Ionisation and discharge in cloud-forming atmospheres of brown dwarfs and extrasolar planets

Ch Helling¹, P B Rimmer¹, I M Rodriguez-Barrera¹, Kenneth Wood¹, G B Robertson¹ and C R Stark²

¹ SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews KY16 9SS, UK
² Division of Computing and Mathematics, School of Arts, Media and Computer Games, Abertay University, Dundee DD1 1HG, UK

E-mail: ch80@st-andrews.ac.uk

Received 17 December 2015, revised 15 March 2016
Accepted for publication 12 April 2016
Published 31 May 2016

Abstract

Brown dwarfs and giant gas extrasolar planets have cold atmospheres with rich chemical compositions from which mineral cloud particles form. Their properties, like particle sizes and material composition, vary with height, and the mineral cloud particles are charged due to triboelectric processes in such dynamic atmospheres. The dynamics of the atmospheric gas is driven by the irradiating host star and/or by the rotation of the objects that changes during its lifetime. Thermal gas ionisation in these ultra-cool but dense atmospheres allows electrostatic interactions and magnetic coupling of a substantial atmosphere volume. Combined with a strong magnetic field $\gg B_{\text{Earth}}$, a chromosphere and aurorae might form as suggested by radio and x-ray observations of brown dwarfs. Non-equilibrium processes like cosmic ray ionisation and discharge processes in clouds will increase the local pool of free electrons in the gas. Cosmic rays and lightning discharges also alter the composition of the local atmospheric gas such that tracer molecules might be identified. Cosmic rays affect the atmosphere through air showers in a certain volume which was modelled with a 3D Monte Carlo radiative transfer code to be able to visualise their spacial extent. Given a certain degree of thermal ionisation of the atmospheric gas, we suggest that electron attachment to charge mineral cloud particles is too inefficient to cause an electrostatic disruption of the cloud particles. Cloud particles will therefore not be destroyed by Coulomb explosion for the local temperature in the collisional dominated brown dwarf and giant gas planet atmospheres. However, the cloud particles are destroyed electrostatically in regions with strong gas ionisation. The potential size of such cloud holes would, however, be too small and might occur too far inside the cloud to mimic the effect of, e.g. magnetic field induced star spots.

Keywords: atmospheres, ionisation, clouds, dust charge, cloud discharge

(Some figures may appear in colour only in the online journal)

1. Introduction

The presence of atmospheric clouds outside the solar system has now been established through multi-wavelength variability observations for brown dwarfs and through transit spectroscopy in extrasolar planets as summarized in Helling and Casewell (2014) and Marley et al (2013). Theoretical efforts have focused on modelling the thermodynamic and chemical structure of such ultra-cool atmosphere in order to predict their spectral appearance from the optical into the far-infrared spectral region (Allard 1995, Burrows et al 1997, Marley et al 2002, Fortney et al 2008, Witte et al 2011). A keystone in these efforts is the modelling of cloud formation and cloud feedback on the atmosphere. Clouds impose an
opacity that is considerably larger than that of the gas (main gas opacity sources: CO/CH₄, H₂O, TiO/VO, Na, K), and they deplete or enrich the element abundance inhomogeneously (e.g., Fe, Mg, Si, O, Ti, Al).

Recently, observations in the near infrared (Sorahana et al. 2014) and in Hα indicate potential chromospheric emission (Schmidt et al. 2015) which would suggest an outward temperature increase in the atmosphere of brown dwarfs. Previously, brown dwarf atmospheres were considered too cold to exhibit any characteristic plasma signature (Mohanty et al. 2002). Radio observations of brown dwarf atmospheres support the expectation that the atmospheres of brown dwarfs exhibit plasma behaviour (e.g., Hallinan et al. 2015), and open up the possibility to study the magnetic behaviour of such ultra-cool objects. Interpretations of such radio detection at present invoke the electron cyclotron maser instability as the reason for radio emission at 1–100 GHz which requires a large magnetic field strength at the site where the cyclotron maser criterion is fulfilled (Vorgul et al. 2011). As the cyclotron frequency, $\nu_c$, scales with the local magnetic field strength $B$ as $\nu_c = eB/(2\pi m_e c)$, a magnetic field strength of $>34$ kG is required, for example, in the case of the M9.5 brown dwarf TVLM 51346546 which was observed to emit at $\sim 100$ GHz (Williams et al. 2015) for cyclotron emission to occur. Typical magnetic field strength for such late M-dwarfs/ brown dwarfs are $\mathcal{O}(10^3)$G which is 30 $\times$ lower than required for cyclotron emission. A more suitable interpretation seems that the TVLM 513 emission detected by ALAMA originates from a population of near speed-of-light (weakly relativistic) electrons in the form of gyrosynchrotron emission, maybe comparable to Auroral km emission on Uranus. Aurora observations from the solar system start to emerge as a guide for radio emission on brown dwarfs (Nichols et al. 2012, Hallinan et al. 2015). All mechanisms, the cyclotron maser instability and Auroral emission, however, require a pool of free electrons that are captured by the magnetic field and therefore can emit as accelerated charges. The challenge is that no brown dwarf has been found to orbit a Sun-like host star from which it could pick up charges from the stellar wind like the solar system planets nor can we assume without proof that brown dwarfs host geologically active moons to provide a steady stream of charges like in the case of the Jupiter moon Io. Studies of possible ionisation processes occurring in the ultra-cool atmospheres of brown dwarfs are therefore conducted, and section 2 discusses processes that effect the ionisation state of ultra-cool atmospheres. Main results of a recent reference study will be summarised against which the effect of additional processes, like Cosmic Ray ionisation or lightning discharges in clouds, can be compared for understanding the radio emission from ultra-cool atmospheres. The Drift-Phoenix atmosphere models utilised here as input for the local gas temperature, gas pressure, thermal electron number density and cloud properties are 1D atmosphere simulations (Helling et al. 2008a, 2008b, Witte et al. 2009, 2011). We therefore performed 3D Monte Carlo radiative transfer simulations of Cosmic Ray induced air showers to understand how spatially extended the effect of cosmic rays on the local atmosphere might be and how this may differ from our previous 1D results. Section 3 investigates the charging of mineral cloud particles through thermal collisions with the atmospheric gas to provide a first insight into the possible number of charges that a mineral cloud particle can carry in comparison to their stability against charge induced destruction processes. We argue that regions with strong local gas ionisation, like Alfvén ionisation, would lead to the destruction of the cloud particles in this region which could then mimic the appearance of cold spots on the brown dwarf’s surface. Electrostatic cloud destruction would also help to understand the increasing variability across the spectral L-T transition for brown dwarfs (e.g., Gizis et al. 2015)). However, our scale estimates show that the resulting cloud holes are too small and potentially too deep inside the cloud to have an observational effect.

