Cloud Academy Activity
“Mapping clouds on exoplanets”

Cloud Academy: Cloud Formation and Properties in Extrasolar Planets
Les Houches, September 2018

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The activity aims to enable participants to apply a kinetic cloud formation code (`static_weather`, Woitke & Helling) and a scattering radiation transfer code (`albedo`, Marley) in order to produce hands-on results of the theoretical background provided during the lectures of Christiane Helling *Cloud models and microphysics* and Mark Marley *RT and Chemistry Models and Clouds in BDs and Imaged Exoplanets* at the Cloud Academy 2018 in Les Houches. We invite the school's participants to join us for a project that aims to map out the atmospheric cloud properties, gas-phase chemistry and optical depths of the hot Jupiter HAT-P-7b.

This activity has three parts of which only Part 1 & 2 are part of the official Cloud Academy programme. Part 3 is offered for those researchers who wish to work in more detail on the cloud mapping of HAT-P-7b. **Please refer to Sect. 2 for all technical details, and to Sect. 2.1 for preparations required from the participants before the Cloud Academy starts.**

1 Mapping out the cloud properties of the hot Jupiter HAT-P-7b

We propose to study cloud formation on HAT-P-7b, one of the ultra-hot Jupiters recently studied. Ultra-hot Jupiters have become accessible to ground-based telescopes and therefore provide perfect test cases for our modelling tools, and hence, for our present understanding. We study the cloud formation, collisional-dominated gas-phase chemistry and scattering properties of exoplanet atmospheres.
We invite the participants of the Cloud Academy 2018 to join us in a cloud mapping exercise in which we aim to show how local cloud properties, the remaining gas-phase and their extinction properties vary globally on highly irradiated extrasolar planets. Such properties include the cloud particles sizes, the material compositions of the cloud particles, their scattering properties, the chemical composition of the cloud forming gas, single scattering albedo, optical depths, to name the most obvious.

1.1 Approach

We use existing, pre-calculated 1D atmosphere trajectories from a 3D GCM solution for HAT-P-7b (Parmentier et al. 2018) as input for the kinetic cloud formation code `static_weather` according to the theoretical approach developed in Woitke & Helling (2003, 2004); Helling & Woitke (2006); Helling et al. (2008a). Figure 1 shows the distribution of these 1D trajectories across the globe, and some preliminary results of where to expect cloud formation to occur. The output from `static_weather` can directly be converted into maps in order to provide a global visualisation, or be post-processed in a radiative transfer code. It will also be used by `albedo` to solve the radiative transfer problem through the 1D cloud forming atmosphere. The initial element abundances are solar (Asplund et al. 2009).

1.2 Project organisation

Part 1 *Cloud formations modelling activity* **(24 Sep, 17:45h):** Each participant chooses one 1D trajectories from Tables 1 or 2. This trajectory will be read into `static_weather`. We will run `static_weather`. The output of each trajectory can be visualised by a python script (provided). We will discuss the output in terms of, for example, nucleation rate, mean particles sizes and material composition. We will collect the results from each participant in GoogleDrive in order to produce global cloud property maps for HAT-P-7b.

Part 2 *Radiative transfer activity* **(25 Sep, 10:15h):** To understand the impact clouds have on the scattered light from an extrasolar planet the second phase of the activity will be to compute albedo

