Extra-solar Weather

Ian Dobbs-Dixon

University of Washington, Seattle

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)
  - Cho et al (2003,2008) Langton and Laughlin (2007,2008) Rauscher et al (2007, 2008)
- Primitive equations (~3D)
  - Showman et al. (2002, 2005, 2006, 2008, 2009), Menou and Rauscher (2009)
- Navier-Stokes equation (2D)
  - Burkert et al. 2007
- Full Navier-Stokes equations (3D)
  - Dobbs-Dixon et al (2008,2009)

Resolution

Radiation Transfer Methods

'Completeness'

- Relaxation methods (Newtonian heating)
  - Cho et al (2003,2008) Langton and Laughlin (2007,2008) Rauscher et al (2007, 2008), Showman et al. (2002, 2005, 2006, 2008), Menou and Rauscher (2009)
- 2/3D one temperature flux-limited radiative diffusion
  - Burkert et al. (2007), Dobbs-Dixon and Lin (2008)
- 3D FLD + decoupled thermal and radiative components
  - Dobbs-Dixon et al (2009)
- 1D (radial) wavelength-dependent radiative transfer
  - Showman et al. (2009)

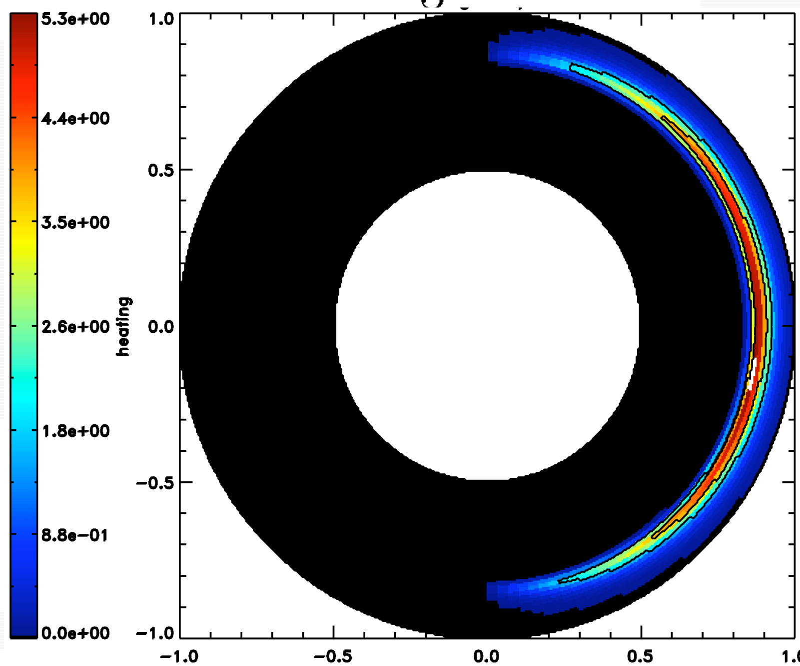
3D Navier-Stokes, flux limited diffusion and decoupled thermal and radiative components

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

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

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

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

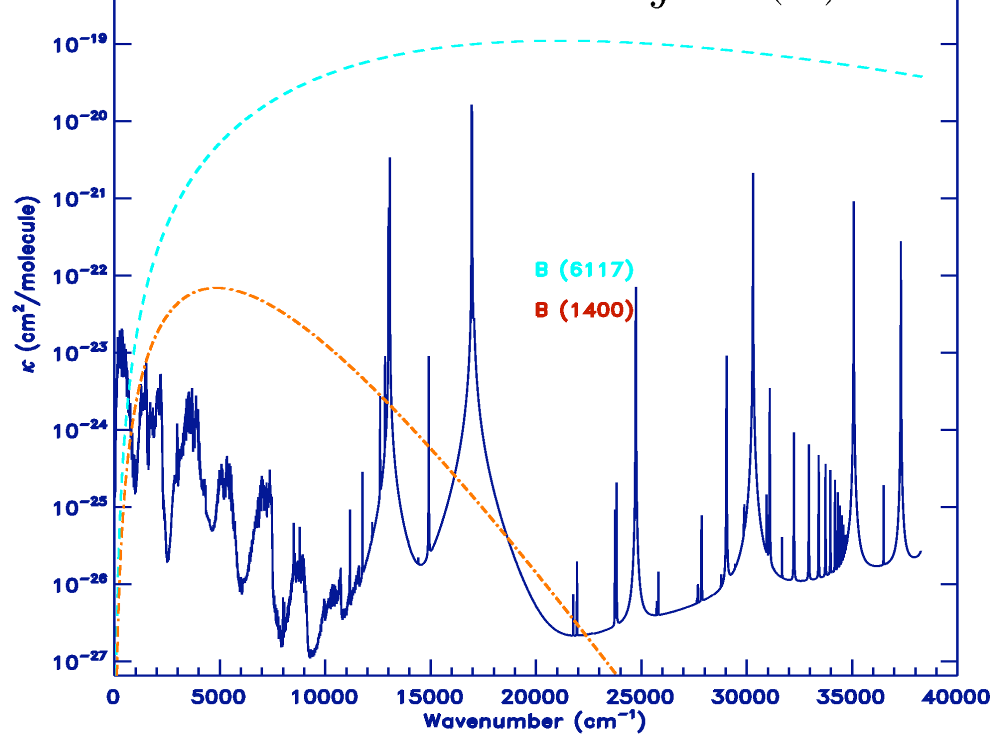


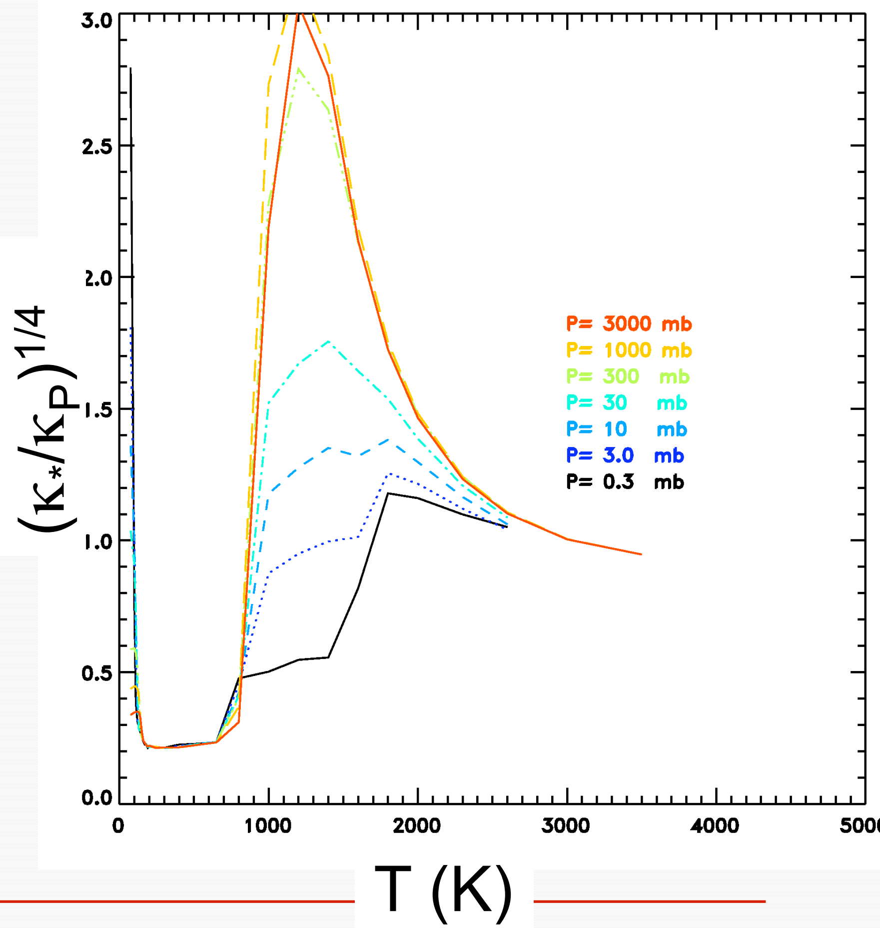
$$\left[\frac{\partial \epsilon}{\partial t}+(\mathbf{u}\cdot\nabla)\epsilon\right]=-P\nabla\cdot\mathbf{u}-\rho\kappa_P(T,P)\left[B(T)-cE_R\right]+\rho\kappa_\star(T,P)\,F_\star e^{-\tau_\star}+\Phi_\nu.$$

Ian Dobbs-Dixon, University of Washington, Seattle, WA

Absorption vs. Emission Opacities

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





Ian Dobbs-Dixon, University of Washington,
Seattle, WA

3D Flux-Limited Radiation Diffusion

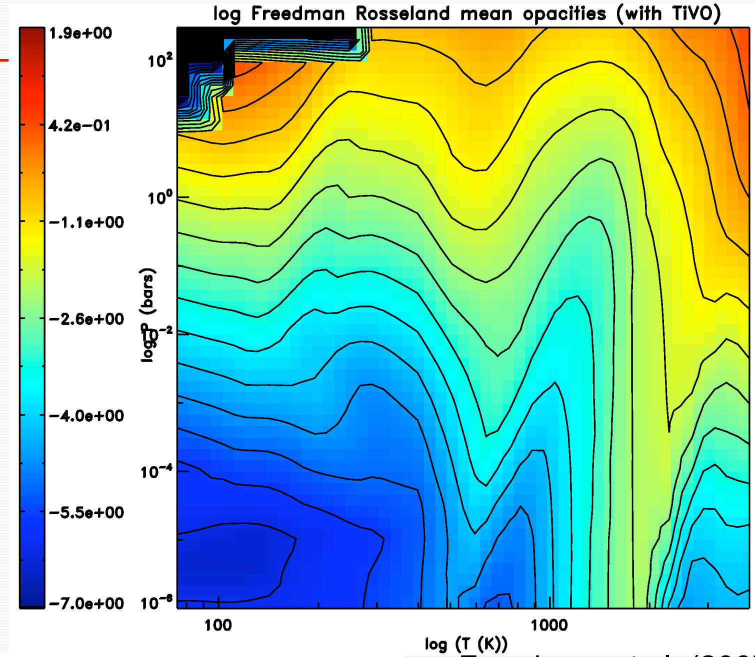
$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \hat{\mathbf{k}} \cdot \nabla I_\nu + \rho\kappa_\nu I_\nu = \rho\left(\frac{j_\nu}{4\pi} + \kappa_\nu^{scat}\Phi_\nu\right)$$

- Slowly varying in space/time:

