Stellar/Planetary Atmospheres

Part 15: extrasolar planets

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Topics

- Extrasolar giant planets

Model assumptions

- Standard classical "stellar atmosphere" problem (at least, that is the usual assumption):
    1. plane parallel
    2. hydrostatic
    3. LTE
    4. radiative plus convective energy equilibrium

The Problems

- convection into optically thin layers (no real theory).
- complex equation of state (molecules, dust).
- highly non-grey opacities.
- poorly known opacities (molecules, dust).
- 100's of millions of lines need to be handled (TiO, water vapor).
- strongly depth dependent line broadening (van der Waals) but mostly unknown interaction constants.

The Problems

- non-ideal EOS effects occur near the bottom of BD atmospheres.
- illumination.
- radiative transfer.
- non-LTE.

Model Construction

- **Basic Physical Model**
  - spherical shell
  - static (stars) or expanding (novae, winds, SNe)
  - hydrostatic or hydrodynamical equilibrium
  - central source provides energy

Model Construction

- **Constraint equations:**
  - energy conservation
    → temperature structure
  - momentum conservation
    → pressure & velocity structure

Model Construction

- “Auxiliary” equations:
  - equation of state → $(T, P_{\rm gas}, \rho)$ relation
    - high temperatures:
      (hot stars, Supernovae, novae)
      → need to include many ions
    - low temperatures:
      (Brown dwarfs, Jupiter-like planets, cool novae)
      → need to include 100’s of molecules & dust species

Model Construction

- atomic line blanketing: $\approx 5 - 30 \times 10^6$ lines dynamically selected from a list of 42×10^6 lines
- molecular line blanketing: $\approx 15 - 300 \times 10^6$ lines dynamically selected from a list of 700×10^6 lines
- direct opacity sampling of line blanketing
- depth dependent Voigt or Gauss profiles
  → no ODF or opacity sampling tables (NLTE!).
- special profiles for important lines
  (work in progress)

Irradiated Planets

- results depend strongly on
    - distance from parent star
    - type of the parent star
    - amount of dust present in the atmosphere
- transit models require transmission spectrum modeling

Irradiated Planets

- usual boundary conditions for an isolated star:
- inward directed flux at the surface = zero
- $\mathrm{I}_\nu^{\downarrow}(\tau_{\mathrm{std}} = 0, \mu) = 0$, where $-1 \leq \mu = \cos(\theta) \leq 0$
- planet close to star $\rightarrow$

Irradiated Planets

- boundary condition on $\mathrm{I}_\nu^\downarrow$ is determined by the incident flux ($\mathrm{F}_\nu^{\mathrm{inc}}$) given by

$$2\pi \int_{-1}^{0} \mathrm{I}_\nu^\downarrow(\mu)\mu d\mu = \mathrm{F}_\nu^{\mathrm{inc}}(\tau_{\mathrm{std}} = 0)$$

where

$$\mathrm{F}_\nu^{\mathrm{inc}}(\tau_{\mathrm{std}} = 0) = \left(\frac{R^\star}{a}\right)^2 \mathrm{F}_\nu^\star$$

Irradiated Planets

- $\mathrm{I}_\nu^\downarrow(\mu)$ are the inward directed intensities along direction μ
- $R^\star$ is the radius of the primary
- a is the surface to surface primary-secondary separation
- $\mathrm{F}_\nu^\star$ is the monochromatic flux from the primary.
- all of the incident radiation from the primary is re-radiated outward by the secondary in the form of reflected flux $(\mathrm{F}^{\mathrm{ref}})$ and as a contribution to the thermal flux $(\mathrm{F}^{\mathrm{therm}})$

Irradiated Planets

- $\rightarrow$ integrated flux at the surface is equal to $\sigma \mathrm{T}_{\mathrm{int}}^4 + \mathrm{F}^{\mathrm{inc}}$
- $\mathrm{T}_{\mathrm{int}}$ refers to the effective temperature of the planet in the *absence* of irradiation
- $4\pi {\mathrm{R}_{\mathrm{p}}}^2 \sigma \mathrm{T}_{\mathrm{int}}^4$ equals the planet's intrinsic luminosity where R_{p} is the planet's radius
- intrinsic luminosity is an age dependent quantity which represents the energy released by the planet as it cools and contracts
- $\mathrm{T}_{\mathrm{int}}$ also relates irradiated planets to isolated planets in which case $\mathrm{T}_{\mathrm{int}}$ is identical to the more commonly used T_{eff}

Irradiated Planets

- for irradiated planets (and stars) $\mathrm{T_{eff}}$ loses some of its connection to the fundamental properties of the planet
- $\rightarrow$ difficult to separate, by observation, those photons which are thermally radiated by the planet from those which originated from the primary and are merely reflected by the planet
- describe the equilibrium temperature of the planet's day side

