Cloud Formation on Exoplanets: Different Cloud Regimes for Changing Global Parameters

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Introduction

The study of exoplanet atmospheres is essential for finding life in our universe. The ability to determine the chemical makeup of an atmosphere allows us to search them for certain elements or compounds, some of which could be indicators of biological activity (bio-tracers). Given that we are only able to observe exoplanet atmospheres, bio-tracers remain the only means for finding life in our universe.

Any models used to explain transit observations of exoplanet atmospheres need to account for cloud formation. The cloud layers block stellar light passing through the atmosphere, limiting the depth to which the atmosphere is observable. Also, cloud formation depletes the gas phase of specific materials, causing them to appear less abundant than they really are.

However, it is still not understood how cloud formation is affected by changing global parameters. Understanding how these parameters affect cloud formation will allow us to predict the cloud properties of upcoming observation targets, and thus allow us to better explain these observations.

This work uses a grid of 3D GCMs (global circulation models) of Hot Jupiter exoplanets as input for cloud formation simulations. The cloud properties for each model are compared to identify trends in cloud formation across the grid.

Methodology

This work investigates how cloud formation is affected by two global parameters: planetary effective temperature and host stellar type.

The effective temperature of the planet is defined as the blackbody temperature of an object of the same radius. The grid used here (produced by Baeyens et al [1]) samples 12 effective temperatures in increments of 200K between 400K and 2600K. This work uses use 4 stellar types: F5 (T$_{star}$=6500K), G5 (T$_{star}$=5650K), K5 (T$_{star}$=4250K) and M5 (T$_{star}$=3100K).

The GCMs are spherical data-cubes with 3 positional co-ordinates: latitude, longitude and pressure (pressure is used here as a substitute for atmospheric height). Each co-ordinate contains the temperature of the gas phase and the velocity vector (v$_x$,v$_y$ and v$_z$).

This work examines 3 properties related to cloud formation: nucleation rate, mean molecular weight and ionisation rate. The nucleation rate is the rate at which nucleation seeds form, and is used to identify cloud forming regions. The mean molecular weight [amu] is the mean mass of a particle in the atmosphere, which is used to calculate the atmospheric scale height. The degree of ionisation (the ratio of the free electron pressure and the total pressure) is used to determine if the cloud layers are ionised.

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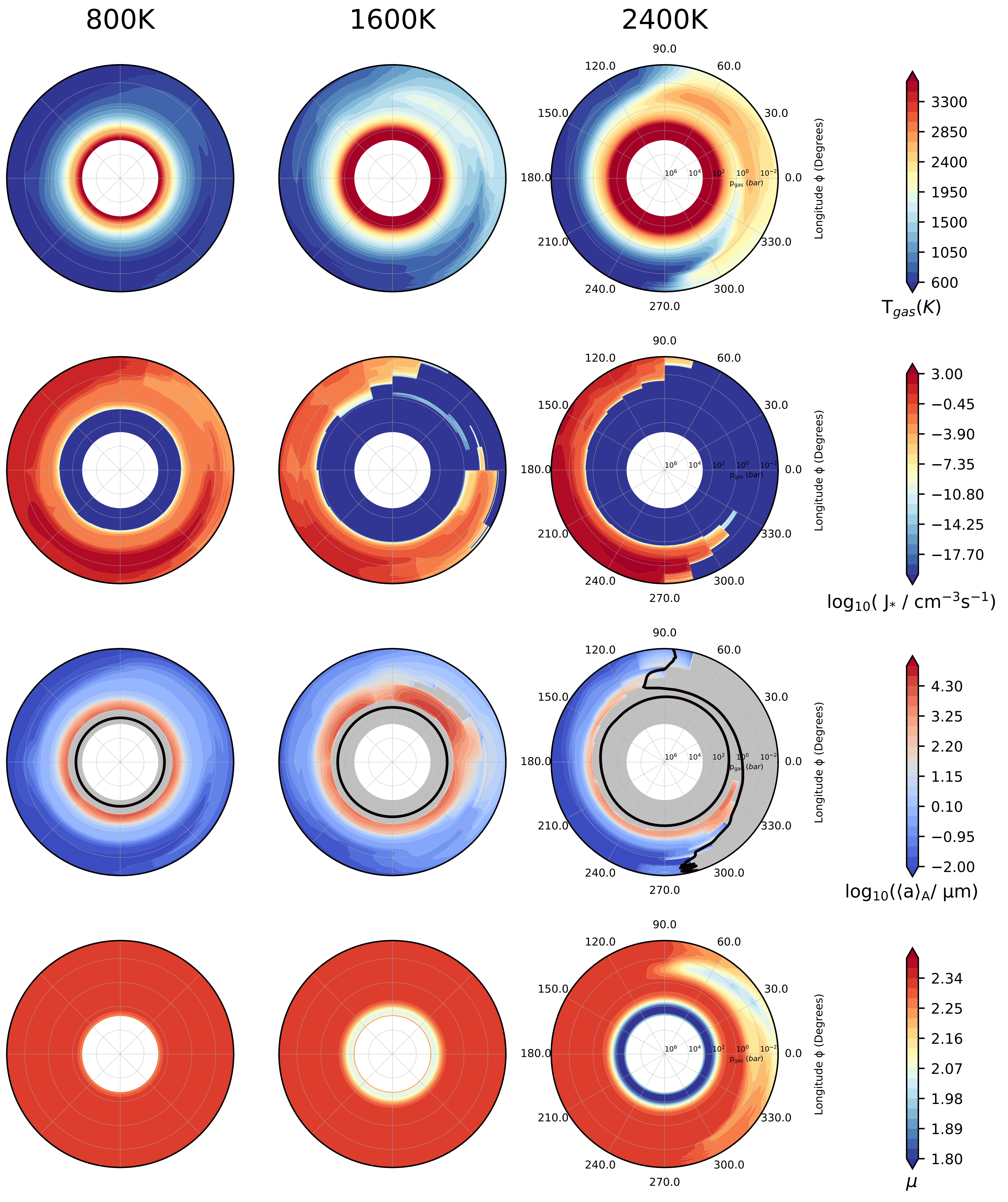
References