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

F α λ(R) **R**

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



Freedman et al. (2007)

$$\lambda = \frac{2+R}{6+3R+R^2}$$

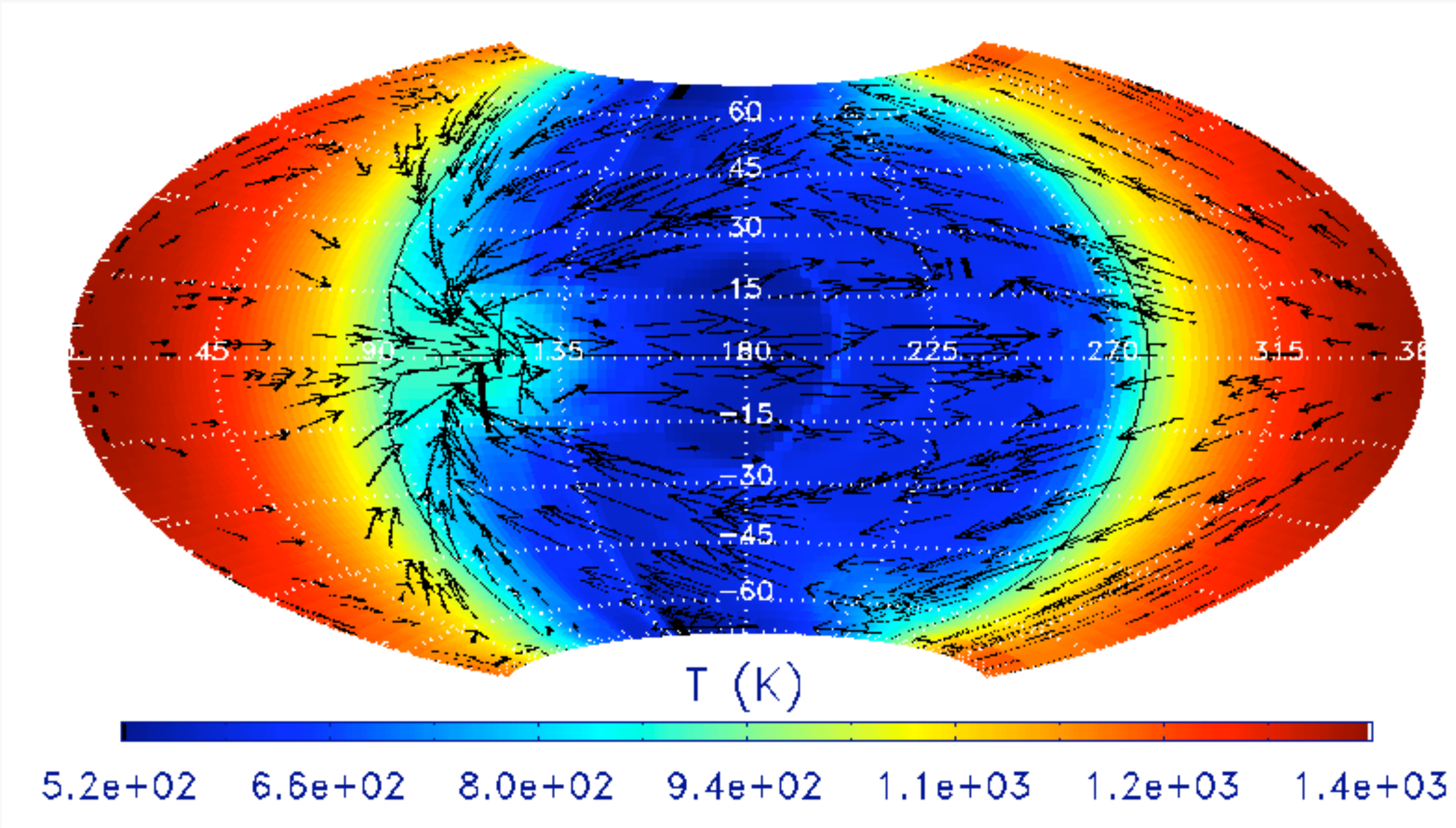
Levermore & Pomraning (1981)

Accurate in the limits

$$\begin{cases} \mathbf{F} = -\dfrac{c}{3\rho\kappa}\nabla E = -\dfrac{4acT^3}{3\rho\kappa}\nabla T \\ \mathbf{F} = cE \end{cases}$$

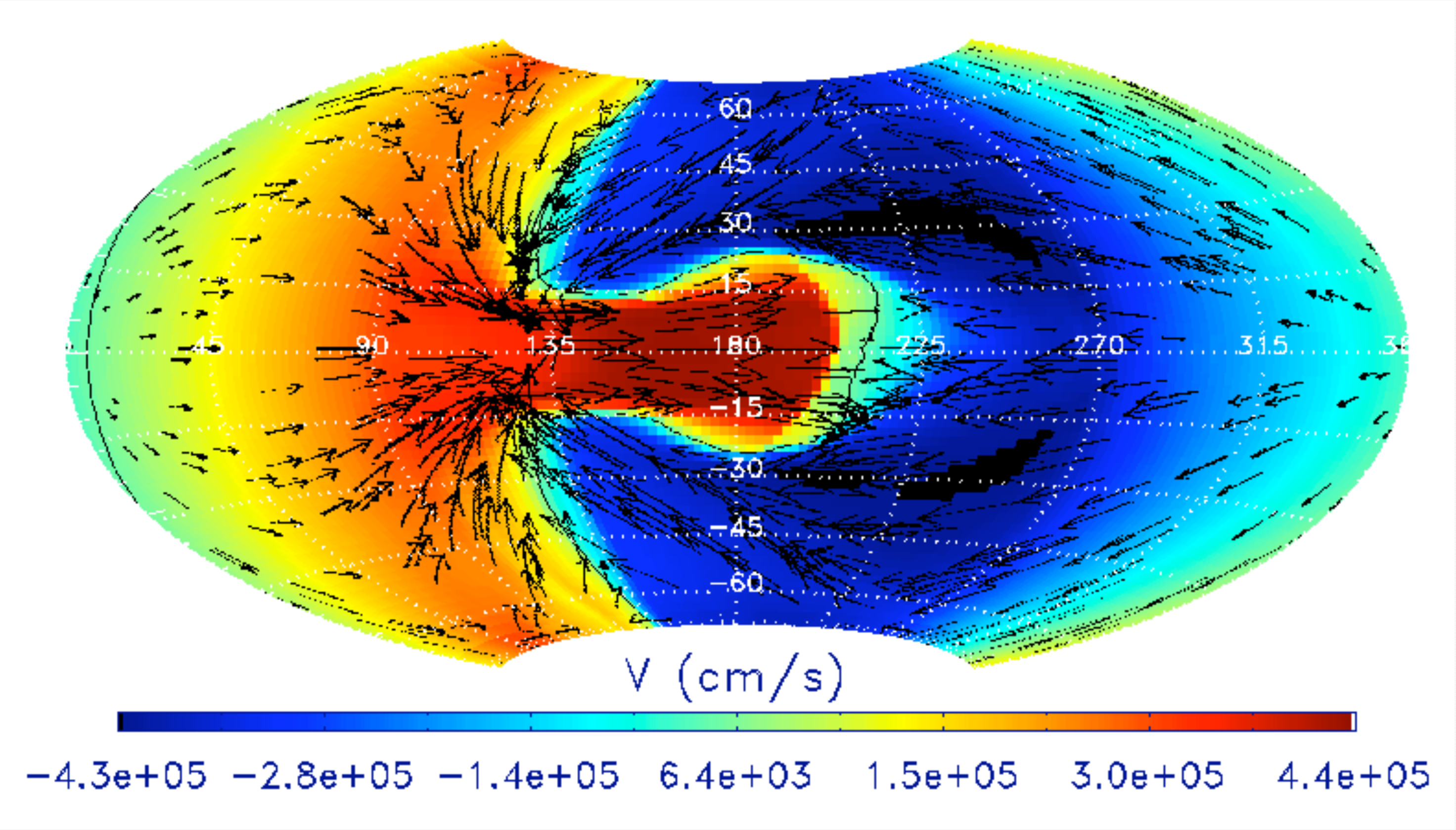
Ian Dobbs-Dixon, University of Washington,
Seattle, WA

P_{rot}=P_{orb}=3.52d, Tstar=6117K



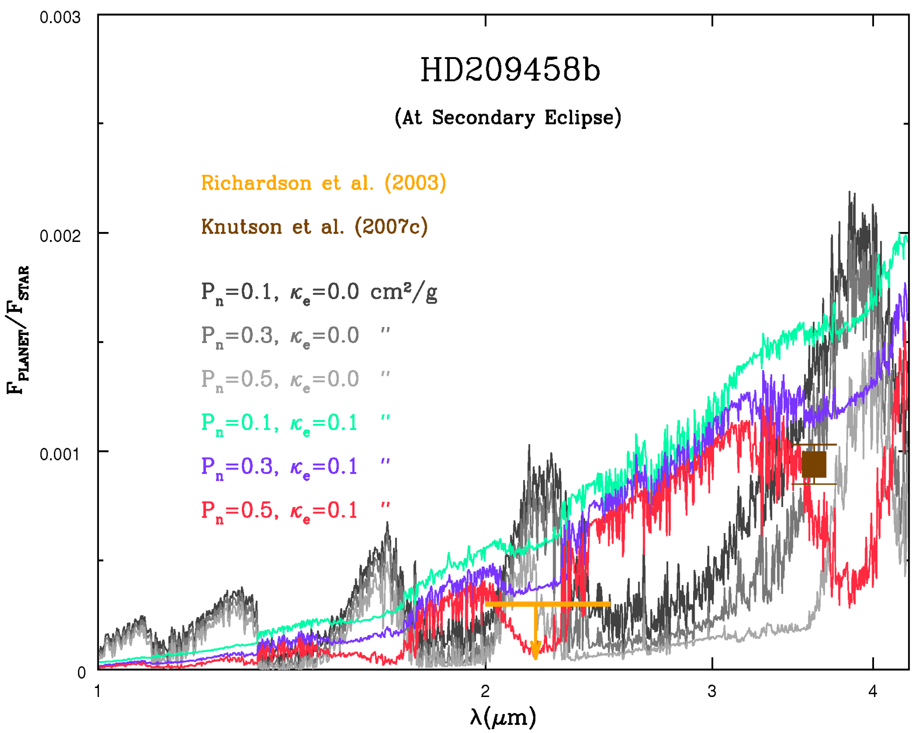
Ian Dobbs-Dixon, University of Washington,
Seattle, WA

