, ArXiv e-prints
- 1629 Hodosán G., Helling Ch., Asensio-Torres R., Vorgul I., Rimmer P. B., 2016, MNRAS
- 1630 Horányi M., Hartquist T. W., Havnes O., Mendis D. A., Morfill G. E., 2004, Reviews of  
1631 Geophysics, 42, 4002
- 1632 Houghton I. M. P., Aplin K. L., Nicoll K. A., 2013, Physical Review Letters, 111, 118501
- 1633 Hutchinson I. H., Patacchini L., 2007, PHYSICS OF PLASMAS, 14
- 1634 Inutsuka S.-i., Sano T., 2005, ApJL, 628, L155
- 1635 Irwin P. G. J., Teanby N. A., de Kok R., Fletcher L. N., Howett C. J. A., Tsang C. C. C.,  
1636 Wilson C. F., Calcutt S. B., Nixon C. A., Parrish P. D., 2008, JQSRT, 109, 1136
- 1637 James M. R., Lane S. J., Gilbert J. S., 1998, Geological Society of London Journal, 155,  
1638 587–590
- 1639 James M. R., Lane S. J., Gilbert J. S., 2000, J. Geophysical Res., 105, 16641
- 1640 Jayaratne E. R., Saunders C. P. R., Hallett J., 1983, Quarterly Journal of the Royal  
1641 Meteorological Society, 109, 609
- 1642 Johnson A. P., Cleaves H. J., Dworkin J. P., Glavin D. P., Lazcano A., Bada J. L., 2008,  
1643 Science, 322, 404
- 1644 Khrapak S. A., Morfill G. E., 2008, Physics of Plasmas, 15, 114503
- 1645 Khrapak S. A., Tolias P., Ratynskaia S., Chaudhuri M., Zobnin A., Usachev A., Rau C.,  
1646 Thoma M. H., Petrov O. F., Fortov V. E., Morfill G. E., 2012, EPL, 97
- 1647 Kirkpatrick J. D., Reid I. N., Liebert J., Gizis J. E., Burgasser A. J., Monet D. G., Dahn  
1648 C. C., Nelson B., Williams R. J., 2000, AJ, 120, 447
- 1649 Kitzmann D., Patzer A. B. C., von Paris P., Godolt M., Stracke B., Gebauer S., Grenfell  
1650 J. L., Rauer H., 2010, A&A, 511, A66
- 1651 Knutson H. A., Charbonneau D., Allen L. E., Fortney J. J., Agol E., Cowan N. B.,  
1652 Showman A. P., Cooper C. S., Megeath S. T., 2007, Nature, 447, 183
- 1653 Kochkin P. O., Nguyen C. V., van Deursen A. P. J., Ebert U., 2012, Journal of Physics  
1654 D-Applied Physics, 45
- 1655 Konopka U., Mokler F., Ivlev A. V., Kretschmer M., Morfill G. E., Thomas H. M.,  
1656 Rothermel H., Fortov V. E., Lipaev A. M., Molotkov V. I., Nefedov A. P., Baturin  
1657 Y. M., Budarin Y., Ivanov A. I., Roth M., 2005, New Journal of Physics, 7, 227
- 1658 Kopnin S. I., Popel S. I., Yu M. Y., 2009, Physics of Plasmas, 16, 063705
- 1659 Kuhn S., Phelps A. D. R., Fang M. T. C., 1981, Physics of Fluids, 24, 1586
- 1660 Langmuir I., Found C. G., Dittmer A. F., 1924, Science, 60, 392
- 1661 Lapenta G., Pierrard V., Keppens R., Markidis S., Poedts S., Šebek O., Trávníček P. M.,  
1662 Henri P., Califano F., Pegoraro F., et al. 2013, Journal of Space Weather and Space  
1663 Climate, 3, A5
- 1664 Lay E. H., Rodger C. J., Holzworth R. H., Cho M., Thomas J. N., 2010, Journal Of  
1665 Geophysical Research-Space Physics, 115

- 1666 Leblanc F., Aplin K., Yair Y., Harrison R., Lebreton J., Blanc M., eds, 2008, Planetary  
1667 Atmospheric Electricity. Springer