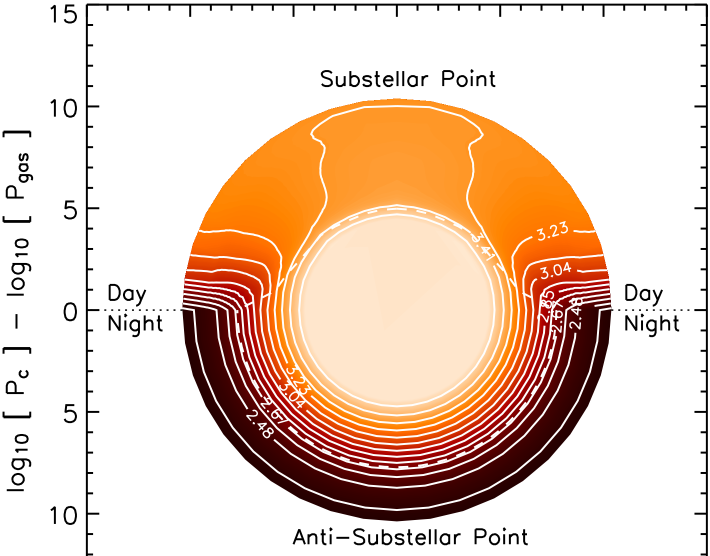
  $$\sigma \mathrm{T}_{\mathrm{eq}}^{4} = \sigma \mathrm{T}_{\mathrm{int}}^{4} + (1 - A_B)\mathrm{F}^{\mathrm{inc}},$$

  where A_B is the Bond albedo

Irradiated Planets

- $\mathrm{T_{eq}}$ represents the equilibrium state at a given age and allows for the possibility that the intrinsic luminosity has not reached zero
- $\mathrm{T_{int}}$ will only be important for young (or more massive) planets when the primary is a solar type star
- for planets orbiting M dwarfs, $\mathrm{T_{int}}$ can be a significant contribution to $\mathrm{T_{eq}}$

Irradiated Planets



Computational Problem

- memory & I/O requirements
  - line lists (far) too large for memory
    → scratch files & block algorithm
    → trade memory for I/O bandwidth

Computational Problem

- memory & I/O requirements
  - number of individual energy levels: $\approx 10,000 \rightarrow \approx 10\,\mathrm{MB}$
  - number of individual NLTE transitions: $\approx 100,000 \rightarrow \approx 150\,\mathrm{MB}$
  - auxiliary storage $\approx 100\,\mathrm{MB}$
  - $\rightarrow$ total memory requirement $\geq 250\,\mathrm{MB}$
  - number of individual energy levels and transitions will increase dramatically $\rightarrow$ memory requirements $> 0.5\,\mathrm{GB}$

Computational Problem

- (serial) CPU time
    - small for each individual point on the wavelength grid: $\approx 10 \ldots 100\,\mathrm{msec}$
    - number of wavelength points for radiative transfer: 30,000-500,000 (can be $> 10^6$)
    - $\rightarrow \approx 50,000$ sec to "sweep" once through all wavelength points

Computational Problem

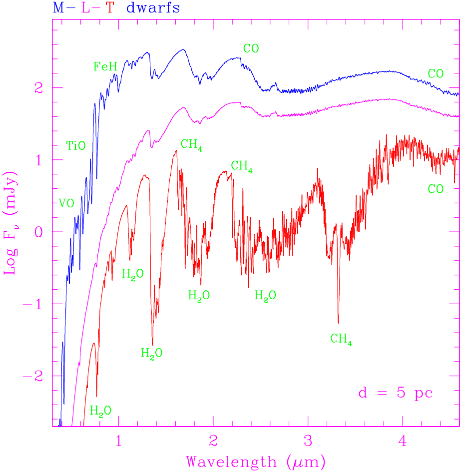
- (serial) CPU time
  - typically, ≈ 10 iterations (sweeps) are required to obtain an equilibrium model
  - $\rightarrow \approx 6$ CPU *days*
  - there are, literally, 1000's of models in a typical grid ...