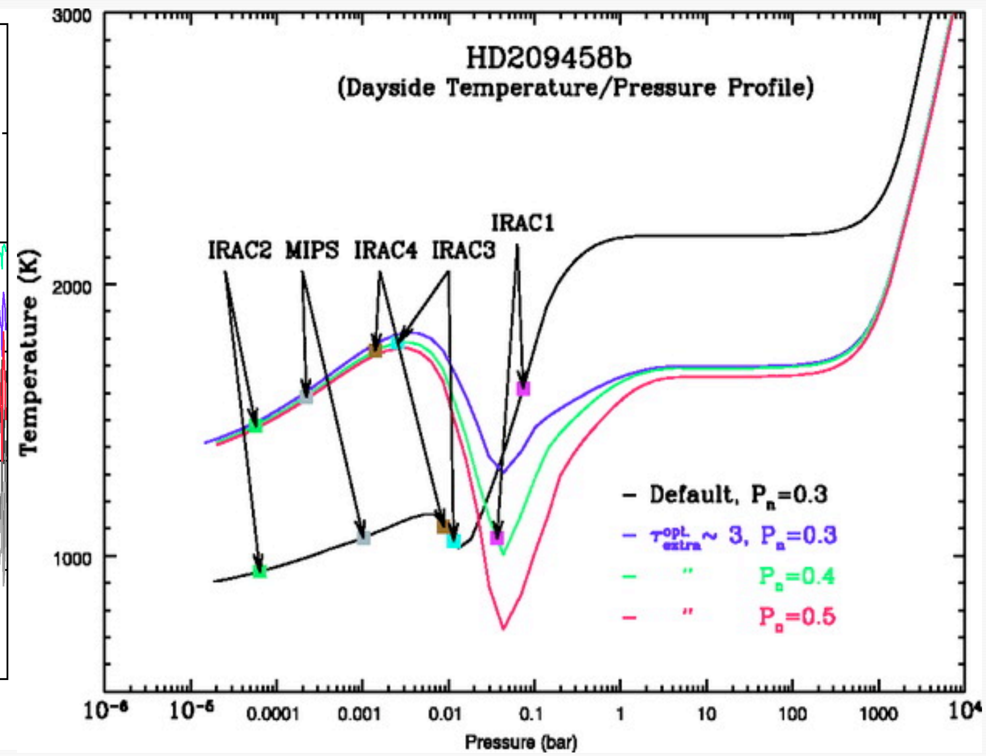
Photospheric Velocities



Ian Dobbs-Dixon, University of Washington,
Seattle, WA

Observed Inversion (HD 209458b)

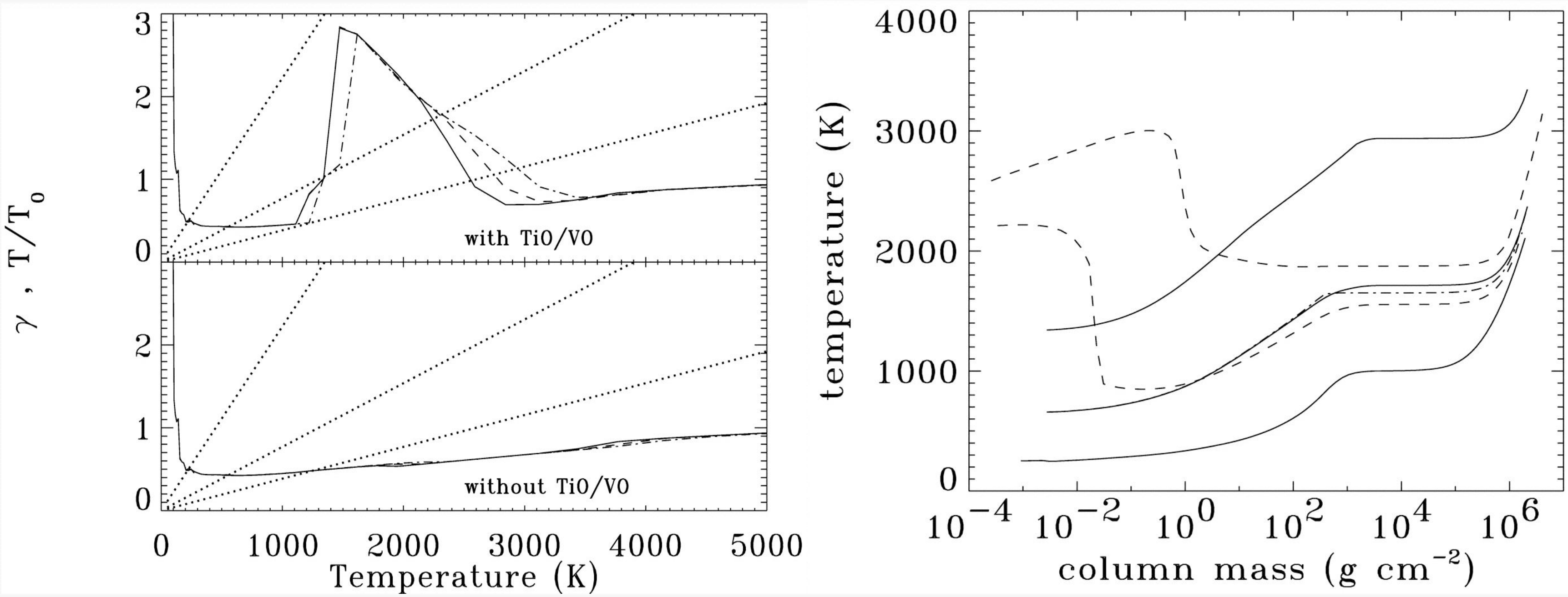




Burrows et al (2007)

Ian Dobbs-Dixon, University of Washington,
Seattle, WA

Outer Temperature Structure



Hubeny et al. (2003)

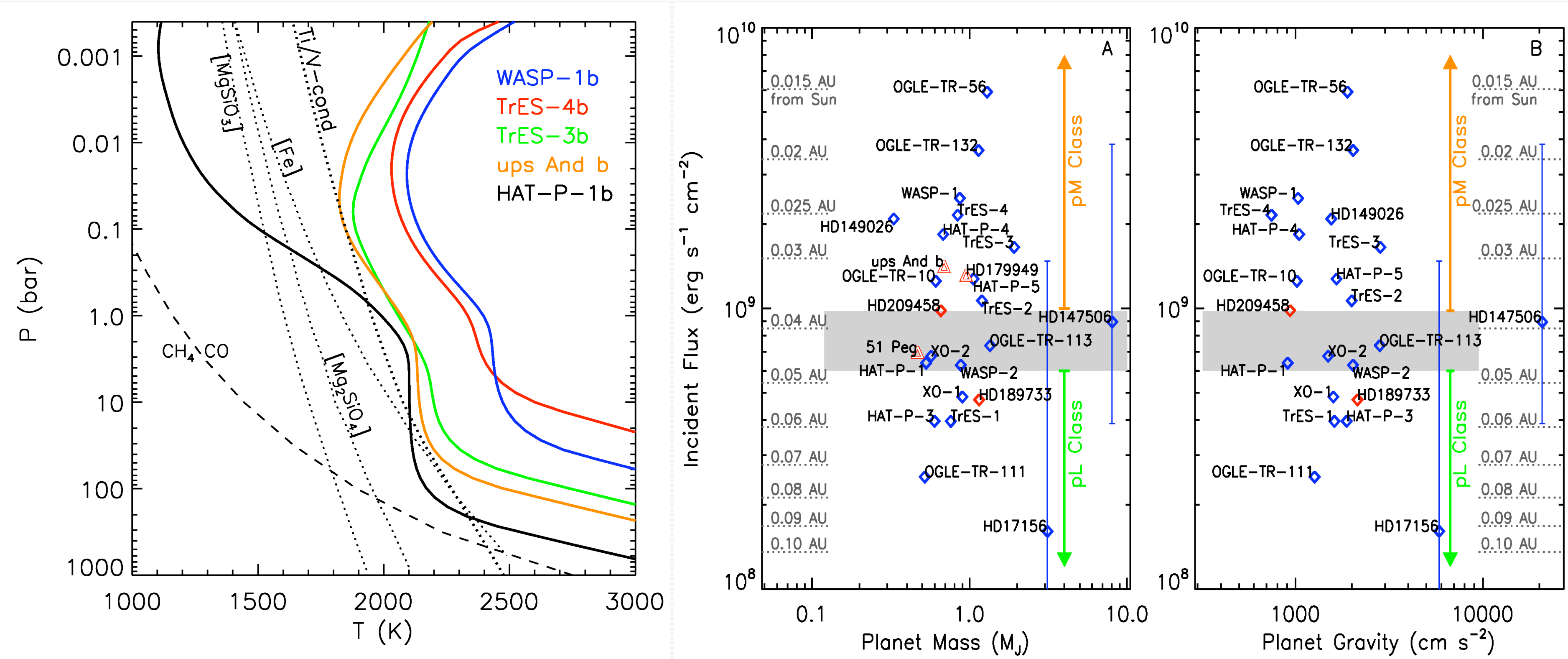
$$\kappa_J J - \kappa_B B = 0$$

$$\frac{\partial K}{\partial m} = \chi_H H$$

$$T^4 = \frac{3}{4} T_{eff}^4 \frac{\kappa_J}{\kappa_B} \left(\frac{1}{3 f_k} \tau_H + \frac{1}{3 f_H} \right) + \frac{\kappa_J}{\kappa_B} W T_\star^4$$

Ian Dobbs-Dixon, University of Washington,
Seattle, WA

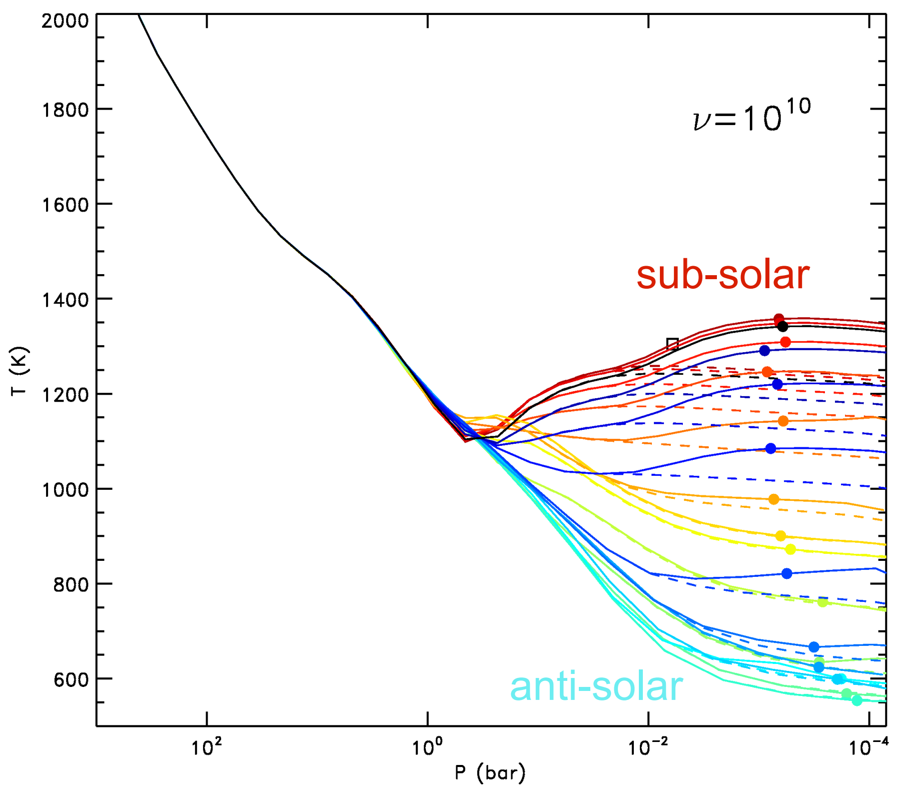
T-Profile Dichotomy?

