Extra-solar Weather

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Outline

- Dynamical Modeling Methodologies
  - Hydrodynamic Models
  - Radiative Models

- Giant Planet Meteorology
  - Thermal inversions
  - Opacity variations
  - Viscous effects
  - Variability
  - Vertical mixing efficiency
  - Eccentric planets
Dynamical Methods

Completeness

- Equivalent Barotropic and Shallow Water (2D)

- Primitive equations (~3D)

- Navier-Stokes equation (2D)
  - Burkert et al. 2007

- Full Navier-Stokes equations (3D)

Resolution
Radiation Transfer Methods

‘Completeness’

- Relaxation methods (Newtonian heating)

- 2/3D one temperature flux-limited radiative diffusion

- 3D FLD + decoupled thermal and radiative components

- 1D (radial) wavelength-dependent radiative transfer
  - Showman et al. (2009)
3D Navier-Stokes, flux limited diffusion and decoupled thermal and radiative components

\[ \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\frac{\nabla P}{\rho} + \mathbf{g} - 2\Omega \times \mathbf{u} - \Omega \times (\Omega \times \mathbf{r}) + \nu \nabla^2 \mathbf{u} + \frac{\nu}{3} \nabla (\nabla \cdot \mathbf{u}) \]

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]

\[ \mathbf{F} = -\lambda \frac{c}{\rho \kappa_R(T, P)} \nabla E_R \]

\[ \frac{\partial E_R}{\partial t} + \nabla \cdot \mathbf{F} = \rho \kappa_P(T, P) [B(T) - cE_R] \]

\[ \left[ \frac{\partial \epsilon}{\partial t} + (\mathbf{u} \cdot \nabla) \epsilon \right] = -P \nabla \cdot \mathbf{u} - \rho \kappa_P(T, P) [B(T) - cE_R] + \rho \kappa_*(T, P) F_* e^{-\tau_*} + \Phi_\nu \]

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Absorption vs. Emission Opacities

\[ \kappa = \frac{\int \kappa_\nu B_\nu (T) \, d\nu}{\int B_\nu (T) \, d\nu} \]

\(0\) \(5000\) \(10000\) \(15000\) \(20000\) \(25000\) \(30000\) \(35000\) \(40000\)

\(0\) \(5\times 10^{-27}\) \(5\times 10^{-26}\) \(5\times 10^{-25}\) \(5\times 10^{-24}\) \(5\times 10^{-23}\) \(5\times 10^{-22}\) \(5\times 10^{-21}\) \(5\times 10^{-20}\) \(5\times 10^{-19}\) \(5\times 10^{-18}\)

\(\nu\) (cm\(^{-1}\), molecule\(^{-1}\))

B (6117) \(B\) (1400)

\(0\) \(500\) \(1000\) \(1500\) \(2000\) \(2500\) \(3000\) \(3500\) \(4000\) \(4500\) \(5000\)

\((K_*/K_P)^{1/4}\)

\(0\) \(0.5\) \(1.0\) \(1.5\) \(2.0\) \(2.5\) \(3.0\)

\(T\) (K)

P = 3000 mb \(P = 1000\) mb \(P = 300\) mb \(P = 30\) mb \(P = 3.0\) mb \(P = 0.3\) mb

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3D Flux-Limited Radiation Diffusion

\[
\frac{1}{c} \frac{\partial I_\nu}{\partial t} + \hat{k} \cdot \nabla I_\nu + \rho \kappa_\nu I_\nu = \rho \left( \frac{j_\nu}{4\pi} + \kappa_\nu^{\text{scal}} \Phi_\nu \right)
\]

- Slowly varying in space/time:

\[
R = \frac{1}{\rho \kappa} \frac{|\nabla E|}{E}
\]

\[F \propto \lambda(R) R\]

\[
F = -\lambda \frac{c}{\rho(\kappa + \sigma)} \nabla E
\]

Accurate in the limits

\[
F = -\frac{c}{3\rho\kappa} \nabla E = -\frac{4acT^3}{3\rho\kappa} \nabla T
\]

\[F = cE\]
$P_{\text{rot}} = P_{\text{orb}} = 3.52 \text{d, } T_{\text{star}} = 6117 \text{K}$
Photospheric Velocities
Observed Inversion (HD 209458b)

Richardson et al. (2003)
Knutson et al. (2007c)

- $\rho_p = 0.1, \kappa_a = 0.0 \text{ cm}^2/\text{g}$
- $\rho_p = 0.3, \kappa_a = 0.0 \ "$
- $\rho_p = 0.5, \kappa_a = 0.0 \ "$
- $\rho_p = 0.1, \kappa_a = 0.1 \ "$
- $\rho_p = 0.3, \kappa_a = 0.1 \ "$
- $\rho_p = 0.5, \kappa_a = 0.1 \ "$


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Outer Temperature Structure

\[ \kappa_j J - \kappa_B B = 0 \]

\[ \frac{\partial K}{\partial m} = \chi_H H \]

\[ T^4 = \frac{3}{4} T_{\text{eff}}^4 \kappa_j \left( \frac{1}{3 f_k} \tau_H + \frac{1}{3 f_H} \right) + \frac{\kappa_j}{\kappa_B} W T^*_4 \]

Hubeny et al. (2003)

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T-Profile Dichotomy?

