Radiative transfer for extra-solar planets: bringing it down to Earth

James Manners 23/5/18
• GCM adaptations for a general planet
• Flexible radiative transfer configuration
• Techniques to generate correlated-k coefficients
• Simulated astronomical observations for exoplanets
• Treatment of spherical geometry for direct solar radiation
• Future extensions to the scheme
Simulating a general planet
Planet parameters

- Planet parameters: Parameters specific to the planet being modelled.

- L_\text{planet}
  - Choose planet or user defined constants
  - User defined
  - Earth

- L_\text{eql}
  - Formulation of the equation of time in the astronomy
  - Not included
  - Smart (1944)

- L_\text{planet_orbit}
  - Set orbital parameters

- L_\text{planet_epoch}
  - Epoch in Julian Days for orbital parameters
  - 2451545.0

- L_\text{planet_e}
  - Eccentricity of the orbit
  - 1.671123e-2

- L_\text{planet_di}
  - Increment to eccentricity by per day number from epoch
  - -1.202464e-9

- L_\text{planet_lpm}
  - Longitude of perihelion in radians
  - 1.796601474

- L_\text{planet_dij}
  - Increment to longitude of perihelion per day number from epoch
  - 1.544747e-7

- L_\text{planet_obl}
  - Oblivity of the orbit in radians
  - 0.40992343

- L_\text{planet_obl}
  - Increment to obliquity of the orbit per day number from epoch
  - -6.178222e-9

- L_\text{planet_a}
  - Semi-major axis in AU
  - 1.00000261

- L_\text{planet_d}
  - Increment to semi-major axis by per day number from epoch
  - 1.538672e-10

- L_\text{planet_m}
  - Mean anomaly at epoch in radians
  - 6.2480214

- L_\text{planet_dm}
  - Increment to mean anomaly per day number from epoch
  - 1.7201969492444045e-2

- L_\text{planet_ha}
  - Planet hour angle at epoch in radians
  - 0.0

- L_\text{planet_dha}
  - Increment to planet hour angle per day number from epoch
  - 6.283185307179586

- L_\text{planet_obs_lat}
  - Orbital latitude of a distant observer for diagnostics
  - 0.0

- L_\text{planet_obs_lon}
  - Orbital longitude of a distant observer for diagnostics
  - 0.0

- L_\text{set_planet_rotation}
  - Set planet rotation rate in radians/second
  - true
Planet parameters

Planet constants:
- `planet Constants`: Parameters specific to the planet being modelled.
- `increment to planet hour angle per day number from epoch`: 0.0
- `planet obs lat`: Orbital latitude of a distant observer for diagnostics 0.0
- `planet obs lon`: Orbital longitude of a distant observer for diagnostics 0.0
- `I sat planet rotation`: Set planet rotation rate (radians/second) `true`
- `omega`: Angular speed of planet rotation (radians/second) 7.292115373e-5
- `I planet grey surface`: Heat surface as grey `true`
- `planet albedo`: Effective surface albedo for broadband SW radiation 0.0
- `planet_emissivity`: Effective surface emissivity for broadband LW radiation 1.0
- `I planet intrinsic flux`: Use an intrinsic thermal flux at the lower boundary `false`
- `I fix solang`: Fix the sun at a particular zenith and azimuth angle `false`
- `I planet aerosol`: Use a constant aerosol mixing ratio for idealised tests `false`
- `planet radius`: Planet radius in metres 6.371229.0
- `g`: Mean acceleration due to gravity at the planet surface 9.80665
- `I planet g`: Use variation of g with height `false`
- `s c`: Solar irradiance at 1 astronomical unit (W/m²) 1361.0
- `r`: Gas constant for dry air of planet 287.05
- `cp`: Specific heat of dry planet air at constant pressure 1005.0
- `p ref`: Reference surface pressure 100000.0
- `s c h t`: Mean scale height for pressure 6.8e+03
- `lapse`: Near surface environmental lapse rate 0.0065
Planets

- nsteps_consv_print
  Frequency of printing of AAM and KE

- tforce_number
  Choice of forcing profile

- trelax_number
  Choice of relaxation timescale

- No forcing (0)
- Held-Suarez (1)
- Tidally-Locked Earth (2)
- Earth-Like (3)
- Shallow-Hot Jupiter (4)
- Jupiter (5)
- HD 209458b (Heng) (6)
- HD 209458b (Heng Smoothed) (7)
- HD 209458b (Iro) (8)
- Y Dwarf (9)

- From a file (99)

- Isothermal (t_surface) (100)
Exotic gas species
Flexible configuration: spectral files

Spectral bands: high / low resolution
Gas $k$-terms
Aerosol / cloud optical properties
Solar spectrum (including time variation) etc.