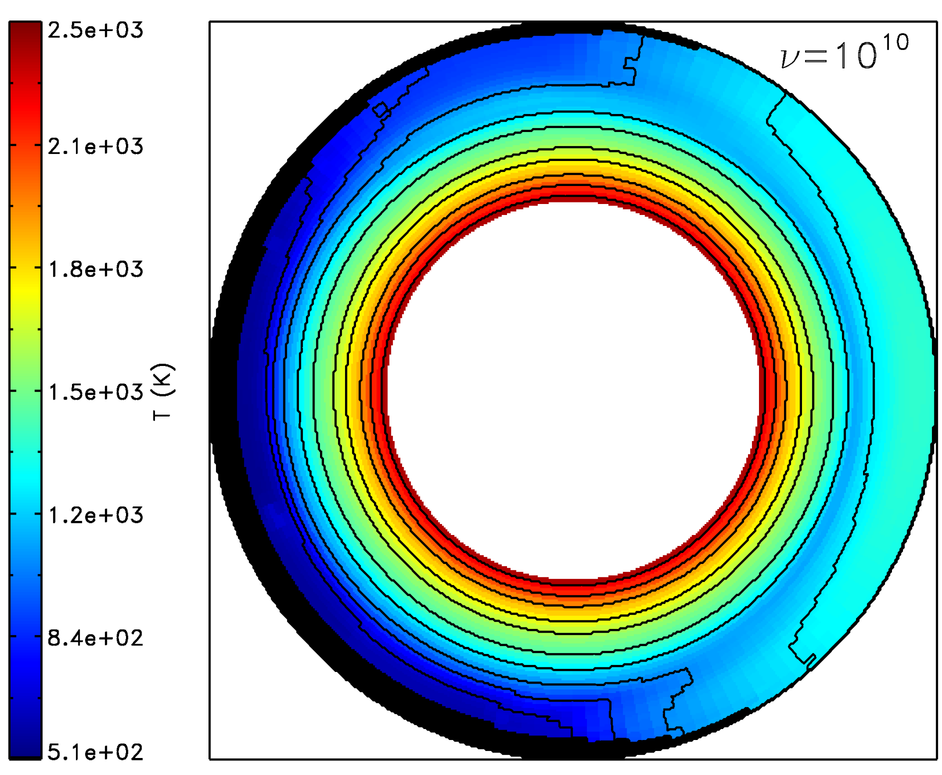


Fortney et al (2007)

Ian Dobbs-Dixon, University of Washington,
Seattle, WA

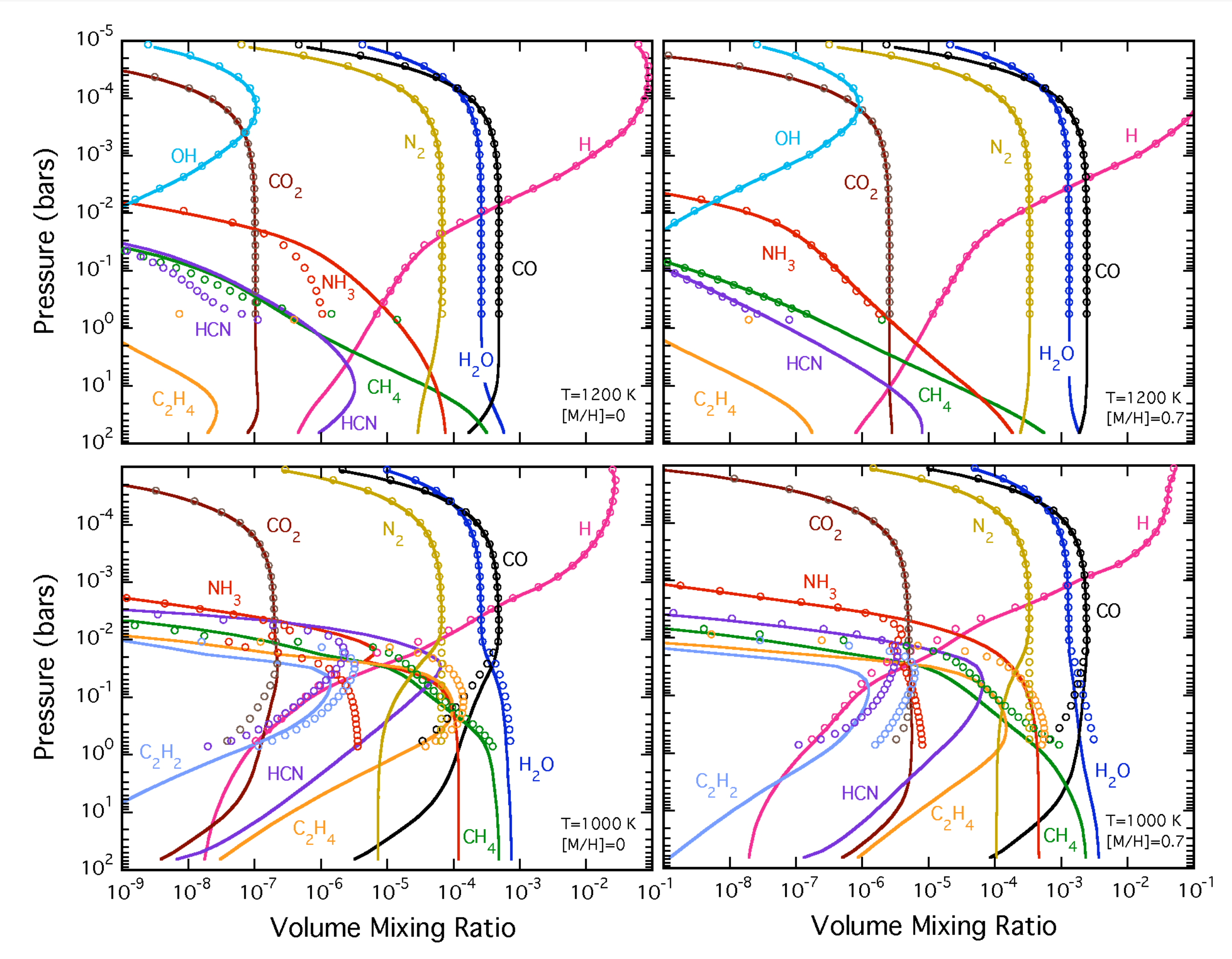
HD209458b





Ian Dobbs-Dixon, University of Washington,
Seattle, WA

Opacity Variations



Zahnle et al 2009

Opacity Variations

$$\tau_{cool} = \frac{E_{thermal}}{\sigma T^4}$$

$$\tau_{cross} = \frac{\pi R_p}{2 v_d}$$

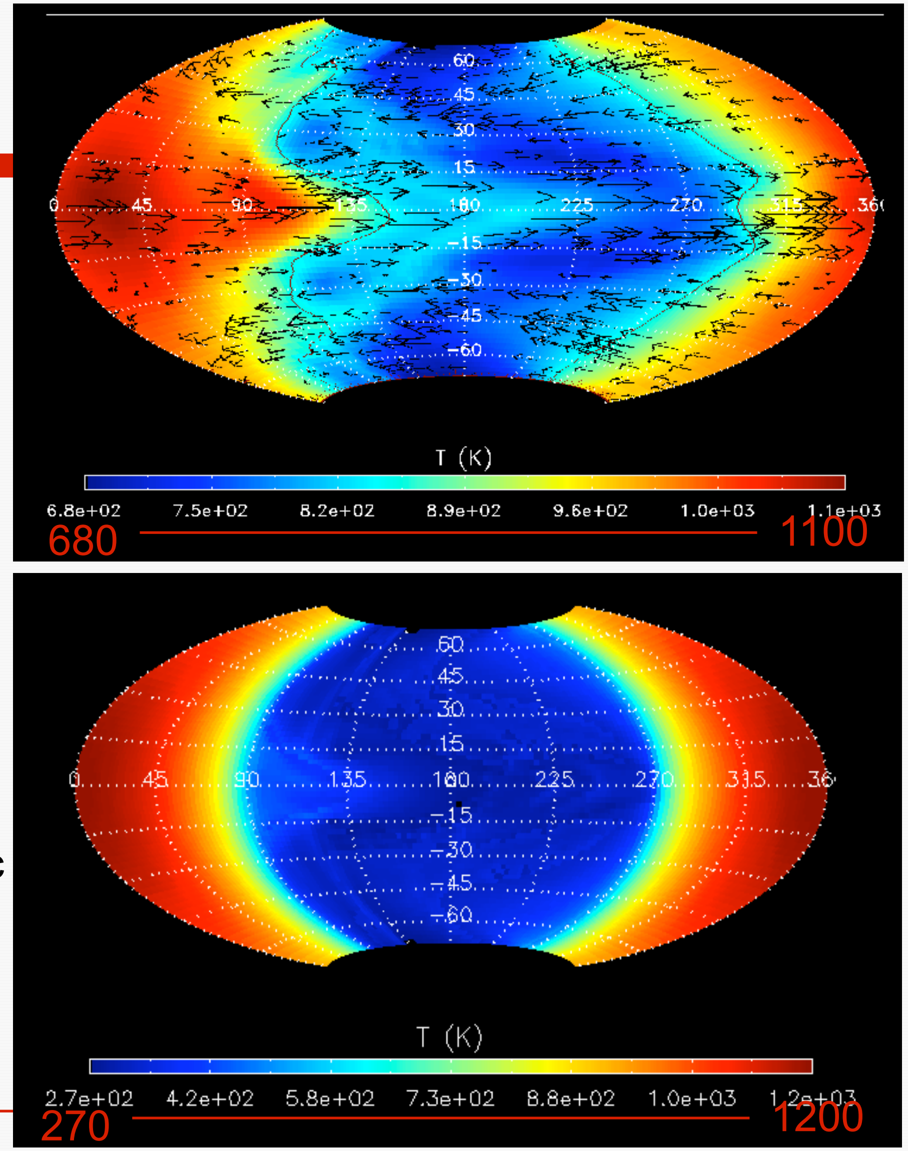
$$\tau_{cool} \approx \tau_{cross}$$

$$T_n = \left(\frac{4 v c_d^2}{3 \pi \kappa_d \sigma R_p} \right)^{1/4}$$

- Freedman Opc

κ ↓

- Interstellar Opc



Dobbs-Dixon and Lin (2007)