- 1668 Lee G., Helling Ch., Dobbs-Dixon I., Juncher D., 2015, A&A, 580, A12
- 1669 Lee P., 1996, Icarus, 124, 181
- 1670 Liebert J., Kirkpatrick J. D., Cruz K. L., Reid I. N., Burgasser A., Tinney C. G., Gizis  
1671 J. E., 2003, AJ, 125, 343
- 1672 Littlefair S. P., Dhillon V. S., Marsh T. R., Shahbaz T., Martín E. L., Copperwheat C.,  
1673 2008, MNRAS, 391, L88
- 1674 Liu N., Pasko V. P., 2004a, Journal of Geophysical Research (Space Physics), 109, 9306
- 1675 Liu N., Pasko V. P., 2004b, Journal of Geophysical Research (Space Physics), 109, 4301
- 1676 Luque A., Dubrovin D., Gordillo-Vázquez F. J., Yair Y., Parra-Rojas F. C., Ebert U.,  
1677 Price C., 2014, Journal of Geophysical Research (Space Physics), 111
- 1678 Luque A., Ebert U., 2009, Nature Geoscience, 2, 757
- 1679 Luque A., Gordillo-Vázquez F. J., 2012, Nature Geoscience, 5, 22
- 1680 Maguire P. D., Mahony C. M. O., Kelsey C. P., Bingham A. J., Montgomery E. P., Bennet  
1681 E. D., Potts H. E., Rutherford D. C. E., McDowell D. A., Diver D. A., Mariotti D.,  
1682 2015, Applied Physics Letters, 106, 224101
- 1683 Mason B. J., 1953, Quarterly Journal of the Royal Meteorological Society, 79, 501
- 1684 Maxted P. F. L., Napiwotzki R., Dobbie P. D., Burleigh M. R., 2006, Nature, 442, 543
- 1685 McConville S. L., Speirs D. C., Ronald K., Phelps A. D. R., Cross A. W., Bingham R.,  
1686 Robertson C. W., Whyte C. G., He W., Gillespie K. M., Vorgul I., Cairns R. A., Kellett  
1687 B. J., 2008, Plasma Physics and Controlled Fusion, 50, 074010
- 1688 McLean M., Berger E., Reiners A., 2012, ApJ, 746, 23
- 1689 McNutt S. R., Williams E. R., 2010, Bulletin of Volcanology, 72, 1153
- 1690 Michel P., Barucci M. A., Cheng A. F., Böhnhardt H., Brucato J. R., Dotto E.,  
1691 Ehrenfreund P., Franchi I. A., Green S. F., Lara L.-M., Marty B., Koschny D., Agnolon  
1692 D., 2014, Acta Astronautica, 93, 530
- 1693 Millward G., Miller S., Stallard T., Aylward A. D., Achilleos N., 2002, Icarus, 160, 95
- 1694 Miura T., Koyaguchi T., Tanaka Y., 2002, Bulletin of Volcanology, 64, 75
- 1695 Moore L. E., Mendillo M., Müller-Wodarg I. C. F., Murr D. L., 2004, Icarus, 172, 503
- 1696 Morin J., Donati J.-F., Petit P., Delfosse X., Forveille T., Albert L., Aurière M., Cabanac  
1697 R., Dintrans B., Fares R., Gastine T., Jardine M. M., Lignières F., Paletou F., Ramirez  
1698 Velez J. C., Théado S., 2008, MNRAS, 390, 567
- 1699 Morin J., Donati J.-F., Petit P., Delfosse X., Forveille T., Jardine M. M., 2010, MNRAS,  
1700 407, 2269
- 1701 Moses J. I., Bézard B., Lellouch E., Gladstone G. R., Feuchtgruber H., Allen M., 2000,  
1702 Icarus, 143, 244



- 1703 Muranushi T., 2010, *Monthly Notices of the Royal Astronomical Society*, 401, 2641
- 1704 Muranushi T., Akiyama E., Inutsuka S.-i., Nomura H., Okuzumi S., 2015, *ArXiv e-prints*
- 1705 Muranushi T., Okuzumi S., Inutsuka S.-i., 2012, *ApJ*, 760, 56
- 1706 Muranushi T., Okuzumi S., Inutsuka S.-i., 2013, *ApJ*, 771, 138