2. Sources of free electrons in ultra-cool atmospheres

2.1. Thermal ionisation

Thermal ionisation provides the background ionisation in every atmospheric gas according to the local gas temperature and pressure. A reference study of the ionisation and magnetic coupling behaviour for the atmospheres of ultra-cool objects considering thermal ionisation can be conducted on the basis of existing model atmosphere grids. We utilise a grid of Drift-Phoenix model atmosphere simulations which include cloud formation modelling. The grid models cloud forming atmospheres of M dwarfs, brown dwarfs and giant gas planets. Rodríguez-Barrera et al. (2015) use the whole set of models, here we only apply a subset. Each atmosphere model is determined by global parameters that unambiguously characterise a specific object. The global parameter for a giant gas planet atmosphere model would be the total flux $T_{\text{eff}} = 1000$ K, the surface gravity $\log(g) = 3.0$; for a brown dwarf it would be $T_{\text{eff}} = 1000$ K, the surface gravity $\log(g) = 5.0$, plus a set of element abundances. A M dwarf (or a young brown dwarf) would have a higher effective temperature, $T_{\text{eff}} = 2800$ K, and a lower surface gravity of $\log(g) = 4.0$. The (initial) element abundances are assumed to be solar but they are altered by element depletion or enrichment because of cloud formation or evaporation. Drift-Phoenix solves equations for non-equilibrium kinetic cloud formation (Woitke and Helling 2003, Helling and Witte 2006, Helling et al. 2008c, Helling and Fomins 2013), hydrostatic and chemical equilibrium, and uses mixing length theory and radiative transfer theory to calculate the temperature structure (Hauschildt and Baron 1999). Drift-Phoenix describes the formation of cloud particles as a phase transition process by considering seed formation, grain growth and evaporation, sedimentation, element depletion and the feedback of these processes on the atmosphere structure (Woitke and Helling 2004, Helling et al. 2008a, 2008b, Witte et al. 2009, 2011). The resulting 1D atmosphere structures are characterised by their local gas temperature, $T_{\text{gas}}$ (K), and gas pressure, $p_{\text{gas}}$ (bar), but also by a cloud structure with results for material composition

$^3$ see https://leap2010blog.wordpress.com/category/drift-phoenix/ for a summary of Drift-Phoenix atmosphere modelling.
of the cloud particles, cloud particle size, cloud particle and gas-phase number densities, all depending on height. These values allow one to derive the local degree of ionisation \( f_e(z) = n_e(z) / n_{gas}(z) \) —total gas number density \( (cm^{-3}) \), \( k_B \)—Boltzmann constant, \( n_e(z) \)—electron number density \( (cm^{-3}) \), the plasma frequency, \( \omega_{pe} = \sqrt{n_e e^2 / (m_e)} \) \( (e) \)—electron charge \( (C) \), \( m_e \)—electron mass), and the Debye length \( \lambda_D = \sqrt{e_0 k_B T_e / (n_e e^2)} \). A certain ionisation is required for a plasma to establish long-distance electrostatic interactions. Figure 1(top) demonstrates that the local degree of thermal ionisation is rather low throughout the low-temperature atmospheres depicted. It, however, reaches a certain threshold of \( f_e > 10^{-7} \) (horizontal line) in the inner (high pressure) atmosphere above which experiments suggest plasma behaviour to set in. The comparison between the plasma frequency, \( \omega_{pe} \), and the electron-neutral collision frequency, \( \nu_{ne} \), demonstrate that the upper, low-pressure part of the atmosphere is most susceptible to long-range electrostatic interactions, i.e. where \( \omega_{pe} \nu_{ne} \gg 1 \). The Debye length shows over which length scale such electrostatic interactions can be expected to occur and figure 1(bottom) shows that they are particularly large for the atmospheres with the lowest effective temperature \( T_{eff} \), in the upper atmosphere where the degree of ionisation is smallest.