Ian Dobbs-Dixon, University of Washington,
Seattle, WA

Opacity Variations

$$\tau_{cool} = \frac{E_{thermal}}{\sigma T^4}$$

$$\tau_{cross} = \frac{\pi R_p}{2 v_d}$$

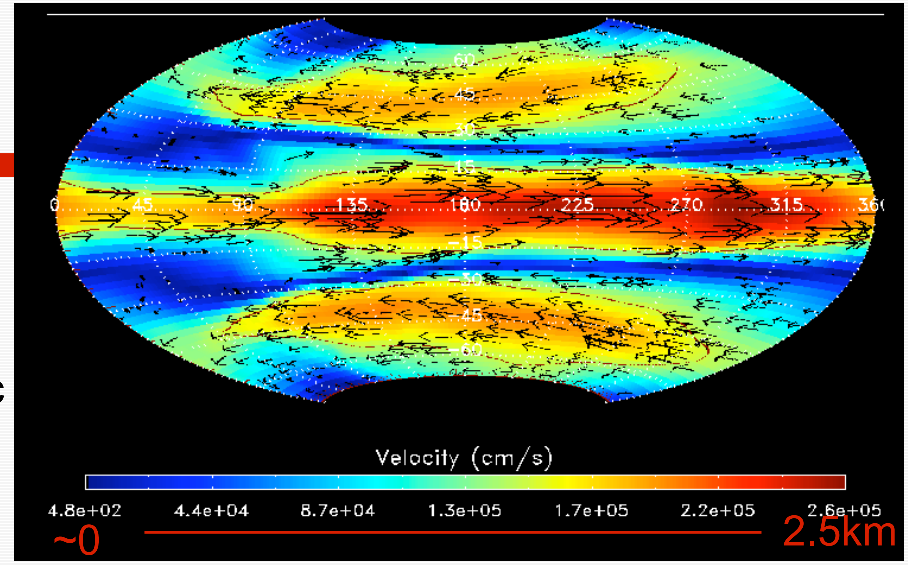
$$\tau_{cool} \approx \tau_{cross}$$

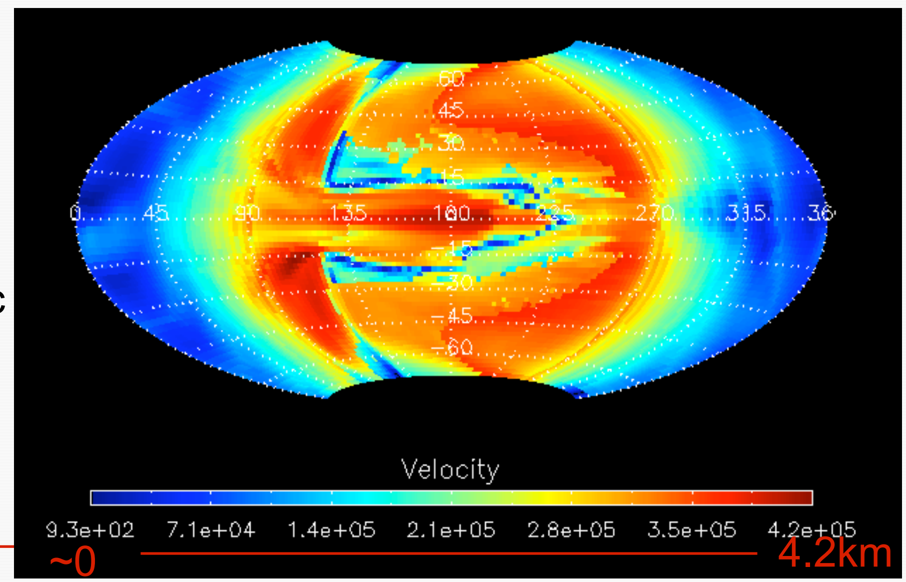
$$T_n = \left(\frac{4 v c_d^2}{3 \pi \kappa_d \sigma R_p} \right)^{1/4}$$

- Freedman Opc

κ ↓

- Interstellar Opc





Dobbs-Dixon and Lin (2007)

Ian Dobbs-Dixon, University of Washington, Seattle, WA

Viscosity

•Momentum eq.

$$\mathbf{u}\cdot\nabla\left(\frac{1}{2}\left|\mathbf{u}\right|^2 + w + \phi_g\right) =$$

$$\mathbf{u}\cdot T\nabla S + \mathbf{u}\cdot\nu\nabla^2\mathbf{u} + \mathbf{u}\cdot\frac{\nu}{3}\nabla\left(\nabla\cdot\mathbf{u}\right)$$

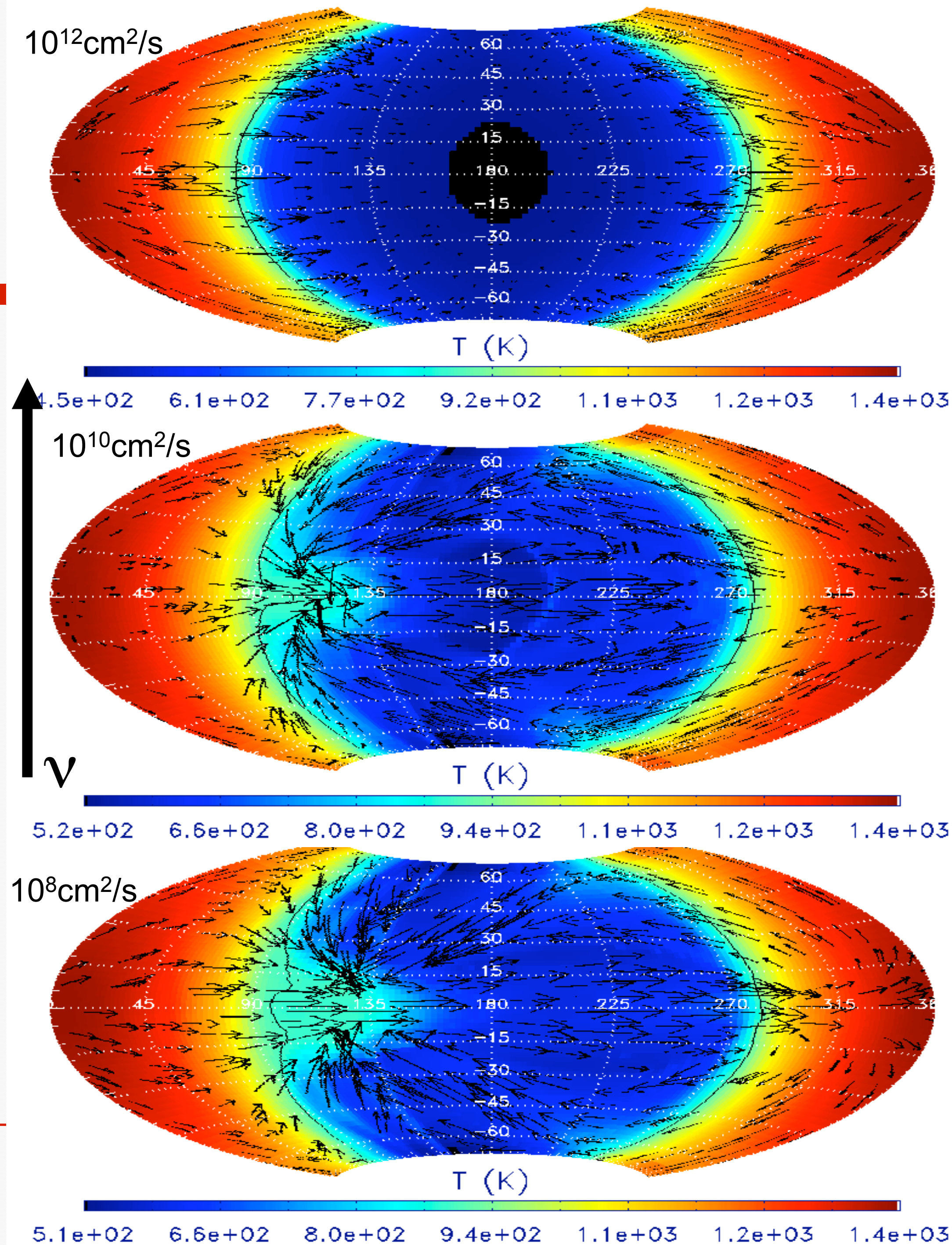
•Add thermal and radiation energy equations

$$\mathbf{u}\cdot\nabla E_B = \rho^{-1}\left[\Phi_v - \nabla\cdot\mathbf{F} + S_\star\right] +$$

$$-\mathbf{u}\cdot\nu\nabla^2\mathbf{u} + \mathbf{u}\cdot\frac{\nu}{3}\nabla\left(\nabla\cdot\mathbf{u}\right)$$

•Radiation determines behavior along streamlines

$$\mathbf{u}\cdot\nabla E_B = \rho^{-1}\left[S_\star - \nabla\cdot\mathbf{F}\right]$$



Ian Dobbs-Dixon, University of Washington, Seattle, WA

Viscosity

•Momentum eq.

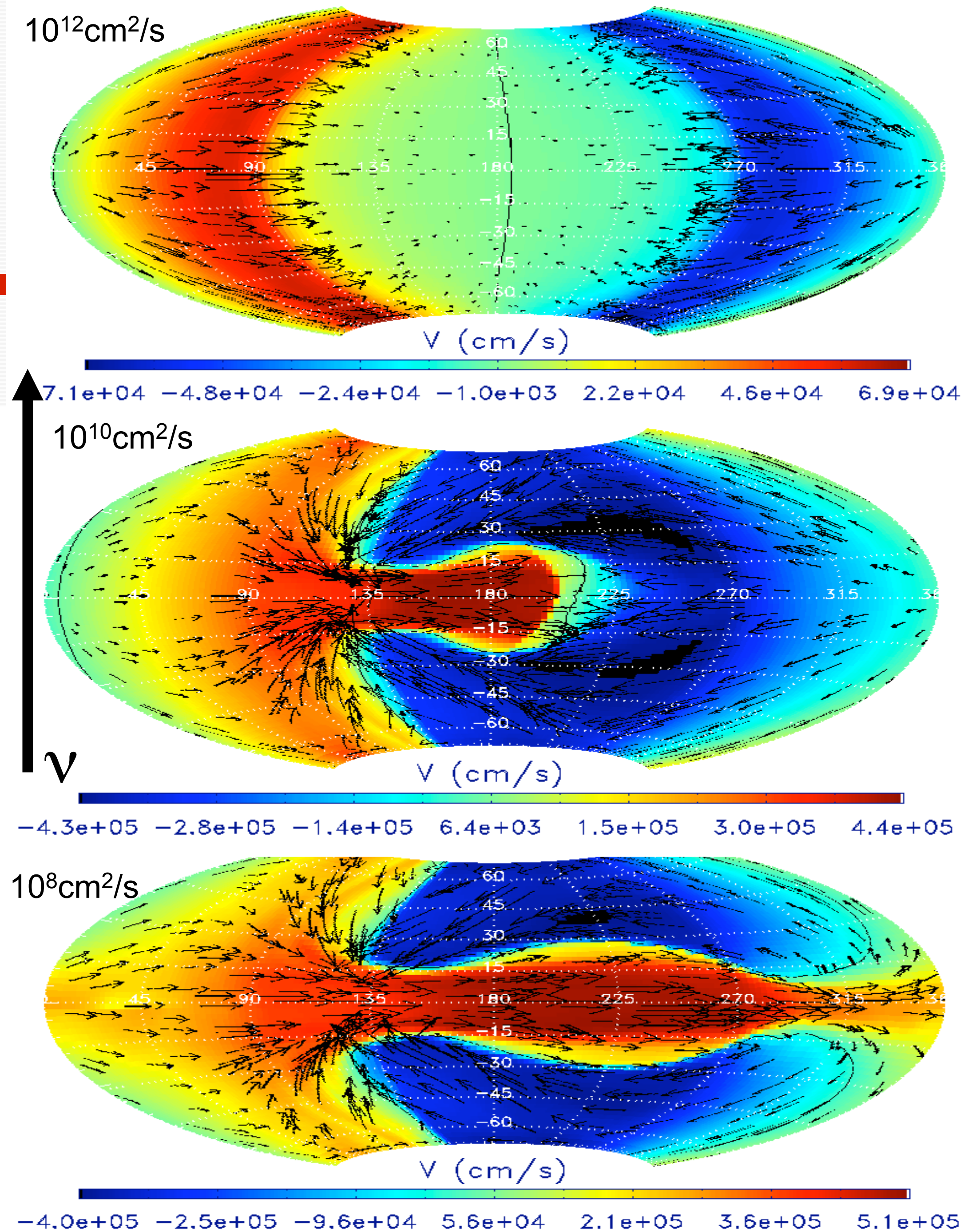
$$\mathbf{u}\cdot\nabla\left(\frac{1}{2}|\mathbf{u}|^2 + w + \phi_g\right) = \mathbf{u}\cdot T\nabla S + \mathbf{u}\cdot\nu\nabla^2\mathbf{u} + \mathbf{u}\cdot\frac{\nu}{3}\nabla\left(\nabla\cdot\mathbf{u}\right)$$