- 1707 Murray-Clay R. A., Chiang E. I., Murray N., 2009, *ApJ*, 693, 23
- 1708 Nichols J. D., Burleigh M. R., Casewell S. L., Cowley S. W. H., Wynn G. A., Clarke  
1709 J. T., West A. A., 2012, *ApJ*, 760, 59
- 1710 Nicoll K. A., 2012, *Surveys in Geophysics*, 33, 991
- 1711 Nicoll K. A., 2013, *Review of Scientific Instruments*, 84, 096107
- 1712 Nicoll K. A., 2014, *Weather*, 69, 238
- 1713 Nicoll K. A., Harrison R. G., 2010, *GRL*, 37, 13802
- 1714 Nijdam S., Takahashi E., Markosyan A. H., Ebert U., 2014, *Plasma Sources Science  
1715 Technology*, 23, 025008
- 1716 Okuzumi S., Inutsuka S.-i., 2014, *ApJ*, in press
- 1717 Oppenheimer C., 2003, *Progress in Physical Geography*, 27, 230–259
- 1718 Parra-Rojas F. C., Luque A., Gordillo-Vázquez F. J., 2013, *Journal of Geophysical  
1719 Research (Space Physics)*, 118, 5190
- 1720 Parra-Rojas F. C., Luque A., Gordillo-Vázquez F. J., 2015, *Journal of Geophysical  
1721 Research (Space Physics)*, 120, 8899
- 1722 Pasko V. P., 2007, *Plasma Sources Science Technology*, 16, 13
- 1723 Pfofzer G., 1972, *SSRev*, 13, 199
- 1724 Phelps A. D. R., Allen J. E., 1976, *Royal Society of London Proceedings Series A*, 348,  
1725 221
- 1726 Pont F., Sing D. K., Gibson N. P., Aigrain S., Henry G., Husnoo N., 2013, *MNRAS*, 432,  
1727 2917
- 1728 Rakov V. A., Uman M. A., 2003, *Lightning. Physics and Effects*. Cambridge University  
1729 Press
- 1730 Rao N. N., 1993, *Physica Scripta*, 48, 363
- 1731 Rao N. N., 1995, *Journal of Plasma Physics*, 53, 317
- 1732 Rao N. N., Shukla P. K., 1990, *Planet. Space. Sci*, 4, 543
- 1733 Regener E., Pfofzer G., 1935, *Nature*, 136, 718
- 1734 Reiners A., Basri G., 2008, *ApJ*, 684, 1390
- 1735 Rimmer P. B., Helling Ch., 2013, *ApJ*, 774, 108
- 1736 Rimmer P. B., Helling Ch., 2015, *ArXiv e-prints*

- 1737 Rimmer P. B., Walsh C., Helling Ch., 2014, in Booth M., Matthews B. C., Graham  
1738 J. R., eds, IAU Symposium Vol. 299 of IAU Symposium, Cosmic Rays, UV Photons,  
1739 and Haze Formation in the Upper Atmospheres of Hot Jupiters. pp 303–304
- 1740 Rodriguez-Barrera M. I., Helling Ch., Stark C. R., Rice A. M., 2015, ArXiv e-prints
- 1741 Rogers T. M., Showman A. P., 2014, ApJL, 782, L4
- 1742 Rosenberg M., 1993, PSS, 41, 229
- 1743 Rosenblum E., Garaud P., Traxler A., Stellmach S., 2011a, ApJ, 742, 132
- 1744 Rosenblum E., Garaud P., Traxler A., Stellmach S., 2011b, ApJ, 731, 66
- 1745 Route M., Wolszczan A., 2012, ApJL, 747, L22
- 1746 Rutherford D., McDowell D., Mariotti D., Mahony C., Diver D., Potts H., Bennet E.,  
1747 Maguire P., 2014, in APS Meeting Abstracts Impact of plasma induced liquid chemistry  
1748 and charge on bacteria loaded aerosol droplets
- 1749 Rycroft M. J., 1965, Radio Science Journal of Research National Bureau of Standards  
1750 D, 69, 1071
- 1751 Rycroft M. J., Harrison R. G., 2012, SSRev, 168, 363