For a charged particle’s motion to be dictated by a magnetic field, and hence producing radio emission, the particle needs to complete a considerable number of gyrations before a collision with a neutral atom occurs. If this charged particle is, for example, an electron, the comparison between the electron cyclotron frequency, \( \omega_{ce} = eBm_e \), and the electron-neutral collision frequency, \( \nu_{ne} \), allows a critical value for the local magnetic field for a magnetic coupling of the gyrating ionised species to be derived. The critical local magnetic field for electrons to be magnetically bound is \( B_c \gg \frac{m_e e^2}{\sigma_{gas} p_{gas} \sqrt{k_B T_e / m_e}} \) which is independent on the local state of gas ionisation (for more details see Rodríguez-Barrera et al (2015)). Figure 2 shows that the upper parts of ultra-cool atmospheres are magnetically coupled for both, electrons and atomic ions, in brown dwarfs and giant gas planets. A comparison to the magnetic field densities expected for M dwarfs, brown dwarfs and giant gas planets (horizontal lines) shows that a larger atmospheric volume can be magnetically coupled in a brown dwarf atmosphere than in a giant gas planet atmosphere.
2.2. Non-thermal processes: winds, clouds and cosmic rays

Brown dwarfs are fast rotators which cause the atmosphere to develop winds. Giant gas planets develop strong winds due to the strong irradiation by their host stars. Global circulation models for giant gas planets (Showman et al. 2008, 2015, Dobbs-Dixon et al. 2010, Dobbs-Dixon and Agol 2013) suggest local wind speeds of several km s\(^{-1}\). High wind speeds are reached in the equatorial jet streams in the upper atmosphere of the giant gas planet HD 189 733b, for example. Zhang and Showman (2014) demonstrate, however, that the global wind speed does not exceed 0.2–0.5 km s\(^{-1}\) in brown dwarf atmospheres based on their present set of 3D atmosphere simulations. Diver et al. (2005) demonstrate that a wind speed of 2–5 km s\(^{-1}\) is required to allow the collisions of the wind with the ions to cause a charge imbalance resulting in a considerable increase of the local degree of ionisation. The required magnetised seed plasma will keep the electrons locked in place by a magnetic field to allow the wind to push away the ions which have a considerably larger collisional cross section than electrons. Therefore, the local charge imbalance imposed by the gas flow must be established on a timescale, \(\tau \approx m_i/\omega_i\) (\(\omega_i = q_Bm_i\)—ion cyclotron frequency, \(q_i\)—ion charge, \(m_i\)—ion mass), shorter than that for electron transport to neutralise it again. Stark et al. (2013) apply this idea to brown dwarf atmospheres. However, this time scale might be more appropriately represented by the collisional frequency with the neutral gas for brown dwarf/giant gas planet atmospheres have very high densities, \(\tau_i \sim \tau_B\) with \(\nu_B \approx \pi \rho H_2 \times n_{\text{gas}} v_{\text{th,h}}\) (\(v_{\text{th,h}}\)—ion temperature, \(T_i = T_{\text{gas}}\). Assuming that the ions follow the wind, the size of the pocket of such an Alfvén ionised gas can be estimated from \(R_{ij} \approx \nu_{\text{wind}}/\nu_B\).

Figure 2 shows that in particular the upper, low-pressure regions of an atmosphere can be expected to be magnetically coupled. Alfvén ionisation will therefore work best at gas pressures <1 bar in brown dwarf atmospheres and <10\(^{-25}\) bar in giant gas planet atmospheres. This pressure range coincides with the atmospheric range where mineral clouds form in brown dwarfs and giant gas planets (figure 2 in Helling et al. (2008c)). This suggests that the charge imbalance caused by the impact of strong winds on a magnetised plasma could contribute to cloud particle ionisation in these pockets of Alfvén ionisation.

Helling et al. (2011a) argue that clouds in brown dwarf and giant gas planet atmosphere are electrostatically charged because particle–particle collisions in turbulent atmosphere clouds alone are energetic enough to overcome the work function of mineral materials (triboelectric charging). The size-dependent gravitational settling (rain-out), which determines the cloud height, causes a large scale charge separation resulting in an electrostatic potential difference inside such a mineral cloud. Helling et al. (2013) demonstrated that such a potential difference can overcome the breakdown field and, hence, initiate an ionisation avalanche that subsequently can lead to a large-scale lighting discharge inside mineral clouds. Bailey et al. (2014) use scaling laws derived from sprite experiments and demonstrate that such large-scale discharges can reach a geometrical extension of \(\approx 3000\) km in brown dwarf clouds but only \(\approx 300\) km in a giant gas planet atmosphere.

![Figure 3](image.png)

Figure 3. The air shower penetration depth (shower age), \(s = s(X)\) (\(X\)—column density) for a Jupiter-like atmosphere and a CR event of \(10^{20}\) eV; \(s = 0\) corresponds to the initial event, \(s = 1\) corresponds to the shower maximum occurring at \(r = 1.0013 R_{\text{Jupiter}}\), and \(s = 3\) for infinite column density \(X \to \infty\).