•Add thermal and radiation energy equations

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

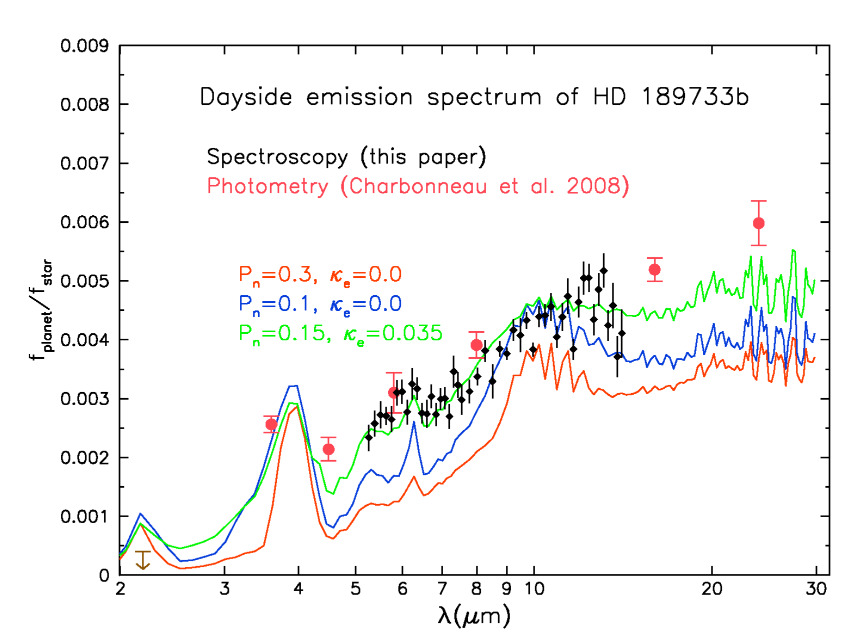
•Radiation determines behavior along streamlines

$$\mathbf{u}\cdot\nabla E_B = \rho^{-1}\left[S_\star - \nabla\cdot\mathbf{F}\right]$$