Computational Problem

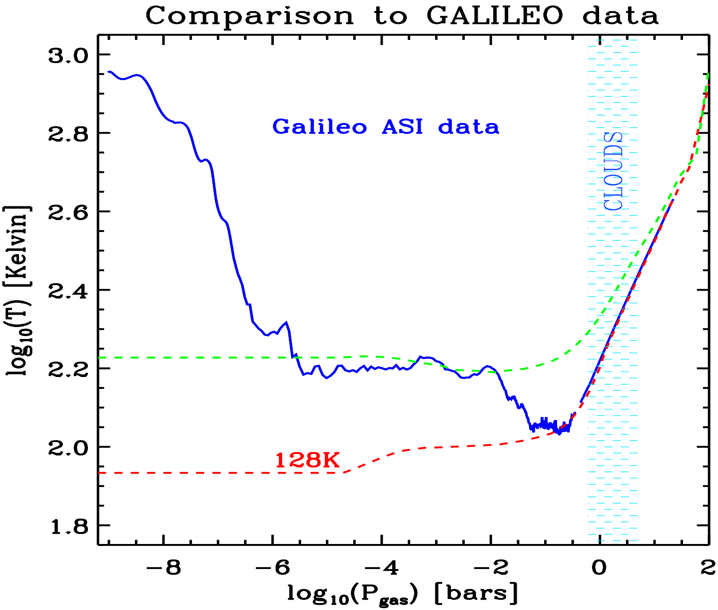
- Solution: parallel computing
    - dramatically reduces wallclock time per model
    - makes full scale model calculations “easy”
    - allows efficient use of existing large supercomputer facilities
    - scaling nearly linear, limited by I/O performance

Results: Trends

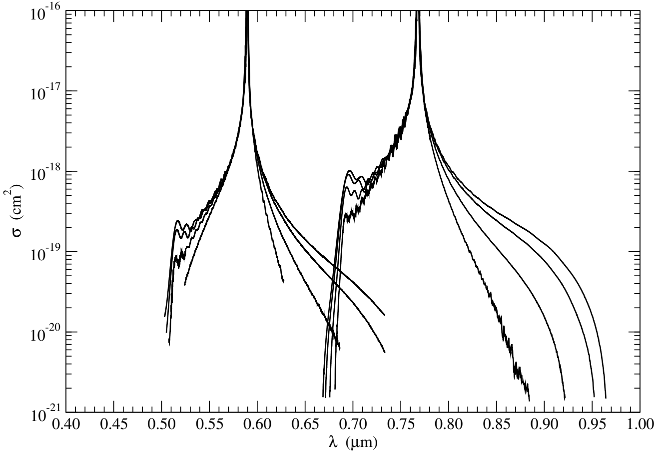
- Trends (Allard et al, 2001)
  - $T_{\text{eff}} = 2500, 1800, 1000\,\text{K}$
  - age 5Gy (Chabrier et al, 2000)



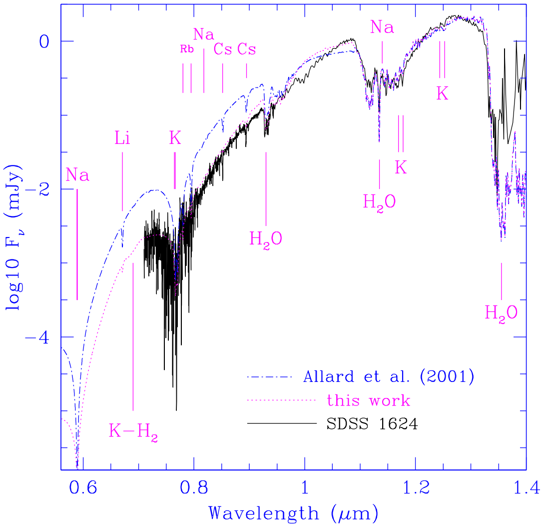
Results: Jupiter



Importance of line profiles

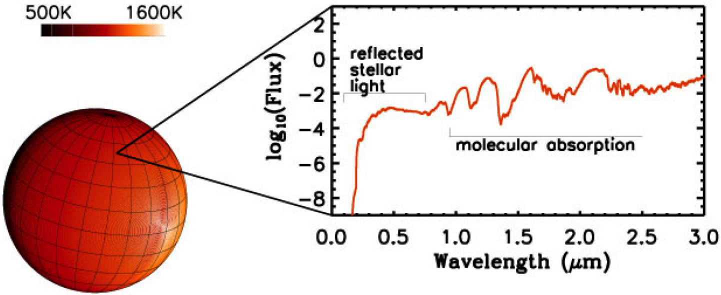


Importance of line profiles



Irradiated Planets

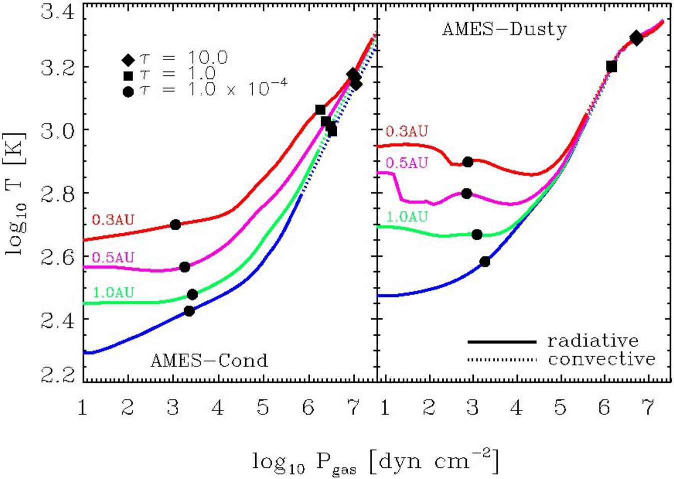
- Close-in exoplanets:
- Impinging radiation raises day-side temperatures to the L-dwarf regime.
- Reflected stellar light dominates the visible spectrum.



