Planetary and Space Science 77 (2013) 152–157

Contents lists available at SciVerse ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Dust cloud lightning in extraterrestrial atmospheres

Christiane Helling [a,*], Moira Jardine [a], Declan Diver [b], Sören Witte [c]

[a] SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews, KY16 9SS, UK
[b] School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK
[c] Hamburger Sternwarte, Gojenbergsweg 112, 21029 Hamburg, Germany

ARTICLE INFO

Article history:
Received 10 December 2011
Received in revised form
13 June 2012
Accepted 3 July 2012
Available online 14 July 2012

Keywords:
Extrasolar planets
Discharge processes
Clouds
Dust formation

ABSTRACT

Lightning is present in all solar system planets which form clouds in their atmospheres. Cloud formation outside our solar system is possible in objects with much higher temperatures than on Earth or on Jupiter: Brown dwarfs and giant extrasolar gas planets form clouds made of mixed materials and a large spectrum of grain sizes. These clouds are globally neutral but we argue that mineral clouds in brown dwarfs and extrasolar planets are susceptible to local discharge events and that the upper cloud layers are most suitable for powerful lightning-like discharges. We discuss various sources of atmospheric ionisation, including thermal ionisation and a first estimate of ionisation by cosmic rays, and argue that we should expect thunderstorms also in the atmospheres of brown dwarfs and giant gas planets which contain mineral clouds.

1. Introduction

Until recently, clouds were believed to be unique to Earth-like planets and to the gas giant planets that are rather far away from their host star (like Jupiter, Saturn, Uranus in our solar system). Extrasolar planets are now a matter of fact and their diversity has increased over the last couple of years due to various ground based observational efforts like SuperWASP, HAT, TrES and regarding giant gas planets, and by the CoRot and the Kepler space mission that include Earth-like, low-mass planets. Compared to the solar system, however, many giant gas planets are orbiting their host star at very short distance. Observations have revealed that hazes appear in the upper atmospheres of such 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) and in Sing et al. (2011) 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. Such direct observations of atmospheric dust have not yet been possible for brown dwarfs. Brown dwarfs have the same size and effective temperature as the gas-giants, and they have been subject to extensive direct spectroscopic observations as they are much more close by and, hence, it is easier to take direct spectroscopic measurements for brown dwarfs than for the majority of the exoplanets. High- and low-resolution spectra, reaching from the optical into the near-IR, were detected and compared to synthetic spectra of model atmosphere simulations (e.g., Stephens et al., 2009; Witte et al., 2011; Patience et al., 2012). Researchers are keen to reproduce both observed spectra and also each others model results, leading to dedicated bench mark efforts for example for dust cloud models (e.g., Helling et al., 2008a). More often, we learn something new only if model simulations do not fit observations. Jones and Tsuji (1997) compared their static model atmosphere results to late M-dwarf spectra. The synthetic spectra only started to be comparable to observations when the authors reduced individual element abundances artificially, arguing these element would be locked in dust grains and, hence, be not available to the formation of molecules. Saumond et al. (2006) showed that the *Spitzer* observation of ammonia (NH_3) indicates vertical mixing of hotter material into detectable layers, hence, a local chemical dis-equilibrium. Their chemical equilibrium model did not fit the observations unless they reduced the NH_3 abundances, arguing that the reaction timescale of N_2 to NH_3 is much slower than the convective mixing timescale.

Clearly, clouds play an important role in every atmosphere where they are forming 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. Furthermore, these cloud form at a highly convective environment which drives a vivid turbulence field that can initiate dust formation (Helling et al., 2001), and which increases relative velocities between grains. Clouds have been observed to produce discharge events like lightning and sprites in planet of

* Corresponding author.
E-mail address: ch80@st-and.ac.uk (Ch. Helling).

0032-0633/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.pss.2012.07.003

our solar system that carry clouds. Therefore, we have good reasons to expect that cloud-forming extrasolar planets and brown dwarfs show similar electrostatic activities.

We summarise our model of mineral cloud formation (Section 2) and discuss in Section 4 if mineral clouds could produce lightning-like discharge events. Section 3 describes collisional ionisation and ionisation by cosmic rays as sources of charge separation in mineral clouds.

2. Mineral cloud formation in extrasolar planets and brown dwarfs

Brown dwarfs and gas giant planets outside of our solar system are likely not to form cloud made only of liquid droplets, but their warmer atmospheres do allow solid dust particles to condense from the gas phase.

We have modelled the formation of such mineral clouds by describing seed formation (by homogeneous nucleation) followed by the growth of 13 silicate and oxide solids by 60 chemical surface reactions, evaporation, gravitational settling (rain out), convective element replenishment, and element conservation (Woitke and Helling, 2003, 2004; Helling and Woitke, 2006; Helling et al., 2008c). Our model calculations start from solar element abundances which are subsequently depleted by seed formation and the growth of the grain mantle. If the grains become thermally unstable and evaporation sets in, the element abundances will be enriched by those elements previously locked in grains. Both processes, element depletion and element enrichment, are non-uniform and individual for each involved element. Processes between dust particles that lead to a further increase in grain size, like for example coagulation, are not part of our kinetic dust model because coagulation acts at a much longer time scale. Coagulation is about 100 × slower than the growth process by surface reactions, hence, the formation processes (nucleation and growth) will be much faster (Helling et al., 2008b).

