Formation, Detection, and Characterization of Extrasolar Habitable Planets
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Cloud and Gas Ionisation in Atmosphere of Gas-Giant Planets

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Abstract. The steady increase of the sample of know extrasolar planets broadens our knowledge and at the same time, reveals our lack of understanding. Habitability is a wide expression, needing planet formation theory and microphysics of cloud formation at the same time. The habitability of a planet depends, amongst other things, on how much radiation reached the ground and how much of potentially dangerous radiation is absorbed on the way through the atmosphere. For this, we need to understand cloud formation and it's impact on the atmosphere.

We have studied the formation of mineral clouds on planetary atmospheres by a kinetic approach which allows us to predict the size distribution and material composition of the cloud particles. With these results we show that mineral cloud particles can be electrically charged and at which point inside a cloud charge separation will cause an electric field breakdown. Such streamer processes result in an extreme increase of the local number of free charges. Given the strong magnetic field in Brown Dwarfs and maybe in giant gas planets, these charges will than be accelerated upward out of the atmosphere where they become detectable as radio emission.

Keywords. giant planets - atmosphere; exoplanet atmosphere; cloud formation

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1. Introduction

Observations have revealed that hazes appear in the upper atmospheres of close-in planets, because the haze absorbing the stellar radiation during transit makes the planet appear larger than expected. The transit spectroscopy of HD 189733b presented in Pont *et al.* (2008), in Sing *et al.* (2011) and in Pont et al. (2012) provides the first proof that small mineral particles do not only populate the highest layers of the terrestrial atmospheres but are also present in extrasolar Jupiters. Clearly, clouds play an important role in every atmosphere where they form because they consume elements, and by this, change the local gas-phase chemistry. Cloud particles have large radiation absorption cross sections and they therefore increase the greenhouse effects, hence affecting the local temperature. Clouds, however, can also play a rather important role in transporting charges through the atmosphere. This may be through winds or through accelerated electrons during or after lightning discharges. The questions is if it is plausible to assume that also clouds in extrasolar planets charge easily and if we should expect large-scale lightning discharge to occur also inside such exotic atmospheres in which clouds are made of mineral particles (Helling 2009 and references therein).

Our study of ionisation processes in ultra-cool atmospheres is also of interest for the explanation of the increasing radio luminosity relative to the X-ray luminosity in L-typ Brown Dwarfs. The observation of X-ray flares and coherent radio emission from brown dwarfs (Berger *et al.* 2010) suggests that they must possess a magnetic field to which free charges can couple. These electron are accelerated and become detectable as coherent or even as sporadic radio emission of such ultra-cool objects. This scenario has been suggested in Helling *et al.* (2011).

2. Results

Helling, Jardine & Mokler (2011) investigated if mineral particles that compose the clouds in gas-giant planets and Brown Dwarfs can be charged and if associated effects, like field break-down, could increase the local degree of gas ionisation. Such an increase of free electrons beyond the thermal values would then couple to magnetic field and be accelerated out of the atmosphere. As Brown Dwarfs have strong magnetic field, observed radio emission is then a natural consequence of such accelerated charges.

2.1. *Grain charging and discharging*

Dust-gas collisions during gravitational settling do not produce enough energy to exceed the work function of a wide range of solid materials (the grain material's ionisation energy, orange bar Fig. 1, top). Grain-grain collisions due to the grains relative motion induced by the gravitational settling (drift) and enhanced by a local, convectively driven turbulent fluid field were also investigated. Figure 1 (top) shows that turbulence enhanced grain-grain collisions can provide enough energy for ionising dust grains. This process seems to be most efficient in the inner, denser part of the cloud in giant planet atmospheres as shown in Figure 1, and it is an efficient mechanism throughout the whole cloud in Brown Dwarfs (Fig. 5 in Helling, Jardine & Mokler 2011). Note that the collisional energy changes throughout the atmosphere because of changing grain masses due to changing grain radii and grain material composition (e.g. Fig. 1 in Helling, Jardine & Mokler 2011).