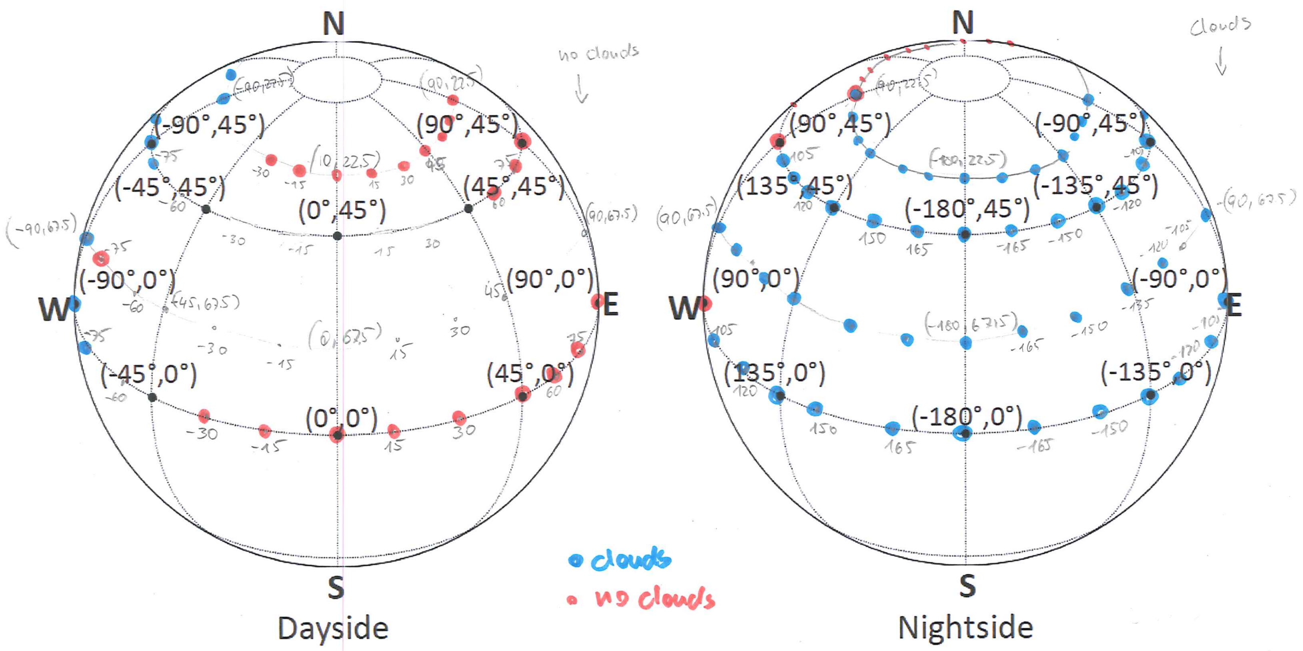

Figure 1: Location of 1D trajectories on HAT-P-7b globe. Preliminary results on where clouds can form in HAT-P-7b.

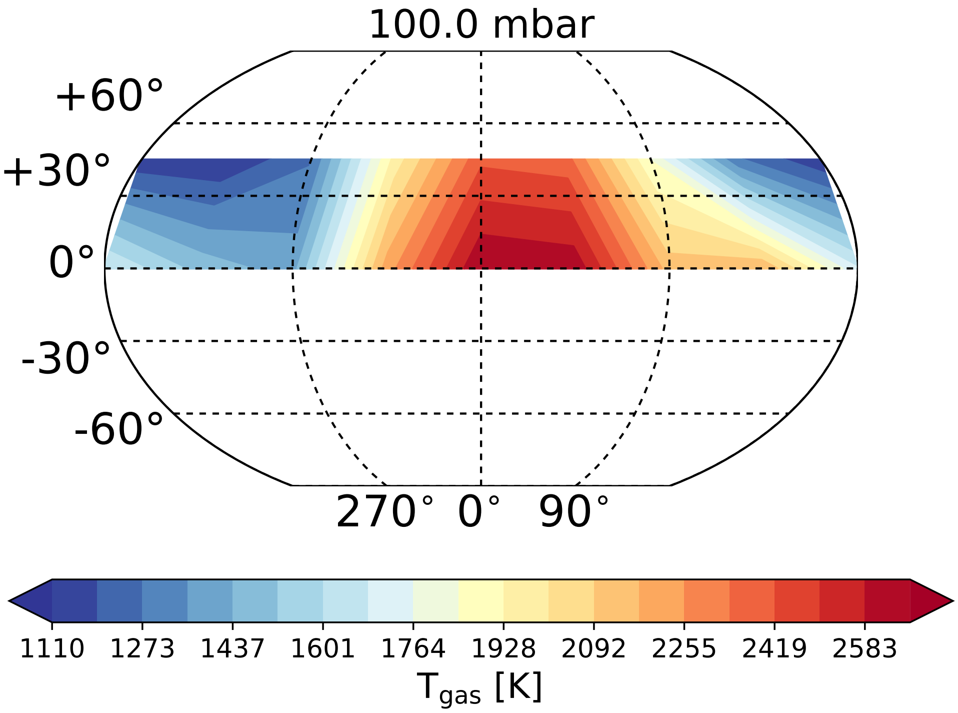

Figure 2: Incomplete map of local gas temperature at 0.1 bar level in the atmosphere of HAT-P-7b.

spectra for planets that are uniformly covered by a cloud deck with the properties of each trajectory. This will help to illustrate the importance of clouds to the radiative transfer within the atmosphere and the detectability of the planet. For this exercise we are making several simplifications, including assuming that the model planet is uniformly covered by clouds and that we can see what is here the night side of the planet in scattered light. Rather than being a high fidelity model of HAT-P-7b, we can think of the albedo calculation as crudely representing a uniform planet that is being moved progressively farther away from its star. As an optional extension to the exercise students could use intermediate output from the albedo code to develop scattered-light maps of the dayside of the planet. The output from `static_weather` will be read into `albedo`.