Cosmic rays (CR) contribute to the ionisation of clouds on Earth and they are discussed as a trigger for lighting initiation in the Earth’s atmosphere (Gurevich and Karashtin 2013). Similar effects occur in brown dwarfs and extrasolar planets (Rimmer and Helling 2013) where each of the systems may be exposed to a different radiation field of a host star or the interstellar medium irradiated by a high-mass O- or B-type star. For the interstellar cosmic ray flux spectrum (e.g. figure 4 in Rimmer and Helling (2013)), the local degree of gas ionisation increases by \(\approx 6\) orders of magnitude in the case of a giant gas planet atmosphere and by \(\approx 4\) orders in a brown dwarf atmosphere that is \(10^2\) times more compact. Cosmic rays also affect the abundance of molecules through ion-neutral kinetic gas chemistry by opening up reaction channels to more and more complex hydro-carbon molecules (Rimmer et al. 2014a). The investigation of the spatial extent of CR triggered events is required to help determine how much of the atmosphere volume might produce chemical tracers. So far, only 1D simulations were done for extrasolar objects (Rimmer and Helling 2013).

We therefore carried out first 3D radiative transfer calculations utilizing the Monte Carlo method (Wood and Reynolds 1999) which has been updated to include algorithms for particle tracking from Dupree and Fraley (2002) as a follow-up of the work presented in Rimmer and Helling (2013) for hydrogen-rich atmospheres. We model the interactions of protons, positive, neutral and negative pions, positive and negative muons, electrons and positrons, and gamma rays with an \(\text{H}_2\)-dominated gas in a three dimensional Cartesian grid representing a homogeneous atmosphere with a radial density-temperature gradient. The atmosphere profile that determines the density-temperature gradient is the same like in Rimmer and Helling (2013) (their figure 3) and is used as input for the local gas number density. The 3D atmosphere is assumed to be isotropic, the density profile only changing with the distance from the center as prescribed by the 1D profile. The air shower is initiated by one CR event which is assumed to have an energy of \(10^{20}\) eV. Rimmer and Helling (2013) demonstrated that high-energy CR events penetrate deeper into the atmosphere. This approach therefore allows us...
to study the maximum effect on the atmospheric volume influenced by one air shower event. Rimmer and Helling (2013) have studied the CR electron production rate for a whole spectrum of initial CR energies but in 1D. Here, we are interested in the geometrical extent of such an event skimming the atmosphere for allowing a maximum of observable volume. For an air shower initiated by one CR event, the number of particles exceeds a million within just a few generations after initiation. We apply a thin sampling method where all particles below a predefined thinning energy level are subject to thin sampling with a chance of survival proportional to their energy (Hillas 1985; Hillas 1997). The shower development can then be studied, for example, by measuring the penetrative depth of an air shower, called shower age $s$, which depends on the integrated column density (see equation (3) in Rimmer et al (2014b)). The shower age is, for example, used to parameterise the energy distribution of secondary electrons (see equation (4) in Rimmer et al (2014b)). The shower age can only be determined in one direction, and figure 3 shows the shower age for the radial direction. The air shower reaches its maximum at a radial depth of $r = 1.0013 \, R_{\text{Jupiter}}$ for a Jupiter-like atmosphere. This value is expected to be lower for denser atmospheres like for brown dwarfs, hence the impact of CRs on the electron gas density will be smaller in brown dwarfs than in Jupiter-like planets.

Figure 4 shows results in 2D cuts for an air shower triggered by a CR event of $10^{20}$ eV. Note that the longitudinal extension of the shower is approximately two orders of magnitude greater than the lateral extension. The opening angle of the air shower remains rather confined despite various singular trajectories branching out. The shower has no significant anisotropies in the $x$-$y$ plane (figure 4, right). Images of the other particle types appear vastly different, for example, the trajectories of neutral pions are mostly sub-centimetre because they decay almost instantaneously, hence, only affecting the uppermost atmosphere.

Our 3D results confirm that also in extrasolar objects only the uppermost atmospheric layers will be affected by cosmic air showers because of the rather high local densities in the atmospheres of giant gas planets and brown dwarfs. Their occurrence statistics will depend on the external cosmic ray flux which will be higher for young brown dwarfs in star forming regions with strongly radiating O- and B-stars or for an object near a super nova outburst compared to an extrasolar planet in a planetary system around a Sun-like star.

### 3. Charging cloud particles by atmospheric gas interaction

Atmospheres of extrasolar planets have been shown to form clouds that are made of mixed mineral particles of various sizes (e.g. Helling et al (2008c)). The growth of these cloud particles is determined by collisions with the ambient gas which they deplete. Cloud particles start to gravitational settle and change their size and composition depending on the local thermodynamic conditions. The distance over which the cloud particle ensemble precipitates does determine the geometrical height of the cloud. Cloud particles will not only collide with neutral species, but also with electrons and ions and by this process pick up charges from the surrounding atmospheric gas. The efficiency of this charging process will depend on the abundance of the electrons and ions in the gas phase and their temperature. In extrasolar, ultra-cool atmosphere,
the amount of free charges will be moderate as discussed in section 2.1 if thermal ionisation is the only gas ionisation process. Section 2.2 summarised other processes that act to increase the pool of free charges in ultra-cool atmospheres. A background of thermal electrons will therefore always be present. In the following section, we offer a first exploration of how such atmospheric charges may affect the cloud particle charges, and argue that regions of strong gas ionisation destroy cloud particles electrostatically. If such a destruction occurs, the cloud opacity would change and possibly allow for an observable change of radiation flux.