The onset of dust formation is triggered by a nucleation process that strongly depends on the local gas temperature and a high supersaturation of the seed forming gas species which requires a temperature well below thermal stability. Typical supersaturation ratios of our nucleation species TiO_2 are well above 10^4 in the nucleation region of the cloud (Fig. 1 in Helling et al., 2008c). The onset of growth requires the growing material to be thermally stable only. The growth rate is determined by the inflow of the growing gas phase constituents, hence, it is proportional to the number density of the (grow-) contributing species and their velocity distributions. We refer to Helling and Rietmeijer (2009) and above mentioned papers for more details regarding the model equations. Our solution of the kinetic dust formation predict a cloud structure as function of the local gas temperature and gas density, T and ρ_{gas}. Our model predicts the mean grain size $\langle a\rangle(T,\rho_{gas})$ (μm), the number density of dust particles $n_d(T,\rho_{gas})$ (cm^{-3}), and the mean material composition of the cloud particles $V_s/V_{tot}(T,\rho_{gas})$ (%) (e.g., Fig. 1). We also calculate the chemical composition of the gas phase, including the degree of ionisation (Section 4). V_s is the dust volume occupied by the solid species s, V_{tot} is the total dust volume. To some extent, the mean grain size, number of dust particles, the total dust volume, and higher dust moments allow us to reproduce the grain size distribution, $f(V,T,\rho_{gas})$ which provides the number of dust grains for each grain volume V.

Clouds in brown dwarfs and extrasolar giant gas planets are composed of a mixture of minerals due to the richness of the atmospheric precursor gas in these objects (Fig. 1), henceforth called 'mineral clouds'. The dust formation process (seed formation, growth/evaporation) is influenced by gravitational settling,

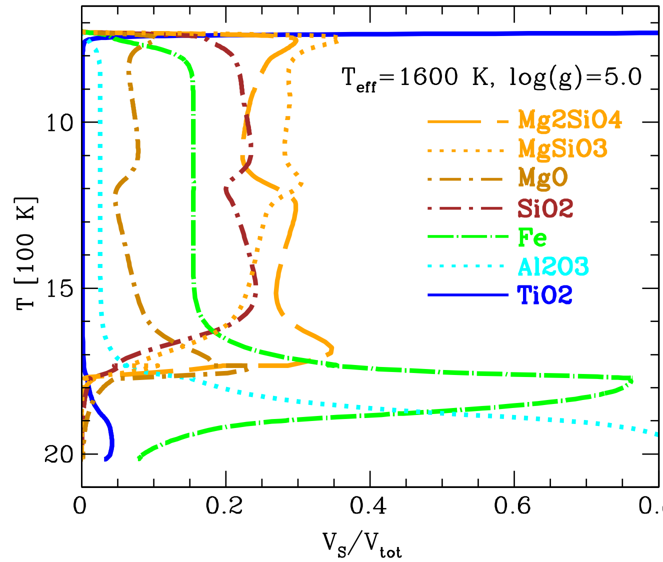

Fig. 1. Dust cloud material composition in volume fractions V_s/V_{tot} in a giant gas planet atmosphere (Helling et al., 2008a) as a result of DRIFT-PHOENIX model atmosphere simulations that include our kinetic dust formation model (Witte et al., 2009; T_{eff}—effective temperature of object, log(g)—surface gravity of object). The composition changes with atmospheric height indicated by the local temperature.

hence, particle growth speeds up while the grains fall inward along a positive density gradient. During this descent, the crystal structure of the cloud particles is evolving (Helling and Rietmeijer, 2009). Fig. 1 indicates that such clouds are made of small (10^{-2} μm) silicate particles at the top which develop into large (10 ... 100 μm) iron/TiO_2 particles. For details on grain sizes see e.g. Figure 8 in Helling et al. (2008c).

Would dust–dust collisions change this picture? The most interesting changes in the grain size distribution by a dust–dust collision likely result from the fragmentation of both collisional partners and the stick-and-hit events of projectile and target. Fragmentation would increase the number of grains and therewith the number of seeds for further grow. As surface growth is rather efficient, the grain fragments can grow rather quickly to their previous sizes until the gas-phase is undersaturated. Hence, dust–dust collisions tend to increase the number of grains but the grain size might not change as long as surface growth is efficient. Stick-and-hit events would produce a higher number of large grains, but the collision energetic need to be just right.

3. Sources of mineral dust cloud ionisation

The reasons for ionisation in clouds are rather diverse, and more complex processes than thermal ionisation need to be taken into account because of the rapidly decreasing gas temperature with height. They include energetic interstellar or interplanetary radiation, radioactive decay, differences between surface potentials of different materials (e.g., metals vs insulators), frictional ionisation, collisional ionisation of accelerated charges, or fragmentation of fractal particles (fracturing). Triboelectric charging is suggested to be of particular interest for dust cloud charging on planetary surfaces (Sickafoose et al., 2001), a scenario which is rather similar to mineral clouds in substellar atmospheres. See also Saunders (2008) for an overview of the subject. Also, gas-phase ions can attach themselves to the grain surface, and by this, contribute to the charging of cloud particles. Nicoll and Harrison (2010) have demonstrated this with observation of Earth clouds.