- 1752 Rycroft M. J., Harrison R. G., Nicoll K. A., Mareev E. A., 2008, SSRev, 137, 83
- 1753 Rycroft M. J., Israelsson S., Price C., 2000, Journal of Atmospheric and Solar-Terrestrial  
1754 Physics, 62, 1563
- 1755 Rycroft M. J., Odzimek A., Arnold N. F., Füllekrug M., Kułak A., Neubert T., 2007,  
1756 Journal of Atmospheric and Solar-Terrestrial Physics, 69, 2485
- 1757 Saunders C., 2008, Charge Separation Mechanisms in Clouds. p. 335
- 1758 Schmidt S. J., Hawley S. L., West A. A., Bochanski J. J., Davenport J. R. A., Ge J.,  
1759 Schneider D. P., 2015, AJ, 149, 158
- 1760 Schumann W. O., 1952, Zeitschrift Naturforschung Teil A, 7, 149
- 1761 See V., Jardine M., Vidotto A. A., Petit P., Marsden S. C., Jeffers S. V., do Nascimento  
1762 J. D., 2014, A&A, 570, A99
- 1763 Sen S., Fukuyama A., Honary F., 2010, Journal of Atmospheric and Solar-Terrestrial  
1764 Physics, 72, 938
- 1765 Shalygin E. V., Markiewicz W. J., Basilevsky A. T., Titov D. V., Ignatiev N. I., Head  
1766 J. W., 2015, GRL, 42, 4762
- 1767 Shao X.-M., Lay E. H., Jacobson A. R., 2013, Nature Geoscience, 6, 29
- 1768 Shukla P. K., Mamun A. A., 2002, Introduction to dusty plasma physics
- 1769 Shukla P. K., Silin V. P., 1992, Physica Scripta, 45, 508
- 1770 Silva H. G., Conceição R., Melgão M., Nicoll K., Tlemcani1 M., Reis A. H., Harrison  
1771 R. G., 2014, Environmental Research Letters, 9, 114025
- 1772 Simões F., Pfaff R., Freudenreich H., 2011, GRL, 38, 22101

- 1773 Sing D. K., Wakeford H. R., Showman A. P., Nikolov N., Fortney J. J., Burrows A. S.,  
1774 Ballester G. E., Deming D. e., 2014, ArXiv e-prints
- 1775 Sorahana S., Suzuki T. K., Yamamura I., 2014, MNRAS, 440, 3675
- 1776 Speirs D. C., McConville S. L., Gillespie K. M., Ronald K., Phelps A. D. R., Cross A. W.,  
1777 Bingham R., Robertson C. W., Whyte C. G., Vorgul I., Cairns R. A., Kellett B. J.,  
1778 2008, Plasma Physics and Controlled Fusion, 50, 074011
- 1779 Stark C. R., Helling Ch., Diver D. A., Rimmer P. B., 2013, ApJ, 776, 11
- 1780 Stenbaek-Nielsen H. C., McHarg M. G., 2008, Journal Of Physics D-Applied Physics, 41
- 1781 Stozhkov Y. V., Okhlopov V., Makhmutov V., Logachev A., 2013, Proceedings - 33rd  
1782 International Cosmic Ray Conference (ICRC)
- 1783 Strobel D. F., Atreya S. K., 1983, Ionosphere. pp 51–67
- 1784 Taddeucci J., Scarlato P., Montanaro C., Cimorelli C., Del Bello E., Freda C., Andronico  
1785 D., Gudmundsson M. T., Dingwell D. B., 2011, Geology, 39, 891
- 1786 Tanaka Y. A., Suzuki T. K., Inutsuka S.-i., 2014, ApJ, 792, 18
- 1787 Thomas R. J., Krehbiel P. R., Rison W., Edens H. E., Aulich G. D., Winn W. P., McNutt  
1788 S. R., Tytgat G., Clark E., 2007, Science, 315, 1097
- 1789 Todd J. F., Barber S. J., Wright I. P., Morgan G. H., Morse A. D., Sheridan S., Leese  
1790 M. R., Maynard J., Evans S. T., Pillinger C. T., Drummond D. L., Heys S. C., Huq  
1791 S. E., Kent B. J., Sawyer E. C., Whalley M. S., Waltham N. R., 2007, Journal of Mass  