Out-of-curriculum Challenge: How would the planet look like if each trajectory is treated individually as a scattering patch on the planet's surface?

Preparation from participant needed: Assure you have the `gfortran` compiler and `python` on your laptop (see Sect. 2.1). Chose one of the blue-colored 1D atmospheric trajectory listed in Table 1 or in Table 2. You may test a red one but this will be gas-phase only as no clouds are expected to form there.

Important data-housekeeping:
a) Include your choice of (ϕ, θ) *with your name* (!) into the google spreadsheet `Cloud_profiles_HAT-P-7b` on GoogleDrive (address below).
b) Resulting data need to be uploaded onto GoogleDrive `https://drive.google.com/drive/folders/1Thh2i3HSYqSbYfX2UhJTbitxAOClFKW9`. Your output files' names need to contain the longitude/latitude (ϕ, θ) that you are looking at (and which you have marked with your name under a) in an *obvious* way. Please rename the files like this: `out3_chem1_Phi180Theta0.dat`

Part 3 *Creative mapping and paper drafting* **(after lunch on 26 and 27 Sep 2018):** We suggest to continue Parts 1 & 2 by 2 follow-up after-lunch meetings for those participants interested. The first of these after-lunch meetings (Wednesday) aims to produce meaningful global visualisations of the large amount of cloud, chemistry and radiative transfer data that has been produced during Part 1 & 2. One possibility will be to produce global maps (python script available, provided by Graham Lee). One, intentionally rather incomplete, example is given in Fig. 2. We will discuss what these properties could be. We will need to keep in mind that the day and the nightside of HAT-P-7b may be very different regarding their cloud and gas-phase chemistry. During the second after-lunch meetings (Thursday) we endeavor to produce a first paper draft and distribute tasks in order to finish the paper before Christmas. We invite everybody but would ask that you only come along if you are willing to contribute actively.

2 Technical details

2.1 Software requirements: `Fortran` and `python`

Both, `static_weather` and `albedo`, are FORTRAN codes. Everybody who wishes to participate in our activities therefore needs to have a fortran compiler installed on his/her laptop. We recommend `gfortran` (free) or `ifort`. `ifort` is free for students[1]. Some parts of the pipeline and the visualisation scripts are written in `python`, hence, make sure your laptop has `python2.7`.

2.1.1 Installing fortran

Mac OS
Unless you want to install `ifort`, you can download and install the free GNU Fortran `gfortran` either via fink `http://www.finkproject.org/`, macport, or simply download the binary at `http://hpc.sourceforge.net/` for your particular OS version. Move the tar file from the download directory to the top directory /. Type

```
> sudo tar -xvf gfortran***.tar
```

[1] `https://software.intel.com/en-us/qualify-for-free-software/student`

Enter your administrator login. gfortran will be install in the /usr/local/ directory, which is a default search path. Open a new terminal and type `gfortran--version` to check whether the installation was correct. If you already have gfortran, please check that you have the most recent version installed as the gfortran team improves and corrects the compiler every few months. You should have at least gfortran version 4.8 or a more recent one.
Mac OS includes an optimized version of the BLAS and LAPACK routines in a form of a library called Veclib. The way to use those routines are described in the compilation section. An alternative free version of GNU Fortran 95 is g95. We do not currently support compilation with this compiler http://www.g95.org. Notice that g95 is somehow not supported.
You need to download and install **Xcode** and its command-line option to enable the use of make. **Xcode** is a free Apple application to be found on the App store.

Windows
Choose to have the gfortran package when you install MinGW or Cygwin.

2.2 How to use static_weather

The source files are here:
https://leap2010.wp.st-andrews.ac.uk/the-project/related-projects/

main file in src15: static_weather15.f

heart piece of static_weather15.f: FF.f
(links all process subroutines as input for LIMEX ODE solver) staticweather uses the ODE solver LIMEX provided by the Konrad-Zuse-Center in Berlin.

global variables and dimensions are set in drift_data.f:
- NELEM=36: number of elements used in the equilibrium chemistry routine GGCHEM.f
- NMOLE=190: number of molecules considered in the equilibrium chemistry routine GGCHEM.f
- NMOM=4: number of dust moments, $L_{\rm j}$, used and solve by FF.f
- NEPS=9: number of elements used for cloud formation
- NSPECIES=38: number of gas-phase species used to built the solids
- NDUST=12 : number of growth species built (e.g. Mg2SiO4[s])
- NNUC=3 : number of nucleation species used (here: TiO2, SiO, C)
- NREAC=126 : number of surface reactions that built growth species