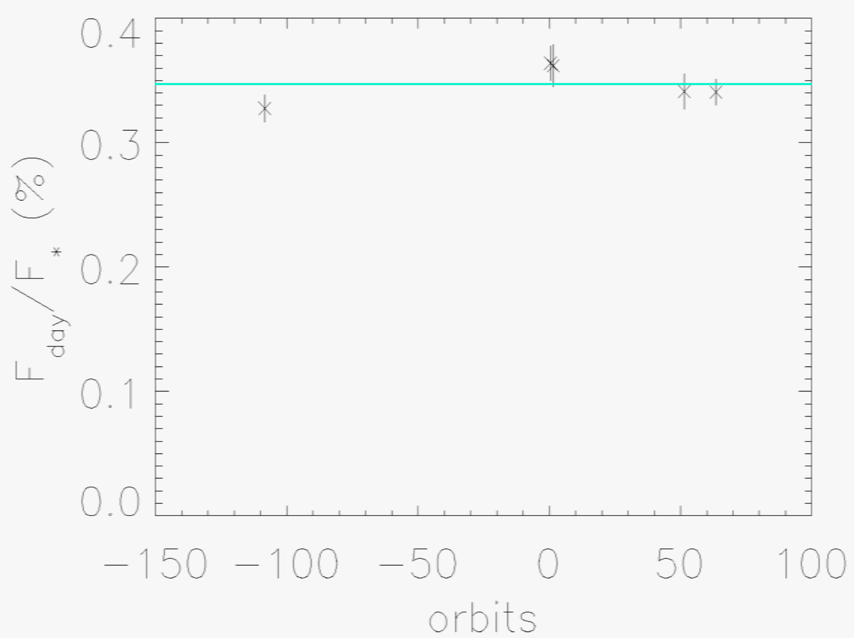


Ian Dobbs-Dixon, University of Washington, Seattle, WA

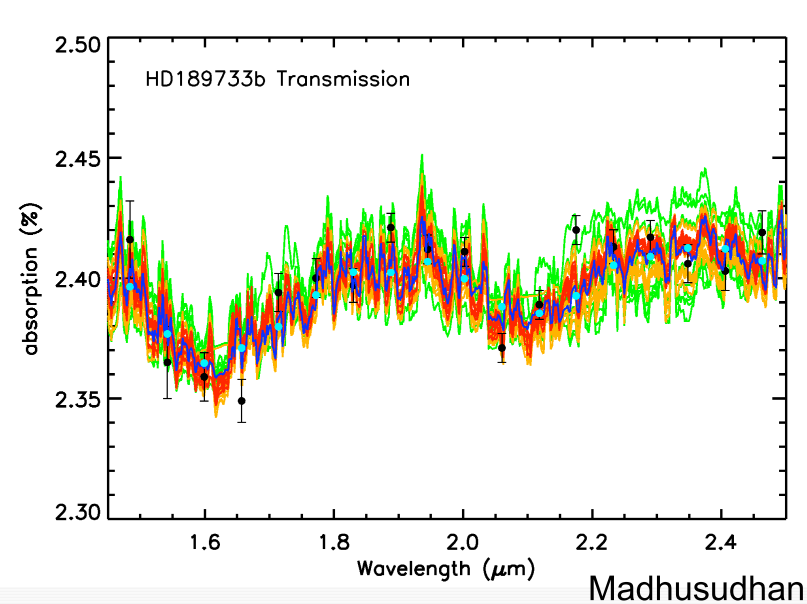
Variability



Grillmair et al 2009

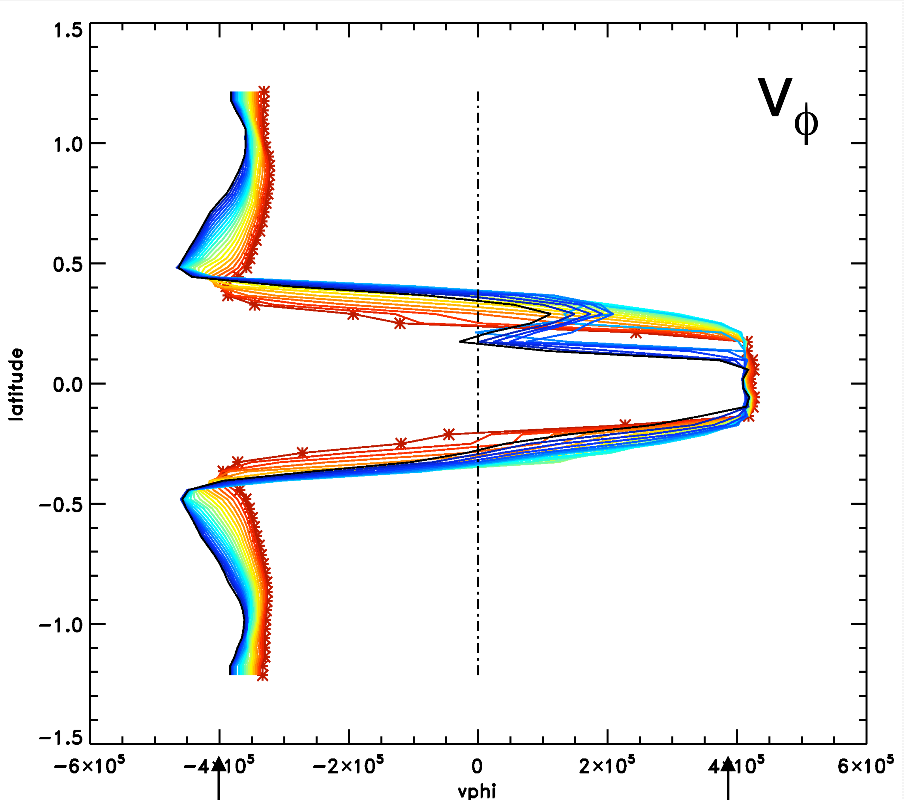


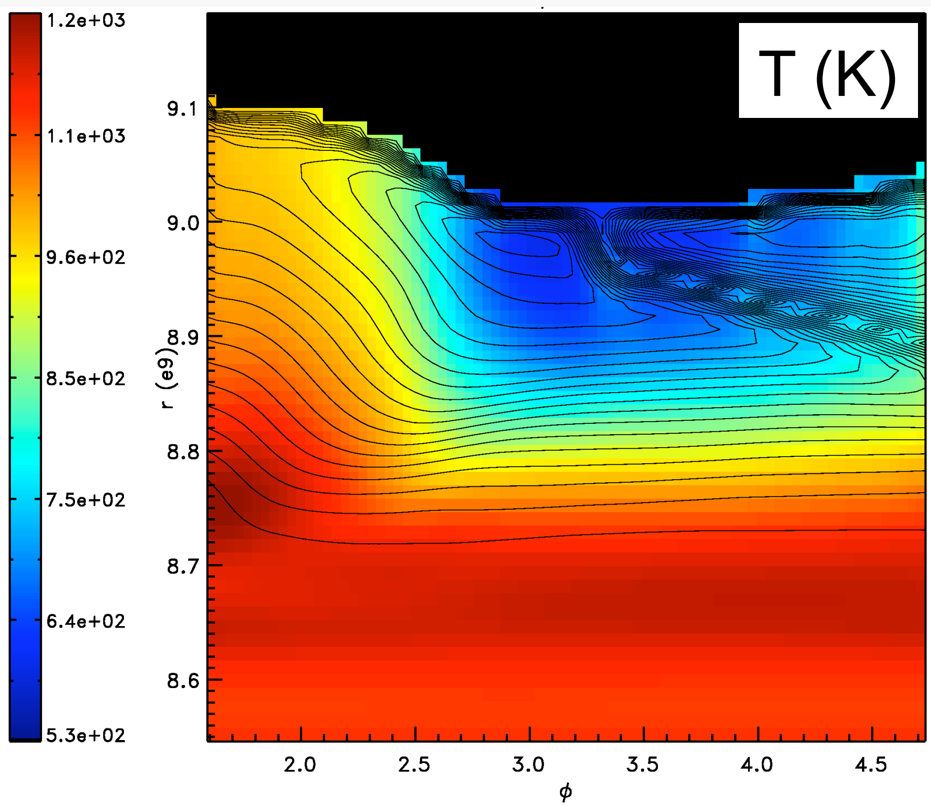
Agol et al 2008



Madhusudhan and Seager 2009

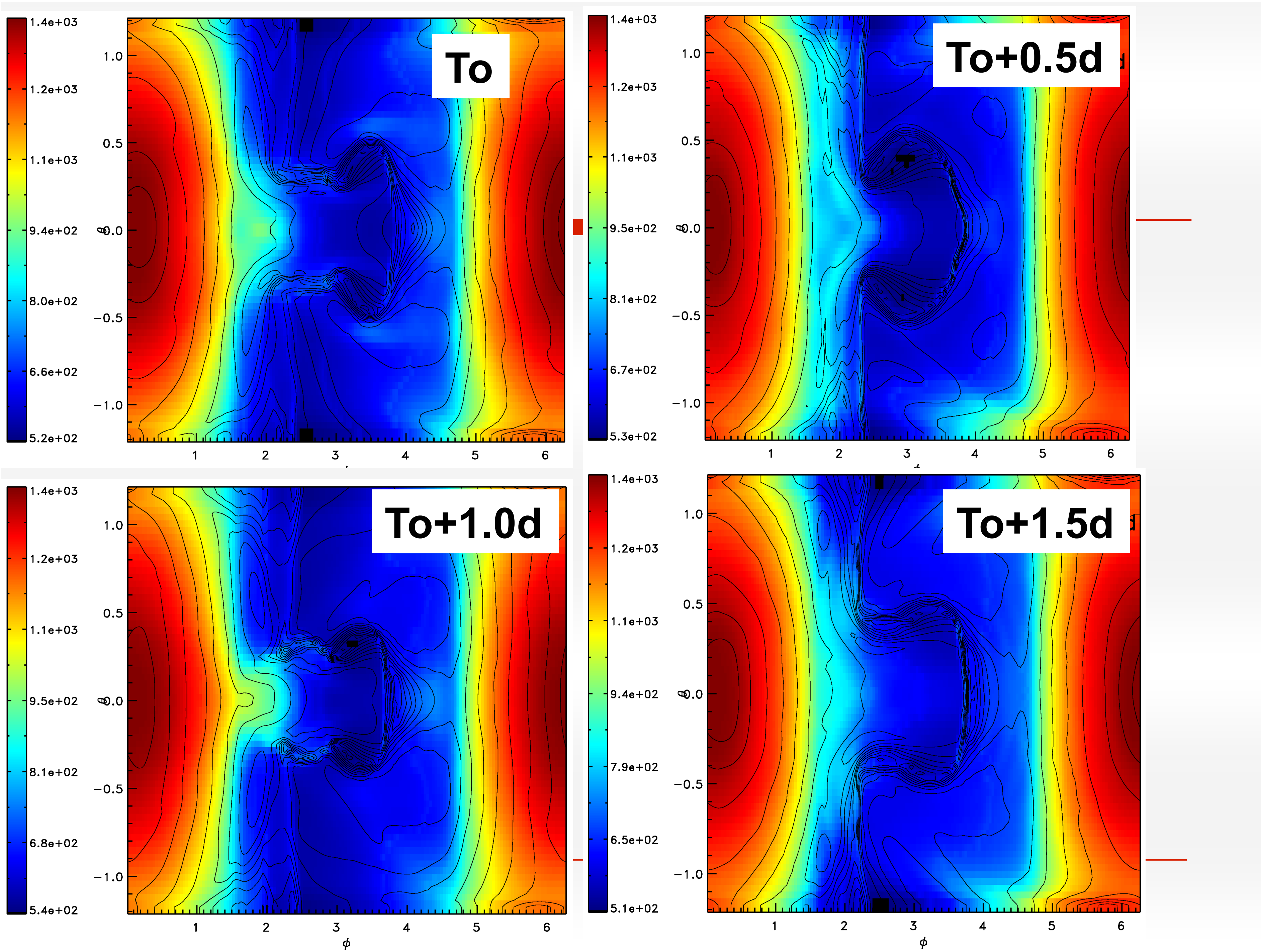
Surface and radial shear





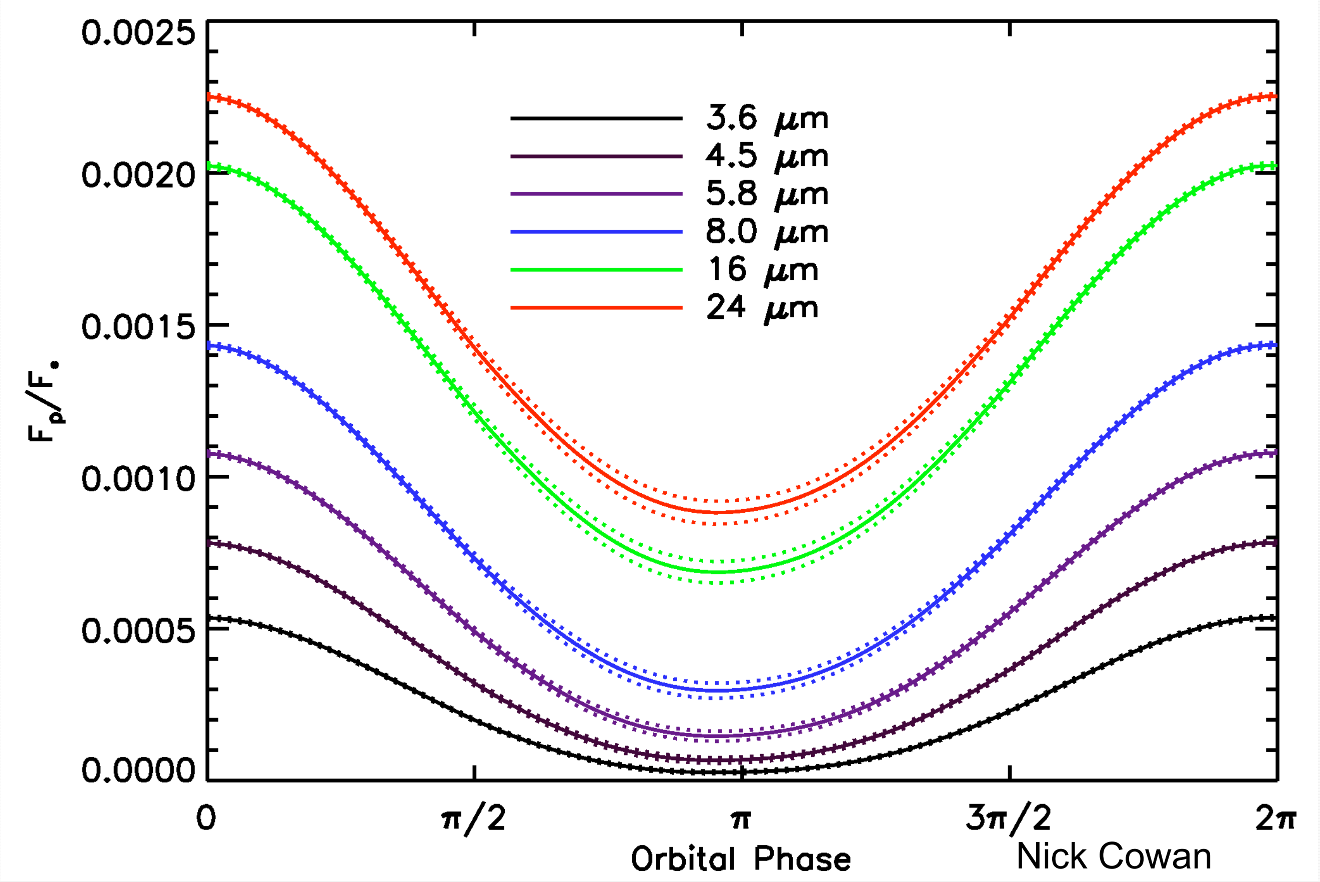
-4 km/s +4 km/s

Ian Dobbs-Dixon, University of Washington,
Seattle, WA



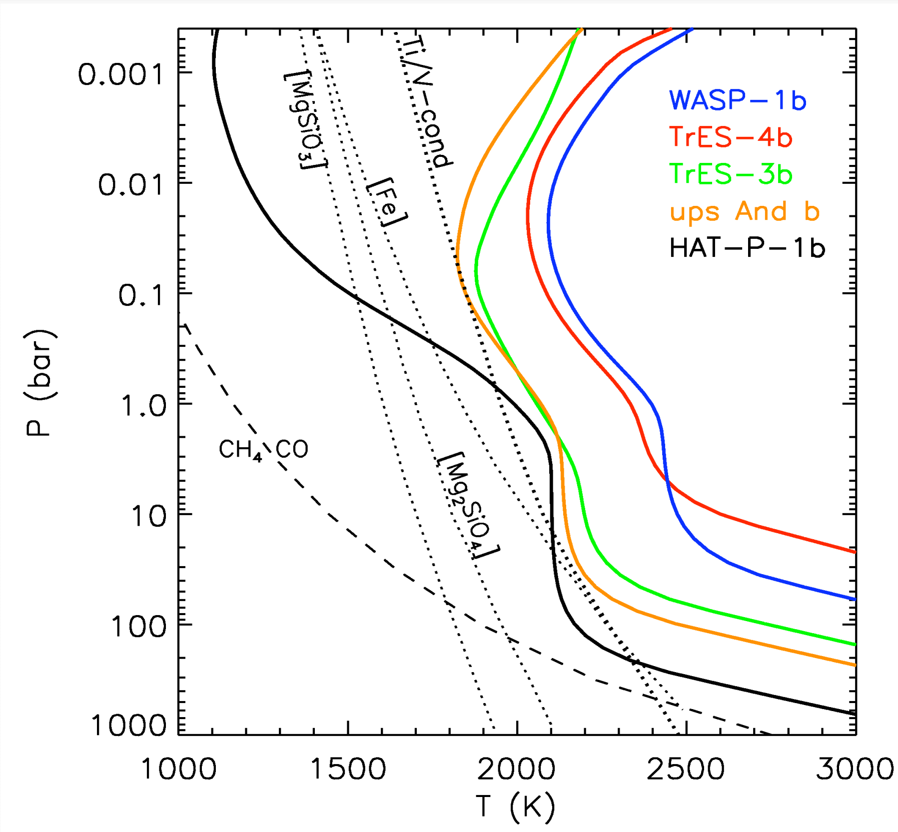
To
To+0.5d
To+1.0d
To+1.5d
1.4e+03
1.2e+03
1.1e+03
9.4e+02
8.0e+02
6.6e+02
5.2e+02
1.2e+03
1.1e+03
9.5e+02
8.1e+02
6.7e+02
5.3e+02
9.5e+02
8.1e+02
6.8e+02
5.4e+02
9.4e+02
7.9e+02
6.5e+02
5.1e+02
θ
ϕ