Once the cloud particles are charged and carry a relative charge difference, for example caused by different grain sizes, a charge separation can establish. This may happen on large scales due to the different settling velocities for different grain masses. Already a charge separation on small scales can cause an electric-field break down due to the development of a self-propagating ionisation front, a 'streamer'. Figure 1 (bottom) compares the timescale on which such a streamer established, $\tau_{\rm str}$ (black solid line), with the Coulomb recombination time scale, $\tau^{\rm dust}_{\rm recomb}$ (dotted red line), of a dust grain that carries a charge of $10e$: $\tau^{\rm dust}_{\rm recomb} > \tau_{\rm str}$ for all atmospheric pressures below $10^{-2.5}$bar in the model atmosphere for the gas-giant planet. This suggests that the cloud particles can remain charged for long enough to allow a streamer discharge to establish. One streamer event increases the locally available free electron by a number of 10^{13} (e.g. Dowds, Barrett & Diver 2003). Such an increase in free electrons is strong enough for the magnetic Reynolds number to increase above 1, which is indicative for a coupling of the electrons to the magnetic field (Fig. 2 in Helling *et al.* 2011).

Figure 1 (buttom) contains also the streamer superposition timescale, $t = n_{\rm d}^{-1/3}/v_{\rm sed}$ (blue lines) with $n_{\rm d}$ the number of dust grains at a certain height in the atmosphere and $v_{\rm sed}$ (dashed blue: $10 \times v_{\rm sed}$) the cloud particle's sedimentation velocity. Multiple encounters of streamer electron clouds with the electric field of charged grains can happen in the 'lightning'-regime, but not in the 'coronal discharge' regime. The extension of the 'lightning' regime decreases if turbulence slows down the grain settling (blue solid line).

Another way to access the atmosphere's potential for the occurrence of lightning, i.e. large-scale, discharges is to study the electric breakdown field strengths dependent on the local atmospheric properties. This ansatz utilises the Paschen curves which allows for some consideration of the local gas-phase chemistry (for more details see Helling, Jardine, Stark, Diver 2012). Figure 2 demonstrates that the electric field strength needed to achieve a field break-down decreases with decreasing pressure, hence, it is considerably