3.1. Electron deposition on cloud particles in ultra-cool atmospheres

We perform a first exploratory estimate of atmospheric regions of extrasolar planets and brown dwarfs where cloud particles are most likely to be stable against electrostatic disruption caused by charges accumulation on their surfaces. As a first attempt to evaluate cloud particle charging in brown dwarf atmospheres, electron deposition on cloud particles is considered as a first order process where the respective rate coefficient depends only linearly on the gas density, $k \sim n_{\text{gas}}$. Gas-phase ionisation mechanisms were discussed in section 2 for brown dwarfs and extrasolar planetary atmospheres. The cloud particles are assumed to be spherical. The gas-phase ionisation is parameterised by an ionisation rate $\zeta$ (s$^{-1}$). Electrons are adsorbed onto the surface of a cloud particle with a certain probability when the electron in the atmospheric gas collides with the cloud particle. Similar to the growth of cloud particles by gas-surface reactions (Woitke and Helling 2003), the electron will approach the surface directly (free molecular flow) or diffusive (viscous) before the electrostatic interaction dominates. We assume that electrostatic attraction/rejection will dominate the approach of the electron or ion. Considerably more elaborate approaches have been published for dust charging in protoplanetary disks by e.g. Fujii et al (2011) and Ilgner (2012). We aim to provide this first estimate in combination with our detailed modelling of cloud formation which provides the local cloud particle number density, $n_{\text{e}}$ (cm$^{-3}$), their size, $a$ (cm), and material composition which is a mix of materials (Woitke and Helling 2004, Helling and Woitke 2006, Helling et al 2008c), in contrast to previous works. Mineral clouds in brown dwarfs and giant gas planets are characterised by cloud particles changing in size and material composition depending on the local temperature and gas density. Generally, the top of the cloud is dominated by small particles (10$^{-6}$ cm) and a mix of Mg/Si/Fe/O materials (see table 7 in Helling et al (2008c)). The cloud base can be made of particles as large as 10$^{-2}$ cm which predominantly contain high-temperature condensates made of Fe/Al/Ti/O. These findings are based on kinetic cloud formation models that described seed formation and subsequent surface growth/evaporation by gas phase—surface reactions. The model derived by Helling et al (2008c), Helling and Woitke (2006) and Woitke and Helling (2004) does fulfil element conservation and takes into account gravitational settling and convective mixing for the cloud particle formation.

In the following, a locally constant grain size is assumed. Changes in grain size could in principle occur but are not considered in our following explorative estimate.

The net number of electrons per grain (net negative charge), $N_{e,d}$, changes depending on the local electron density, $n_e$, through electron and ion adsorption as

$$\frac{dN_{e,d}}{dt} = (k_- - k_+)n_e.$$  

(1)

The electron number density, $n_e$, in the gas phase changes therefore through cloud particle ionisation as

$$\frac{dn_e}{dt} = \zeta n_{\text{gas}} - \alpha n_e^2 - k_n g n_e.$$  

(2)

The first term parameterises the gas ionisation by a prescribed ionisation rate $\zeta$ (s$^{-1}$). The second term describes the gas-phase recombination, the third term is the loss through the adsorption of an electron onto the grain surface. The total rate coefficient for recombination in the gas-phase, $\alpha$ (cm$^3$ s$^{-1}$), can be written as

$$\alpha = \alpha_2 + n_{\text{gas}} \alpha_3,$$  

(3)

where $\alpha_2$ (cm$^3$ s$^{-1}$) is the 2-body gas-phase recombination rate, and $\alpha_3$ (cm$^6$ s$^{-1}$) is the 3-body rate:

$$\alpha_2 = 8.22 \times 10^{-8} \left( \frac{T}{300 \text{ K}} \right)^{-0.48} - 1.3 \times 10^{-8},$$  

(4)

$$\alpha_3 = 2 \times 10^{-25} \left( \frac{T}{300 \text{ K}} \right)^{-2.5}.$$  

(5)

The adsorption rate for electrons onto a cloud particle, $k_-$, and for ions $k_+$, both with units (cm$^3$ s$^{-1}$), can be expressed as

$$k_- = \sigma_{fr} \frac{v_e^2}{2 \pi \varepsilon_0 m_e a},$$  

(6)

$$k_+ = \sigma_{fr} \frac{8k_B T}{nm_p} + \frac{N_{e,d} \varepsilon_e^2}{2 \pi \varepsilon_0 m_e a},$$  

(7)

where $k_B = 1.38 \times 10^{-16}$ erg K$^{-1}$ is Boltzmann’s constant, $\varepsilon_e$ (cm s$^{-1}$) is the electron velocity, $m_e = 9.11 \times 10^{-28}$ g, and $m_p = 1.67 \times 10^{-24}$ g. The cross-section for a spherical dust grain is $\sigma_{fr} = \pi a^2$, with $e$ the elementary charge and $\varepsilon_0$ the permittivity of free space. The second terms in equations (6) and (7) account for the effect of the electrostatic field of the negatively charged grain upon the gas-phase electrons and ions. The free electrons are not necessarily in thermal equilibrium with the ambient neutral gas, or the ions. Brown dwarf atmospheres are, however, very dense and therefore collisional dominated. We use $T_e = T = T_{\text{gas}}$ unless stated otherwise. The velocity of the electron is therefore taken to be its thermal velocity, $v_e = \sqrt{2 e e}$. This will, however, not be true during the development of a discharge or other high-energy events. As the number of surface electrons grows, the resulting electrostatic field of the cloud particle begins to inhibit further electron attachment. However, the field attracts ions and now the probability of ion attachment increases. Ion attachment neutralises the grain, lowering the net negative charge of the grain.
The steady-state solution of equation (1), \( \frac{dN_{e,d}}{dt} = 0 \), is satisfied when \( k_- = k_+ \) (equations (6) and (7)). The maximum value, \( N_{e,d,\text{max}} \), of charges that a cloud particle of size \( a \) can acquire by adsorption from a surrounding ionised gas of temperature \( T = T_{\text{gas}} \) is therefore

\[
N_{e,d,\text{max}} = \left( \frac{16k_B e^{2}}{e^3} \right) \alpha T. \tag{8}
\]