Input data files:
DustChem.dat – sets chemical data for dust complex
(NEPS, NSPECIES,NDUST, NNUC, NREAC)
is read in INIT_DUSTCHE.f
present version: DustChem15_3Nuc.dat

dispol_large.dat – material data for equilibrium gas-phase chemistry

2Drift.data – initialises prescribed (T, pgas, rhogas, vconv, z)
– this corresponds to welche=5 in static_weather15.f

Compile and run:
chose compiler and adjust makefile in /src15
(usually we used IFORT which is the intel fortran compiler, but everything is available for fortran, too)
type 'make realclean' first
compile with makefile (make) in directory /src15
the executable file static_weather15 is created in the directory /StaticWeather15
(one directory above src15)

start program with `./static_weather15>out &`
this starts the program and redirects the screen output into the file 'out'
both processes run in the background due to the use of '&'
use 'more out' to see content of the file 'out'

Output files:
Remember the Important housekeeping: Your output files' names need to contain the longitude/latitude (ϕ, θ) that you are looking at in an *obvious* way. Please rename the files like this: `out3_chem1_Phi180Theta0.dat`.

The original name are:
3 files containing gas-phase number densities in [cm^{-3}]:
`out3_chem1.dat`
`out3_chem2.dat`
`out3_chem3.dat`

5 files containing results of cloud properties:
`out3_dist.dat` – grain size distribution function
`out3_dust.dat` – many details on the cloud
`out3_imp.dat` – compares time scales
`out3_nuclea.dat` – nucleation relates results
`out3_thermo.dat` – gas-phase species participating in cloud formation directly [cm^{-3}]:

2 files containing results of cloud extinction properties:
`out3_albedo.dat` – single scattering albedo
`out3_extinction.dat` – extinction coefficient

1 file for re-start purposes:
`restart.dat` needs to be removed if you want the program to start from the beginning

1 file to link with the radiative transfer program PHOENIX if wanted: `2Phoenix.data` [not needed if `static_weather` is run as separate programme]

2.3 How to use `albedo`

Details about how to use the code as well as the source code are here:
`https://github.com/natashabatalha/CloudAcademyAlbedo`

For the implementation here, the albedo code will read in the $P(T)$, composition, and cloud properties profiles computed by the other codes. It will then compute a full phase geometric albedo spectrum and albedo spectra at 10° spacings. The goal is to understand how clouds and changing atmospheric composition impact the scattered light component of the planets flux. For this exercise we are ignoring the thermal component of the flux which, of course, will be substantial.

References: The albedo code we will use was originally developed by Chris McKay (McKay et al., 1989) to model the geometric albedo spectrum of Titan, accounting for its clouds and hazes. It was subsequently modified (Marley et al., 1999a,b) to also handle Solar System gas giant and extrasolar gas giant planets. Later Cahoy et al. (2010) modified the code to compute albedo spectra at phase angles other than full phase. Natasha Batalha has updated the opacity set used by the code and streamlined its use by interfacing with a Jupyter notebook. She has also written a python translator which takes the output files from `static_weather` and translates them to the input required by the albedo code.

3 Note of caution / Health & Safety

Note that all code implementations that we are sharing at the Les Houches 2018 school are still in beta test, while you are welcome to use the codes, please do so very carefully. Given the large number of recent changes made in our current code update we cannot guarantee that numerical answers are correct in every application.

References

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARAA, 47, 481

Cahoy, K. L., Marley, M. S., & Fortney, J. J. 2010, ApJ, 724, 189

Helling, Ch. & Woitke, P. 2006, A&A, 455, 325

Helling, Ch., Woitke, P., & Thi, W.-F. 2008a, A&A, 485, 547

Marley, M. S., & McKay, C. P. 1999, Icarus, 138, 268

Marley, M. S., Gelino, C., Stephens, D., Lunine, J. I., & Freedman, R. 1999, ApJ, 513, 879

McKay, C. P., Pollack, J. B., & Courtin, R. 1989, Icarus, 80, 23

Parmentier, V., Line, M. R., Bean, J. L., et al. 2018, ArXiv e-prints [[arXiv]1805.00096]

