Radiation hydrodynamics simulations of brown dwarf atmospheres

Bernd Freytag
& France Allard & Derek Homeier

CRAL ENS-Lyon

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Dynamical stellar atmospheres

Sun  Betelgeuse  CO5BOLD code:

- (Magneto-)Hydrodynamics: 2D/3D, compressible, transsonic flow, shocks, ionization, gravity, advection of additional densities
- Radiation transport: optically thick and thin, non-local, frequency-dependence via opacity binning
- 2 geometrical setups: local ’box-in-a-star’ & global ’star-in-a-box’ models
General properties of solar-like granulation

Surface intensity snapshot and entropy slice of solar model; 5782 K, log $g=4.44$, $5.6^2 \times 2.8$ Mm$^3$, $800^2 \times 400$ grid points

- Bright granules and dark intergranular lanes
- Overshoot
- Downdrafts: largest convective velocities, shear, turbulence, vorticity
- Waves travel into the photosphere and transform into shocks
Transition from the Sun to brown dwarfs

Entropy and rms vertical velocity for selected (sub)stellar models

- Energy flux ↓, velocities, Mach numbers ↓
- Radiative time scales ↑
- Stabilizing buoyancy forces ↑, horizontal vs. vertical velocities ↑
- Overshoot velocity scale height in BDs ↓
- Acoustic waves ↓↓, gravity waves ↓
Consequences for RHD models

- **Solar-like stars**
  - Two state variables, e.g. $\rho$ and $e_i$
  - EOS and $\kappa$ from lookup tables

- **Dusty objects**
  - Dust properties depend on history
  - Additional density arrays $\rho_{\text{dust},i}$
  - Nucleation, growth, grains sizes, composition, opacities
  - Simple dust models:
    - 4-moment model for carbon-rich dust in AGB stars (Freytag & Höfner 2008)
    - 2-bin model for forsterite in brown dwarfs (Freytag et al. 2010)
    - Multi-size-bin model for forsterite in brown dwarfs
  - Mach numbers from $\sim 1$ to small values
  - Local and global scales
Dust cloud layers above the convection zone

Entropy fluctuations and dust concentration of 2D model with 1800 K/log $g=5$.

- Dust clouds (affect spectra and cause variability)
- Mixing by waves, overshoot, and cloud convection (Freytag et al. 2010)
- Parametrized mixing put into Phoenix code (Allard et al. 2010, 2012)
Small-scale cloud patterns in local 3D models

- Surface intensity
- $T$ sequence:
  - 2600 K
  - 2200 K
  - 2000 K
  - 1800 K
  - at log $g$=5
- Increasing thickness of the dark dust clouds above the granules
Global 3D toy models

- **BD/planet toy models:**
- 2200 K/log $g=3.5$
- Radius scaled 1:20
- $375^3$ points, no dust:
  - Surface intensity
- $415^3$ points, dust (2-bin forsterite)
  - Surface intensity
  - Entropy slice
  - Dust concentration slice
Conclusions

- Local mixing and transport of dust
  - Overshoot, gravity waves, dust-cloud convection
  - Fast small-scale intensity fluctuations
- Feedback mechanisms
  - Dust clouds $\rightarrow$ convection $\rightarrow$ mixing $\rightarrow$ dust clouds
  - Dust clouds $\rightarrow$ no nucleation $\rightarrow$ no new grains
- Future work
  - Larger local and "global" models
  - Improved dust microphysics
  - Rotation
  - Magnetic activity (M dwarfs)
  - Postprocessing: spectrum synthesis with Phoenix