The quantity \( N_{e,d,\text{max}} \) denotes the number of electrons a grain will have at steady state. \( N_{e,d,\text{max}} \) is independent of the gas ionisation rate \( \zeta \) (equation (2)). Processes that requires a critical surface charge, \( N_{d,\text{crit}} \), will occur if \( N_{d,\text{crit}} < N_{e,d,\text{max}} \) (e.g. electrostatic disruption, (Stark et al 2015); electron avalanches, (Helling et al 2011b, Dubrovin et al 2015)). If \( N_{d,\text{crit}} > N_{e,d,\text{max}} \) then the number of electrons on the cloud particle surface would achieve steady state before the critical process has a chance to occur. The time needed to achieve steady state is characterised by \( k_- \neq k_+ \), and hence \( N_{e,d} < N_{e,d,\text{max}} \). In this case, the electrostatic contributions to the adsorption rates \( k_- \) and \( k_+ \) become very small, and equations (6) and (7) can be approximated by

\[
k_- = \alpha g v_e, \tag{9}
\]
\[
k_+ = \alpha g \sqrt{8kT}{\pi m_p}. \tag{10}
\]

### 3.2. Time evolution of cloud particle charging

Equation (2) can be integrated to obtain an analytic expression for the gas electron number density, \( n_e \), that changes because of electron depletion through grain collisions before steady state is reached or if it is not reached at all

\[
n_e = \frac{1}{\alpha \tau} \tanh \left[ \frac{t}{\tau} + \arctanh \left( \frac{k_- n_d}{2} \right) \right] - \frac{k_- n_d}{2 \alpha}, \tag{11}
\]

with

\[
\tau = \frac{2}{\sqrt{4\alpha Z n_{\text{gas}} + k^2 n_d^2}}. \tag{12}
\]

The first term in equation (12) represents the electron-gas recombination, the second term the electron adsorption onto the grain’s surface. Inserting equation (11) into equation (1) results in

\[
\frac{dN_{e,d}}{dt} = \frac{k_- - k_+}{\alpha \tau} \tanh \left[ \frac{t}{\tau} + \arctanh \left( \frac{k_- n_d}{2} \right) \right] - \frac{(k_- - k_+) n_d}{2 \alpha}. \tag{13}
\]

Integrating equation (13) results in an expression for the total number of charges, \( N_{e,d} \), on an ensemble of cloud particles due to a first-order gas-phase ionisation process as a function of time before steady state is achieved,

\[
N_{e,d} = \frac{k_- - k_+}{\alpha} \log \left[ \cosh \left( \frac{t}{\tau} + \arctanh \left( \frac{k_- n_d}{2} \right) \right) \right]
- \frac{(k_- - k_+) n_d}{2 \alpha} - \frac{k_- - k_+}{\alpha} \log \left[ 1 - \frac{k^2 n_d^2 \tau^2}{4} \right]^{1/2}. \tag{14}
\]

This solution is only accurate when \( N_{e,d} < N_{e,d,\text{max}} \), hence before the cloud particles have achieved a charge steady state. The predicted time (equation (12)) can only be considered as a lower limit because the electrostatic effects of the charged grain on free electrons and cations is neglected in our approximations of equations (9) and (10) which have not been used in the whole of section 3.2.

For spherical grains the maximum number of net charges that can reside on a grain of radius \( a \) before Coulomb explosion can be expressed as (equation 8 in Stark et al (2015)),

\[
N_{e,c} = \frac{\pi(32e_0 \Sigma_c)^{1/2}}{e \alpha} a^2. \tag{15}
\]

with \( \Sigma_c \) the mechanical tensile strength of the dust grain (the maximum stress or pressure that a material can withstand). By setting \( N_{e,d} = N_{e,c} \) (equations (14) and (15)), a critical time scale, \( t_{\text{crit}} \), can then be evaluated numerically. \( t_{\text{crit}} \) is the time during which the cloud particle can accumulate charges by electron deposition and still be stable against Coulomb disruption. For times larger than \( t_{\text{crit}} \), i.e. \( t > t_{\text{crit}} \), cloud particles of a given size will explode due to the electrostatic force. The solution for \( t_{\text{crit}} \) is depicted in figure 6.

### 3.3. Grain charge deposition time-scales in ultra-cool atmospheres of extrasolar planets

**Approach:** we evaluate the maximum charge number densities possible through charge adsorption and the critical survival time scale against electrostatic disruption of mineral cloud particles in the ionised gases of extrasolar atmospheres. We utilised one example Drift-PHOENIX atmosphere simulation (Witte et al 2009, 2011) and use the model results for the local gas density, \( n_{\text{gas}}(z) \) (\( z \)-cm\(^{-3} \)), the gas temperature, \( T_{\text{gas}}(z) \) (K) (\( z \)-0.1 eV), and the cloud particle size \( a(z) \) (\( z \)-cm) in order to evaluate equation (8), and the critical time scale, \( t = t_{\text{crit}} \), from \( N_{e,d} = N_{e,c} \) with equations (14) and (15). We represent the cloud particle size \( a \) by the height-dependent mean particle size, \( \langle a(z) \rangle \) instead of a height-dependent particle size distribution function. We demonstrate the results for the model simulation of a giant gas planet atmosphere with the effective temperature \( T_{\text{eff}} = 1600 \) K (total radiative flux), the surface gravity \( \log g = 3 \), and the set of solar element abundances. The electron velocity, \( v_e(z) \) (\( z \)-cm\(^{-1} \)), is calculated assuming \( T_e(z) = T_{\text{gas}}(z) \) unless stated otherwise. The first-order ionisation rate, \( \zeta \) (\( z^{-1} \)) is used as a parameter and different values are explored.