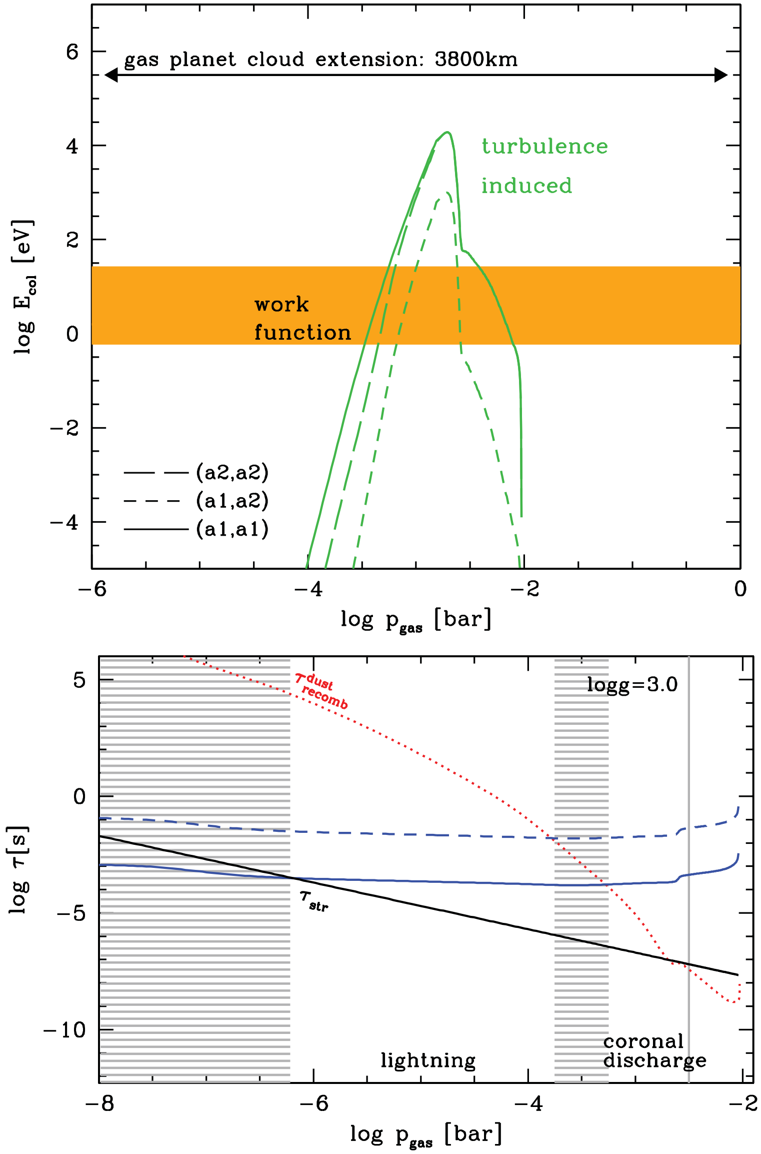

Figure 1. Top: Turbulence enhanced grain-grain collisional energies (green lines) compared to ionisation energies for various materials (orange bar) for a Drift-Phoenix atmosphere model for $T_{\rm eff}$ = 1600K, log(g) = 3.0 and initial solar element abundances. The extension of the cloud layer is indicated. **Bottom:** Potential lightning and coronal discharge regime. Multiple encounters of streamer electron clouds with the electric field of charged grains can happen in the lightning-regime, but not in the coronal discharge regime. The extension of the lightning regime decreases if turbulence slows down the grain settling process (blue solid line).

smaller higher up in the atmosphere. This means that in principle, lightning-like events would be easier to initiate higher up in an atmosphere given that a population of seed electrons exists. In reality, the electric field strength at which a field break-down occurs in thunderstorms on Earth are by at least one order of magnitude lower.

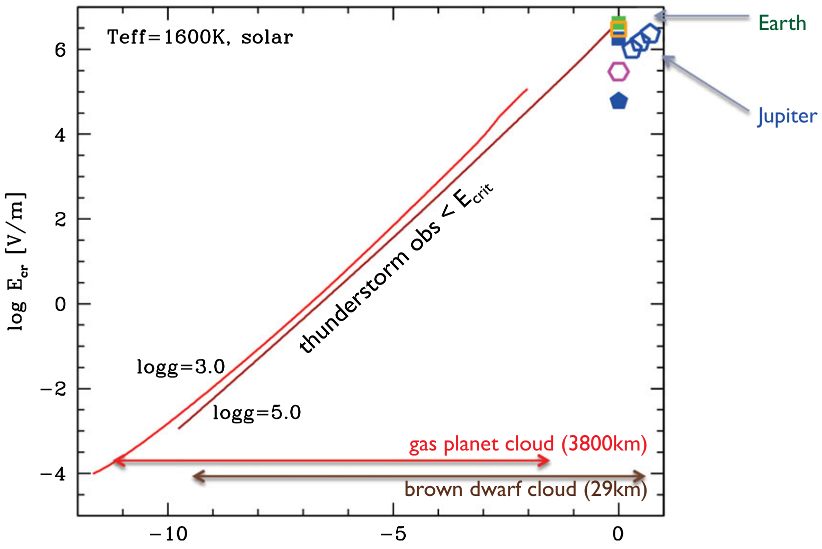

Figure 2. The critical electrical break-down field strength, $E_{\rm cr}$ [V/m], for the atmosphere of a giant gas planet (log(g) = 3.0, red lines) and a Brown Dwarfs (log(g)=5.0, brown lines). The vertical cloud extensions are indicated by red and brown arrows, respectively. Measured values for Earth and Jupiter are included for comparison (symbols).

3. Other ionisation mechanisms

Thermal ionisation is very low in atmospheres of gas-giant planets because of the low gas temperatures. Other sources of atmospheric ionisation can be of dynamical nature or external. One example is the ionisation of the atmospheric gas (and maybe also of the cloud particles) by Cosmic Ray (CR) impacts. Using a simple optical depth ansatz, Helling *et al.* (2013a) demonstrated that CRs can ionise the upper atmosphere. Rimmer & Helling (2013) used a Monte Carlo code to follow the cosmic ray impacts through the exosphere into the atmosphere. They show that the local degree of gas ionisation changes by a factor of 500 . . . 1000. This is not enough to push the magnetic Reynolds number above one, but it will affect the gas-phase chemistry in these atmospheric layers above the cloud.

4. Conclusion

Naturally, one would expect ultra-cool atmosphere like on non-irradiated gas-giant planets to be a good example for a neutral gas. However, our work suggests that cloud particles are easily charged by collisional processes alone, and that discharge processes of large or small scale charge separation will increase the local degree of gas ionisation considerably. In fact, this increase can be large enough to suggest a coupling of the free charges to the magnetic field which in turn would suggest radio emission coming from these accelerated charges. The outer part of the atmosphere are influenced by the ambient Cosmic Rays impinging onto the gas and thereby also increasing the number of free electrons.

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