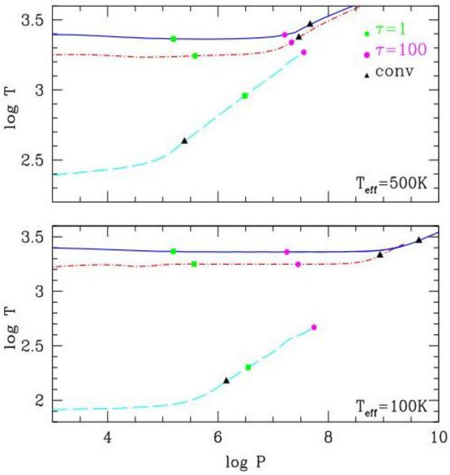
Clouds and Temperature Structure

- Clouds effectively reflect impinging radiation.
- Dust also contributes to heating of outer cloud layers.
- Cooler interior than in brown dwarfs of equal luminosity.

Clouds and Temperature Structure

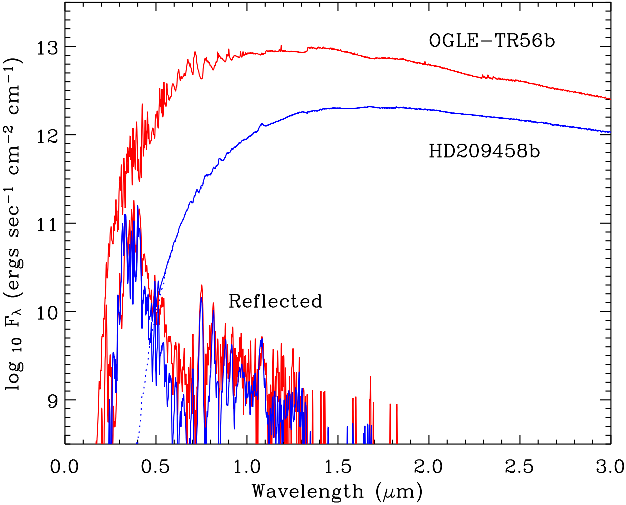


Evolution & Radii



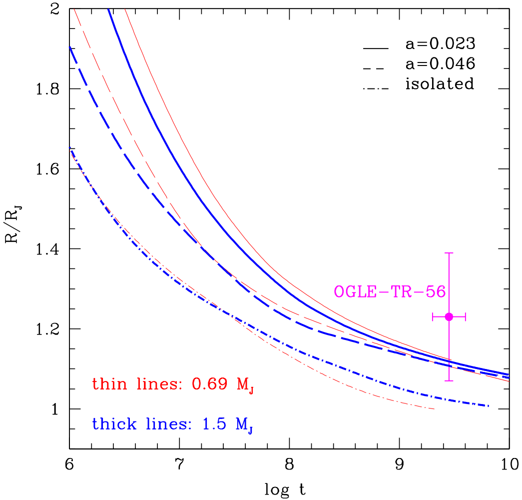
- isolated (long dash)
- 0.046AU (short dash)
- 0.023AU (solid)

Evolution & Radii



- from Chabrier et al, ApJL, 2004

Evolution & Radii



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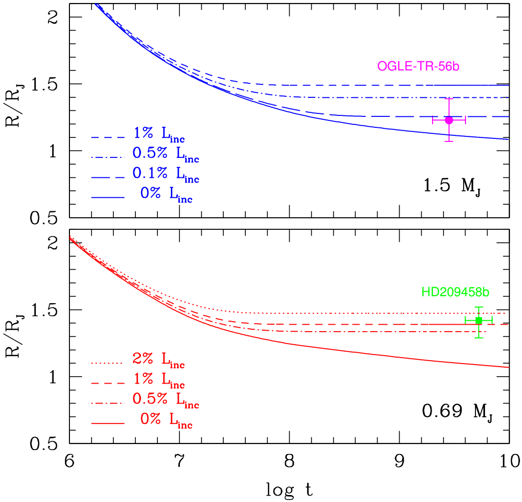
Evolution & Radii



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