**Results:** we first explore the atmospheric regions in our example giant gas planet/brown dwarf atmosphere where the cloud particles are stable against electrostatic disruption caused by the charges accumulated on their surfaces. This can be accomplished by comparing the number of charges necessary for Coulomb explosion, \( N_{e,c} \) (equation (15)), to the maximum possible number of charges that a cloud particle can adsorb from the ionised atmosphere, \( N_{e,d,\text{max}} \) (equation (8)),

\[
\frac{N_{e,c}}{N_{e,d,\text{max}}} = \frac{\sigma^2 \Sigma_c}{8 e_0 T_e}. \tag{16}
\]
where \( T_e (\text{eV}) \) is the electron temperature. Only if \( N_{\text{ce}} / N_{\text{max}} \gg 1 \), the cloud particles are stable against electrostatic disruption for a given electron temperature, \( T_e \). Coulomb explosion will only take place if \( N_{\text{ce}} / N_{\text{max}} \ll 1 \). Figure 5 demonstrates that in the model atmosphere considered here, \( T_e \) needs to be much greater than the thermal energy to achieve \( N_{\text{ce}} / N_{\text{max}} \ll 1 \). Since the average composition of the dust will change as a function of atmospheric height, this value of \( \Sigma \) will vary between 1 and 100 MPa, and we set \( \Sigma = 50 \text{ MPa} \) for the exploratory purpose of this paper. Generally, the cloud layer is stable against Coulomb explosion for \( T_e < 10^5 \text{ K} \) \((< 10 \text{ eV})\) and at high pressures inside the atmosphere also above \( 10^3 \text{ K} \) (figure 5).

The timescale for Coulomb explosion to occur can be derived from equation (14) using setting \( N = N_{\text{ce}} \) for a given grain size (equation (15)). This timescale is plotted as a function of atmospheric pressure \( p_{\text{gas}} \)\((\text{dyne cm}^{-2})\) in figure 6, and the ionisation rate parameter is explored. The timescale for Coulomb explosion depends critically upon the ionisation rate. For fast electrons, when \( T_e > 10 \text{ eV} \)\((\approx 10^5 \text{ K})\) , the timescale ranges from about 100 d for a weak source of ionisation, \( \zeta = 10^{-17} \text{ s}^{-1} \). For cosmic rays as an example of a weak ionisation source, the timescale for Coulomb explosion drops to on the order of one day, and for a strong ionising process, such as Alfvén ionisation, the timescale drops significantly to between 1 \( \mu \text{s} \) to 1 ms. This broad range of timescales means that the ionising source has a significant effect on the size distribution of grains in the upper atmosphere. This leads in particular to the conclusion that the occurrence of highly efficient local ionisation processes like Alfvén ionisation lead to a local destruction of cloud particles through electrostatic effects. The resulting sputtering products increase the number of small grains which will lead to a local increase of cloud opacity. Each of these sputtering products may carry different charges depending on their individual size. There is no reason to believe that sputtering products are of the same size similar to mechanical destruction processes (e.g. Güttler et al (2010)). Cloudy atmosphere of brown dwarfs with strong winds that result in Alfvén ionisation could therefore mimic the presence of star spots or similar variability pattern if the affected area is large enough. The ‘dark spot’ would only be present until the cloud particles have grown to larger sizes so that no opacity contrast to its surrounding will be detectable any more. The size of such spots would be \( R_{\text{Alf}} \approx v_{\text{wind}} / \nu_{\text{ci}} \) assuming the ion can follow the hydrodynamic wind. Figure 7 demonstrates the potential sizes of such spots for the case of a fully ionised molecular hydrogen gas (solid line) and the case of that only potassium (K, dotted line) could be ionised. Simulations by Dobbs-Dixon and Agol (2013) show that a maximum wind speed of 5 \( \ldots 6 \text{ km s}^{-1} \) is reached in the pressure interval \( p_{\text{gas}} = 10^{-4} \ldots 10^{-2} \text{ bar} \)\((\text{red shaded area})\) in an irradiated giant gas planet atmosphere. Similar models for irradiated brown dwarfs are not available yet. Brown dwarf circulation models for non-irradiated but fast rotating objects achieve hydrodynamic velocities in the atmosphere below the necessary Alfvén ionisation threshold at present (Zhang and Showman 2014). In the case of giant gas planets where the local wind speed is sufficient inside the atmosphere where \( p_{\text{gas}} = 10^{-4} \ldots 10^{-2} \text{ bar} \), the diameter of an Alfvén ionisation induced cloud hole would be 0.1 m at the lowest pressure end of the interval, too small to make any observational effect. If appropriate velocities occur at lower pressures, cloud-free spots could be just 10 m of size, still far below an observational effect.