[1] Baeyens, R., Decin, L., Carone, L., et al. 2021, MNRAS, 505, 5603

Results

Figure 1 shows the three properties (alongside the gas temperature) for 3 effective temperatures for the G star models (similar figures were produced for the other 4 four stellar types). The following trends were identified:

- The colder Hot Jupiters (T$_{eff}$=800K, also known as Warm Saturns) experience cloud formation on the day and night sides, with less cloud formation on the day-side. Hot Jupiters with T$_{eff}$=1600K, experience limited cloud formation on the day-side in a thin layer extending from the morning terminator, caused by equatorial superrotation. Ultra-Hot Jupiters (T$_{eff}$=2400K) experience very limited day-side cloud formation near the morning terminator.
- Only the Ultra-Hot Jupiters have a mean molecular weight that varies throughout the atmosphere. There exists a 'cool spot' ($\mu \approx 2$) of lower mean molecular weight on the day-side.
- The Ultra-Hot Jupiters have an ionosphere that overlaps with the cloud layers on the day-side. However, photo-ionisation will need to be incorporated into the modelling process to explore a potentially deeper ionosphere.



2D equatorial plane slices ($\theta = 0°$) showing the main cloud formation properties. The cloud formation properties are as follows: local gas temperature [K] (first row), total nucleation rate [$\log_{10}$(J$_*$ / cm^{-3}s^{-1})] (second row), surface averaged mean particle size [$\log_{10}(\langle a \rangle_A / \mu m)$] overlayed with the ionisation rate threshold for an ionosphere (third row) and mean molecular weight (fourth row). These properties are shown for 3 planetary effective temperatures: 800K, 1600K and 2400K. All models have g=10ms^{-2} and orbit G stars.

Conclusions

A grid of global circulation models was used as input for a kinetic cloud formation model couped with a chemical network. This was done to study how cloud formation on Hot Jupiters is affected by varying the planetary effective temperature and the host star type. Cloud formation on the day-side of Hot and Ultra-Hot Jupiters is made possible by the transfer of cool air onto the day-side by equatorial super-rotation, therefore a detailed understanding of this phenomenon is key for the improvement of cloud formation models. Since the day-sides of the Ultra-Hot Jupiter models have a non-constant mean molecular weight, future GCMs of such planets should use a dynamic mean molecular weight. Also, the day-side cloud layers on Ultra-Hot Jupiters will experience thermal ionisation, and the implications of this (lightning processes etc.) will require further study.