1792 Spectrometry, 42, 1
- 1793 Trakhtengerts V. Y., Rycroft M. J., 2008, Whistler and Alfvén Mode Cyclotron Masers  
1794 in Space. Cambridge University Press
- 1795 Treumann R. A., Zbigniew K., Parrot M., 2008, in Leblanc F., Aplin K. L., Yair Y.,  
1796 Harrison R. G., Lebreton J. P., Blanc M., eds, Planetary Atmospheric Electricity  
1797 Vol. 137 of Space Science Series of ISSI, Physics of Electric Discharges in Atmospheric  
1798 Gases: An Informal Introduction. p. 133
- 1799 Tsai S.-M., Dobbs-Dixon I., Gu P.-G., 2014, ApJ, 793, 141
- 1800 Van Eaton A. R., Muirhead J. D., Wilson C. J. N., Cimorelli C., 2012, Bulletin of  
1801 Volcanology, 74, 1963
- 1802 Ververka J., et al. 2013, Icarus, 222, 424
- 1803 Vidotto A. A., Gregory S. G., Jardine M., Donati J. F., Petit P., Morin J., Folsom C. P.,  
1804 Bouvier J., Cameron A. C., Hussain G., Marsden S., Waite I. A., Fares R., Jeffers S.,  
1805 do Nascimento J. D., 2014, MNRAS, 441, 2361
- 1806 Vidotto A. A., Jardine M., Morin J., Donati J. F., Opher M., Gombosi T. I., 2014,  
1807 MNRAS, 438, 1162
- 1808 von Blohn N., Diehl K., Mitra S. K., Borrmann S., 2009, Journal of Atmospheric Sciences,  
1809 66, 2359
- 1810 Vorgul I., Kellett B. J., Cairns R. A., Bingham R., Ronald K., Speirs D. C., McConville  
1811 S. L., Gillespie K. M., Phelps A. D. R., 2011, Physics of Plasmas, 18, 056501

- 1812 Walsh C., Nomura H., Millar T. J., Aikawa Y., 2012, ApJ, 747, 114
- 1813 Wasilewski P., Dickinson T., 2000, Meteoritics and Planetary Science, 35, 537
- 1814 Weidenschilling S., 1997, in Lunar and Planetary Science Conference Vol. 28, Production  
1815 of chondrules by lightning in the solar nebula? not so easy!. p. 1515
- 1816 Whipple E. C., 1981, Reports on Progress in Physics, 44, 1197
- 1817 Whipple F. J. W., Scrase F. J., 1936, Geophys Mem Met Off Lond, 38, 1
- 1818 Williams E. R., McNutt S. R., 2005, in Pontikis C., ed., , Recent Progress in Lightning  
1819 Physics. Research Signpost, pp 81–94
- 1820 Williams P. K. G., Cook B. A., Berger E., 2014, ApJ, 785, 9
- 1821 Wilson C. T. R., 1906, Proceedings - Cambridge Philosophical Society, 13, 363
- 1822 Wilson C. T. R., 1921, Royal Society of London Philosophical Transactions Series A, 221,  
1823 73
- 1824 Wilson C. T. R., 1929, J Frankl Inst, 208, 1
- 1825 Witte S., Helling Ch., Barman T., Heidrich N., Hauschildt P. H., 2011, A&A, 529, A44
- 1826 Wolszczan A., Frail D. A., 1992, Nature, 355, 145
- 1827 Wu C. S., Lee L. C., 1979, ApJ, 230, 621
- 1828 Xu W., Celestin S., Pasko V. P., 2012, Geophysical Resreach Letter, 39
- 1829 Yair Y., 2008, in Leblanc F., Aplin K. L., Yair Y., Harrison R. G., Lebreton J. P., Blanc  
1830 M., eds, Planetary Atmopsheric Electricity Vol. 137 of Space Science Series of ISSI,  
1831 Charge Generation and Separation Processes. p. 119
- 1832 Yair Y., 2012, Advances in Space Research, 50, 293