4. Summary

Thermal ionisation in brown dwarf and giant gas planet atmospheres with local temperatures between 100 K … 4000 K and...
cause the emergence of cloud holes. The potential size of such holes in an extended cloud deck is too small and would occur too far inside the cloud to mimic the effect of magnetic field induced star spots.

Acknowledgments

We highlight financial support of the European Community under the FP7 by the ERC starting grant 257431.

References

Allard F 1995 Nature 378 441–2
Bailey R L, Helling Ch, Hodosan G, Bilger C and Stark C R 2014 Astrophys. J. 784 43
Burrows A et al 1997 Astrophys. J. 491 856–875
Diver D A, Fletcher L and Potts H E 2005 Sol. Phys. 227 207–15
Dobbs-Dixon I and Agol E 2013 Mon. Not. R. Astron. Soc. 435 3159–68
Dobbs-Dixon I, Cumming A and Lin D N C 2010 Astrophys. J. 710 1395–407
Dubrovin D, Nijdam S, Clevis T T J, Heijmans L C J, Ebert U, Yair Y and Price C 2015 J. Phys. D: Appl. Phys. 48 055205
Dupree S A and Fraley S K 2002 A Monte Carlo Primer (New York: Kluwer)
Fortney J J, Marley M S, Saumon D and Lodders K 2008 Astrophys. J. 683 1104–16
Fuji Y I, Okuzumi S and Inutsuka S I 2011 Astrophys. J. 743 53
Girsz J E et al 2015 Astrophys. J. 813 104
Gurevich A V and Karashin A N 2013 Phys. Rev. Lett. 110 155007
Güttler C, Blum J, Zsom A, Ormel C W and Dullemond C P 2010 Astron. Astrophys. 513 A56
Hallinan G et al 2015 Nature 523 568–71
Hauschildt P H and Baron E 1999 J. Comput. Appl. Math. 109 41–63
Helling Ch and Casewell S 2014 Astron. Astrophys. Rev. 22 80
Helling Ch, Dehn M, Woitke P and Hauschildt P H 2008a Astrophys. J. Lett. 675 L105–8
Helling Ch, Dehn M, Woitke P and Hauschildt P H 2008b Astrophys. J. Lett. 677 L157–7
Helling Ch and Fedins A 2013 Phil. Trans. R. Soc. A 371 10581
Helling Ch, Jardine M and Mokler F 2011a Astrophys. J. 737 38
Helling Ch, Jardine M, Stark C and Diver D 2013 Astrophys. J. 767 136
Helling Ch, Jardine M, Witte S and Diver D A 2011b Astrophys. J. 727 4
Helling Ch and Woitke P 2006 Astron. Astrophys. 455 325–38
Helling Ch, Woitke P and Thi W F 2008 Astron. Astrophys. 485 547–60
Ilgen M 2012 Astron. Astrophys. 538 A124
Marley M S, Ackerman A S, Cuzzi J N and Kitzmann D 2013 Clouds and Hazes in Exoplanet Atmospheres ed S J Mackwell et al (Tucson, AZ: University Of Arizona Press) pp 367–91
Marley M S, Seager S, Saumon D, Lodders K, Ackerman A S, Freedman R S and Fan X 2002 Astrophys. J. 568 335–42
Mohanty S, Basri G, Shu F, Allard F and Chabrier G 2002 Astrophys. J. 571 469–86
Nichols J D, Burleigh M R, Casewell S L, Cowley S W H, Wynn G A, Clarke J T and West A A 2012 Astrophys. J. 760 59
Rimmer P B, Helling Ch and Bilger C 2014a Int. J. Astrobiol. 13 173–81
Rimmer P B and Helling Ch 2013 Astrophys. J. 774 108
Rimmer P B, Stark C R and Helling Ch 2014b Astrophys. J. Lett. 787 L25
Rodriguez-Barrera M I, Helling Ch, Stark C R and Rice A M 2015 Mon. Not. R. Astron. Soc. 454 3977–95
Schmidt S J, Hawley S L, West A A, Bochanski J J, Davenport J R A, Ge J and Schneider D P 2015 Astron. J. 149 158
Showman A P, Cooper C S, Fortney J J and Marley M S 2008 Astrophys. J. 682 559–76
Showman A P, Lewis N K and Fortney J J 2015 Astrophys. J. 801 95
Sorahana S, Suzuki T K and Yamamura I 2014 Mon. Not. R. Astron. Soc. 440 3675–84
Stark C R, Helling Ch, Diver D A and Rimmer P B 2013 Astrophys. J. 776 11
Stark C R, Helling Ch and Diver D A 2015 Astron. Astrophys. 579 A41
Vorgul I et al 2011 Phys. Plasmas 18 056501
Williams P K G, Casewell S L, Stark C R, Littlefair S P, Helling Ch and Berger E 2015 Astrophys. J. 815 64
Witte S, Helling Ch, Barman T, Heidrich N and Hauschildt P H 2011 Astron. Astrophys. 529 A44
Witte S, Helling Ch and Hauschildt P H 2009 Astron. Astrophys. 506 1367–80
Woitke P and Helling Ch 2003 Astron. Astrophys. 399 297–313
Woitke P and Helling Ch 2004 Astron. Astrophys. 414 335–50
Wood K and Reynolds R J 1999 Astrophys. J. 525 799–807
Zhang X and Showman A P 2014 Astrophys. J. Lett. 788 L6