Fortney et al (2007)

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HD209458b

\[ \nu = 10^{10} \]

\( T \) (K)

\( P \) (bar)

sub-solar

anti-solar
Opacity Variations

Zahnle et al 2009
Opacity Variations

\[ \tau_{\text{cool}} = \frac{E_{\text{thermal}}}{\sigma T^4} \]

\[ \tau_{\text{cross}} = \frac{\pi R_p}{2 v_d} \]

\[ \tau_{\text{cool}} \approx \tau_{\text{cross}} \]

\[ T_n = \left( \frac{4v c_d^2}{3 \pi \kappa d \sigma R_p} \right)^{1/4} \]

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Dobbs-Dixon and Lin (2007)
Opacity Variations

\[ \tau_{\text{cool}} = \frac{E_{\text{thermal}}}{\sigma T^4} \]

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\[ \tau_{\text{cool}} \approx \tau_{\text{cross}} \]

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Freedman Opc

Interstellar Opc

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Dobbs-Dixon and Lin (2007)
Viscosity

- Momentum eq.
  \[ \mathbf{u} \cdot \nabla \left( \frac{1}{2} |\mathbf{u}|^2 + w + \phi_y \right) = \]
  \[ \mathbf{u} \cdot \nabla T S + \mathbf{u} \cdot \nu \nabla^2 \mathbf{u} + \mathbf{u} \cdot \frac{\nu}{3} \nabla (\nabla \cdot \mathbf{u}) \]

- Add thermal and radiation energy equations
  \[ \mathbf{u} \cdot \nabla E_B = \rho^{-1} \left[ \Phi_v - \nabla \cdot \mathbf{F} + S_\star \right] + \]
  \[ \mathbf{u} \cdot \nu \nabla^2 \mathbf{u} + \mathbf{u} \cdot \frac{\nu}{3} \nabla (\nabla \cdot \mathbf{u}) \]

- Radiation determines behavior along streamlines
  \[ \mathbf{u} \cdot \nabla E_B = \rho^{-1} \left[ S_\star - \nabla \cdot \mathbf{F} \right] \]

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Viscosity

- Momentum eq.
  \[ \mathbf{u} \cdot \nabla \left( \frac{1}{2} |\mathbf{u}|^2 + w + \phi_y \right) = \]
  \[ \mathbf{u} \cdot T \nabla S + \mathbf{u} \cdot \nu \nabla^2 \mathbf{u} + \mathbf{u} \cdot \frac{\nu}{3} \nabla (\nabla \cdot \mathbf{u}) \]

- Add thermal and radiation energy equations
  \[ \mathbf{u} \cdot \nabla E_B = \rho^{-1} \left[ \Phi_v - \nabla \cdot \mathbf{F} + S_\star \right] + \]
  \[ -\mathbf{u} \cdot \nu \nabla^2 \mathbf{u} + \mathbf{u} \cdot \frac{\nu}{3} \nabla (\nabla \cdot \mathbf{u}) \]

- Radiation determines behavior along streamlines
  \[ \mathbf{u} \cdot \nabla E_B = \rho^{-1} \left[ S_\star - \nabla \cdot \mathbf{F} \right] \]
Variability

Grillmair et al 2009

Spectroscopy (this paper)
Photometry (Charbonneau et al. 2008)

P = 0.3, \( \kappa \approx 0.0 \)
P = 0.1, \( \kappa \approx 0.0 \)
P = 0.15, \( \kappa \approx 0.035 \)

Agol et al 2008

HD189733b Transmission

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Madhusudhan and Seager 2009
Surface and radial shear

-4 km/s  +4 km/s

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Variability

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Vertical Mixing

Fortney et al (2007)

Zahnle et al 2009

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Vertical Mixing

\[ K_{zz} = V_{r,rms} H_p \]

Eccentric Planets
Eccentric Planets

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Eccentric Planets

3.52d
Conclusions

- Numerical treatment of radiation and dynamics must be included as coupled model.
- Both opacity and dynamically derived temperature inversions play roles in dynamics and spectra. The location of stellar energy deposition governs efficiency of redistribution to the night-side.
- Three jets (one equatorial and two mid-lat.) are common features, with width decreasing with increased planetary rotation.
- Changing viscosity drastically alters streamlines, changing overall thermal structure.
- Dynamically driven variability may cause variations transit spectra, but variation in hemispherically averaged phase curves will be difficult.
- Vertical mixing throughout the atmosphere is significant. Potential for maintaining species aloft.
- Continuing obs. programs, and coupling of dynamical/spectral models will allow tighter constraints on dynamical processes: eccentric planets, multiple (and continuous) observations, lower masses, younger planets, thermal forcing.