Woitke, P. & Helling, Ch. 2003, A&A, 399, 297

Woitke, P. & Helling, Ch. 2004, A&A, 414, 335

ChH & MM, St Andrews & Ames, September 19, 2018

Table 1: 1D trajectories at the equator and $\theta = 45^o$ latitude. $\theta = 22.5^o$ and $\theta = 67.5^o$ are listed in Table 2. no clouds, clouds, [sl] – slow, [vsl] – very slow

$(\phi,\ \theta)$	Name	$(\phi,\ \theta)$	Name
$(-180^o, 0^o)$		$(-180^o, 45^o)$	
$(-165^o, 0^o)$		$(-165^o, 45^o)$	
$(-150^o, 0^o)$		$(-150^o, 45^o)$	
$(-135^o, 0^o)$		$(-135^o, 45^o)$	
$(-120^o, 0^o)$		$(-120^o, 45^o)$	
$(-105^o, 0^o)$		$(-105^o, 45^o)$	
$(-90^o, 0^o)$		$(-90^o, 45^o)$	
$(-75^o, 0^o)$		$(-75^o, 45^o)$	
$(-60^o, 0^o)$		$(-60^o, 45^o)$	
$(-45^o, 0^o)$		$(-45^o, 45^o)$[sl]	
$(-30^o, 0^o)$		$(-30^o, 45^o)$	
$(-15^o, 0^o)$		$(-15^o, 45^o)$	
$(+0^o, 0^o)$		$(+0^o, 45^o)$[vsl]	
$(+15^o, 0^o)$		$(+15^o, 45^o)$[vsl]	
$(+30^o, 0^o)$		$(+30^o, 45^o)$[sl]	
$(+45^o, 0^o)$		$(+45^o, 45^o)$	
$(+60^o, 0^o)$		$(+60^o, 45^o)$	
$(+75^o, 0^o)$		$(+75^o, 45^o)$	
$(+90^o, 0^o)$		$(+90^o, 45^o)$	
$(+105^o, 0^o)$		$(+105^o, 45^o)$	
$(+120^o, 0^o)$		$(+120^o, 45^o)$	
$(+135^o, 0^o)$		$(+135^o, 45^o)$	
$(+150^o, 0^o)$		$(+150^o, 45^o)$	
$(+165^o, 0^o)$		$(+165^o, 45^o)$	

Table 2: 1D trajectories at t $\theta = 22.5^o$ and $\theta = 22.5^o$ latitude.
no clouds, clouds, [sl] – slow, [vsl] – very slow

$(\phi,\, \theta)$	Name	$(\phi,\, \theta)$	Name
$(-180^o, 22.5^o)$		$(-180^o, 67.5^o)$	
$(-165^o, 22.5^o)$		$(-165^o, 67.5^o)$	
$(-150^o, 22.5^o)$		$(-150^o, 67.5^o)$	
$(-135^o, 22.5^o)$		$(-135^o, 67.5^o)$	
$(-120^o, 22.5^o)$		$(-120^o, 67.5^o)$	
$(-105^o, 22.5^o)$		$(-105^o, 67.5^o)$	
$(-90^o, 22.5^o)$		$(-90^o, 67.5^o)$	
$(-75^o, 22.5^o)$		$(-75^o, 67.5^o)$	
$(-60^o, 22.5^o)$		$(-60^o, 67.5^o)$	
$(-45^o, 22.5^o)$[sl]		$(-45^o, 67.5^o)$	
$(-30^o, 22.5^o)$		$(-30^o, 67.5^o)$	
$(-15^o, 22.5^o)$		$(-15^o, 67.5^o)$	
$(+0^o, 22.5^o)$		$(+0^o, 67.5^o)$	
$(+15^o, 22.5^o)$		$(+15^o, 67.5^o)$[sl]	
$(+30^o, 22.5^o)$		$(+30^o, 67.5^o)$[sl]	
$(+45^o, 22.5^o)$		$(+45^o, 67.5^o)$[vsl]	
$(+60^o, 22.5^o)$		$(+60^o, 67.5^o)$[vsl]	
$(+75^o, 22.5^o)$		$(+75^o, 67.5^o)$	
$(+90^o, 22.5^o)$		$(+90^o, 67.5^o)$	
$(+105^o, 22.5^o)$		$(+105^o, 67.5^o)$	
$(+120^o, 22.5^o)$		$(+120^o, 67.5^o)$	
$(+135^o, 22.5^o)$		$(+135^o, 67.5^o)$	
$(+150^o, 22.5^o)$		$(+150^o, 67.5^o)$	
$(+165^o, 22.5^o)$		$(+165^o, 67.5^o)$	