Many configurations can be run

Hot Jupiters
Mars

HadCM3
HadGEM1
HadGEM2
GA3
GA7
300 band LW / 260 band SW
Stage 1: generate line-by-line absorption coefficients

HITRAN line data

HITRAN cross-sections

Other sources (e.g. ExoMol for Exo-planet spectral files)

line-by-line absorption coefficients (netCDF)
Stage 2: 
generate k-terms separately for each gas

- Pressures and temperatures
- Line-by-line absorption coefficients (netCDF)
- Max column amount of absorber

$k$-terms in each spectral band
Optimal selection of $k$-term weights

Effective absorption coefficient for column down to $\tau=1$

Use weights that give equal increments in log $k_{\tau=1}$

( Based on similar ideas from Hogan 2010 )
Calculate k-terms for P/T look-up table

Re-order absorption coefficients for each P/T

Within each g-interval fit the k-terms to match transmission over a range of paths
Simulated observations
Figure 5. Top: emission phase curves in several spectral bands. The observed 4.5 μm Spitzer/IRAC channel curve (Zellem et al. 2014) is included (black) with 1σ uncertainty. Middle and Bottom: secondary eclipse emission and transmission spectra with PandExo simulated observations for the NIRSpec G395H (circles) and MIRI LRS (squares) modes, binned to a resolution of $R \sim 60$ and $R \sim 30$, respectively.
Fig. 1: Spherical shell geometry used for the calculation of transmission spectra. Left-hand plot (a) shows the view perpendicular to the transit. Right-hand plot (b) shows the view from the night side in line with the transit. Parameters are shown for a model column located in the position of the dotted line in each plot, giving a transmission spectrum at the point where the arrow leaves the top of the atmosphere (indicated by the dot in the right-hand plot). $\zeta$ denotes the stellar zenith angle, $b$ the impact parameter, and $ds$ the path length element for the layer bounded by radii $r_1$ and $r_2$. Note the path of the beam will pass through each layer twice, except for the layer in which the impact parameter is found.
Spherical geometry for SW heating

Figure 1.2: Spherical shell geometry. Layer centres are denoted by dotted lines and layer edges by solid lines. Parameters are shown for the slant path to a particular layer for a model column located in the position of the dashed line. $\zeta$ denotes the local solar zenith angle (which may be greater than 90 degrees), $b$ the impact parameter, and $ds$ the path length element for the layer bounded by radii $r_1$ and $r_2$. 
\[ S_{up} = \frac{1}{2} [(1 + \cos \zeta \sec \zeta') S^{'+} + (1 - \cos \zeta \sec \zeta') S^{' -}] \]

\[ S_{down} = \frac{1}{2} [(1 + \cos \zeta \sec \zeta') S^{'-} + (1 - \cos \zeta \sec \zeta') S^{'+}] \]
Energy balance

\[ h \sim 1\% \text{ of } R \]

Area increase \( \sim 2\% \)

Tropopause lit \(~450\text{ km into nightside}\)

(an extra 30 minutes daylight)

Surface area for emission should also increase (to be done)
20-year climate run

Outgoing SW at TOA
June-July-August
Outgoing SW at TOA
Dec-Jan-Feb
Zonal mean Temperature
June-July-August
Zonal mean Temperature
Dec-Jan-Feb

a) Zonal mean Temperature for djf
U-AW857: SphGeom

b) Zonal mean Temperature for djf

c) Zonal mean Temperature for djf

d) Zonal mean Temperature for djf
Future enhancements and uses of this scheme:

- spherical treatment for diffuse fluxes needed for energy balance
- different cloud overlap for slant path to each layer
- orography can cast shadows into the atmosphere
- photolysis in upper atmosphere
Photolysis and heating in the upper atmosphere

**Fig. 5** Solar irradiance atmospheric penetration depth, unitary optical depth, for photons from hard X-rays to 300 nm (from Chamberlain 1978)
Questions
Figure 5: Scaling behaviour of three k-terms for CO2 in band 4 of the HadGEM spectral file. The x-axis is the pressure/temperature combination which is logarithmically spaced in pressure starting from 1 Pa on the left to 1000 hPa on the right. Three temperatures are used for each pressure: 190, 240, 290K.