Variability



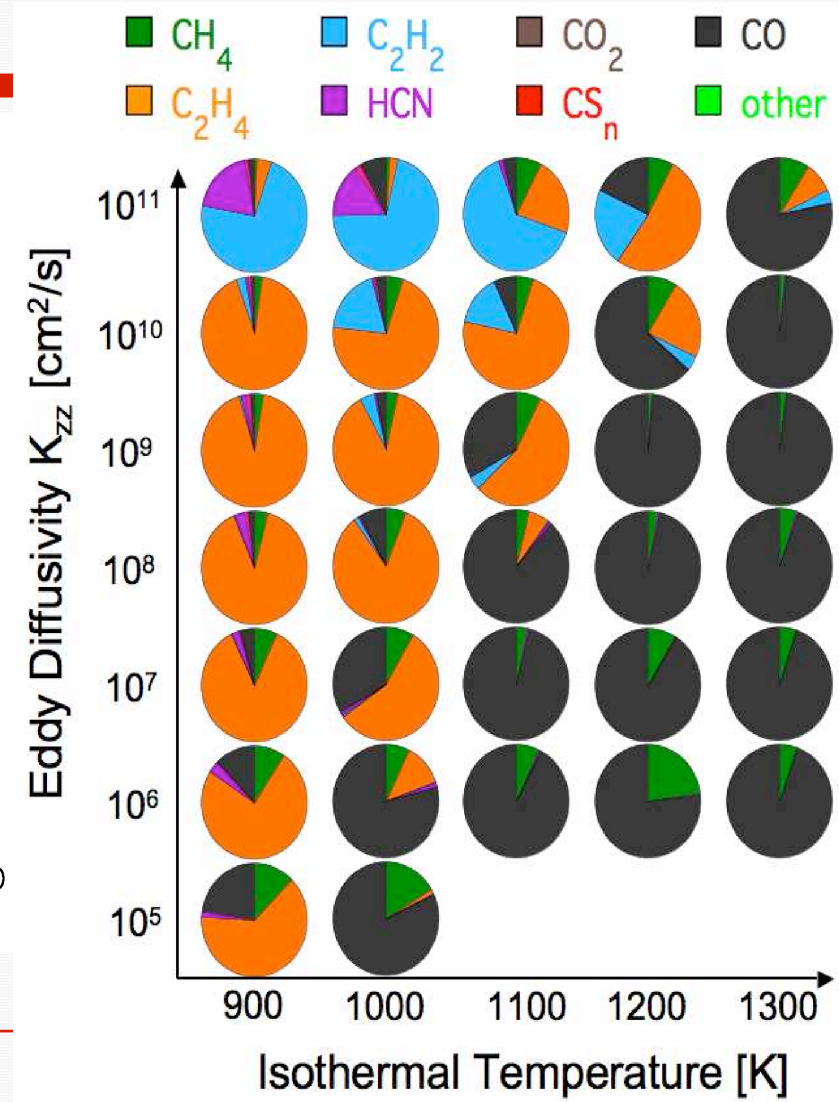
Ian Dobbs-Dixon, University of Washington, Seattle, WA

Vertical Mixing



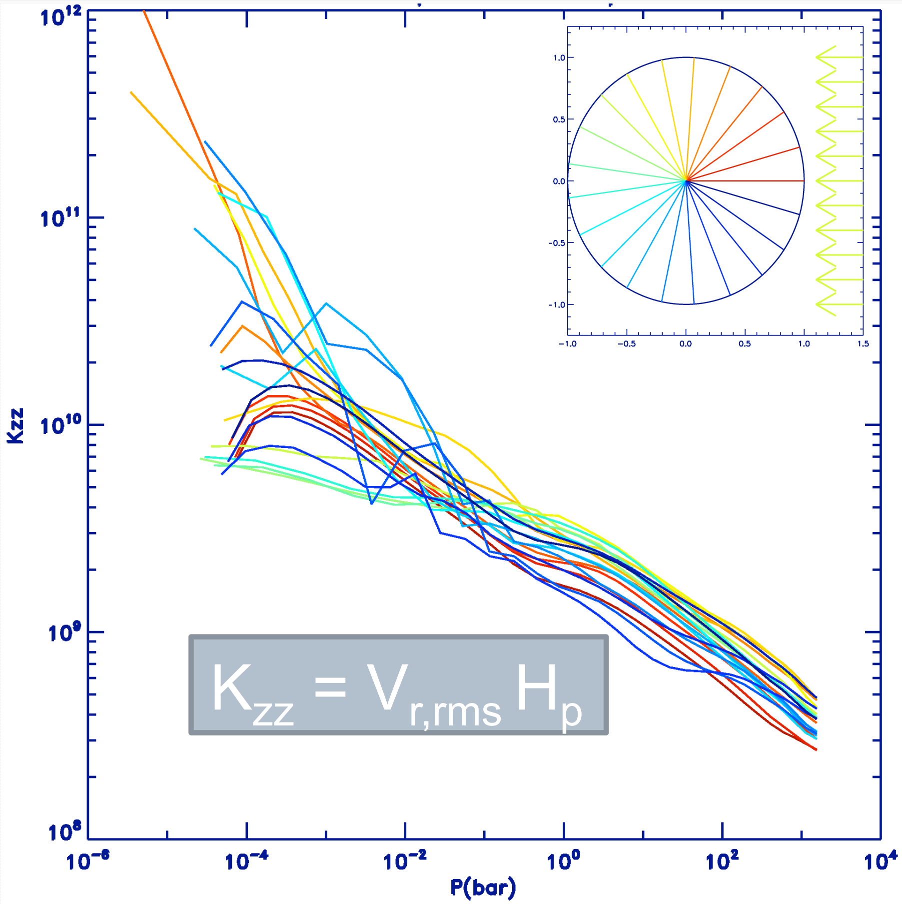
Fortney et al (2007)

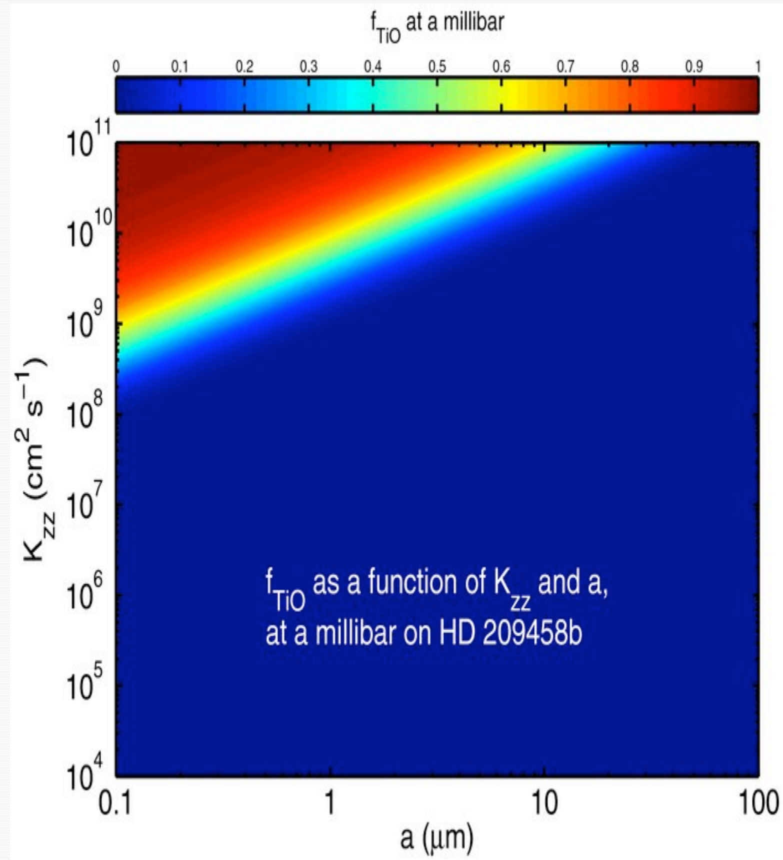
Zahnle et al 2009



Ian Dobbs-Dixon, University of Washington,
Seattle, WA

Vertical Mixing

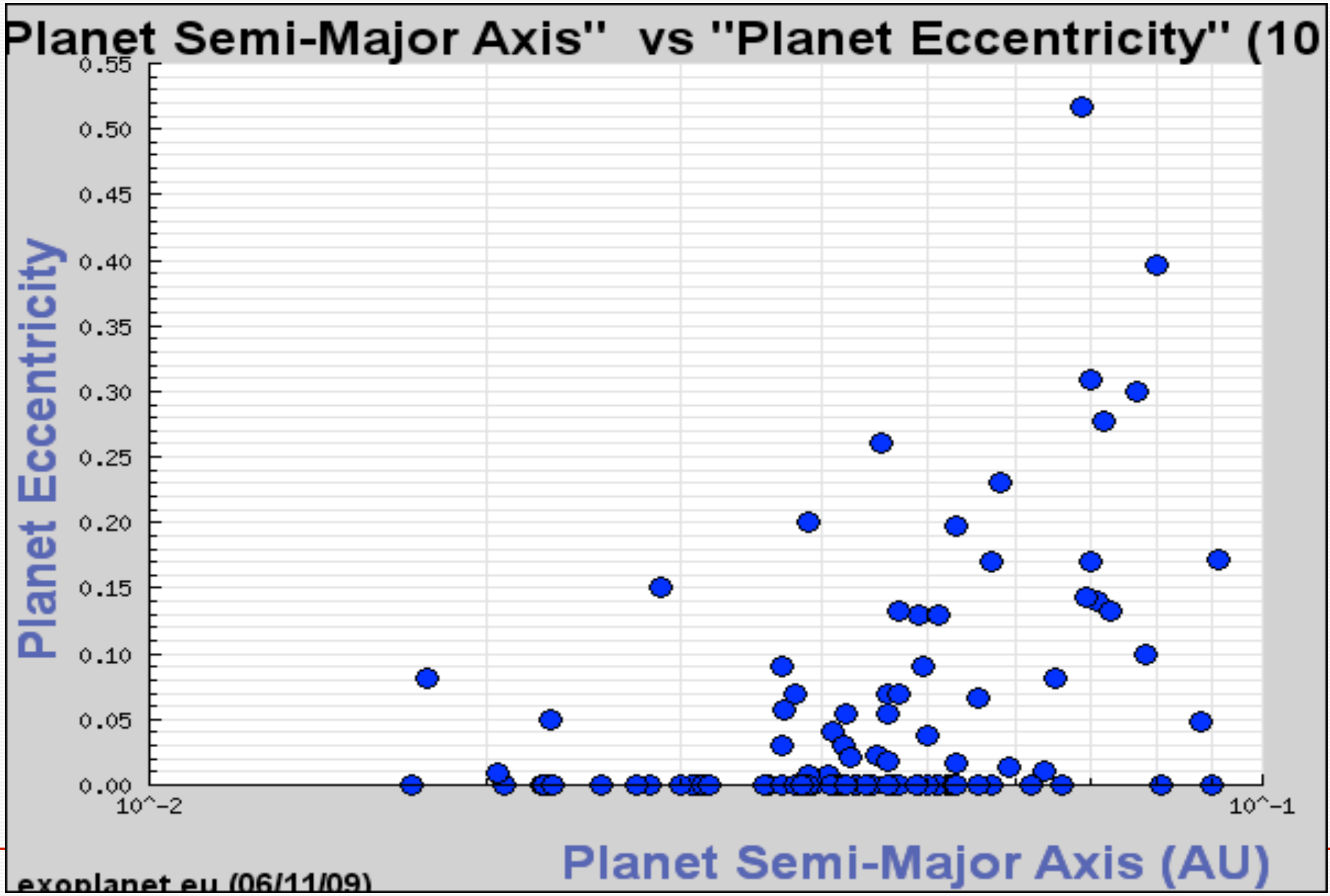




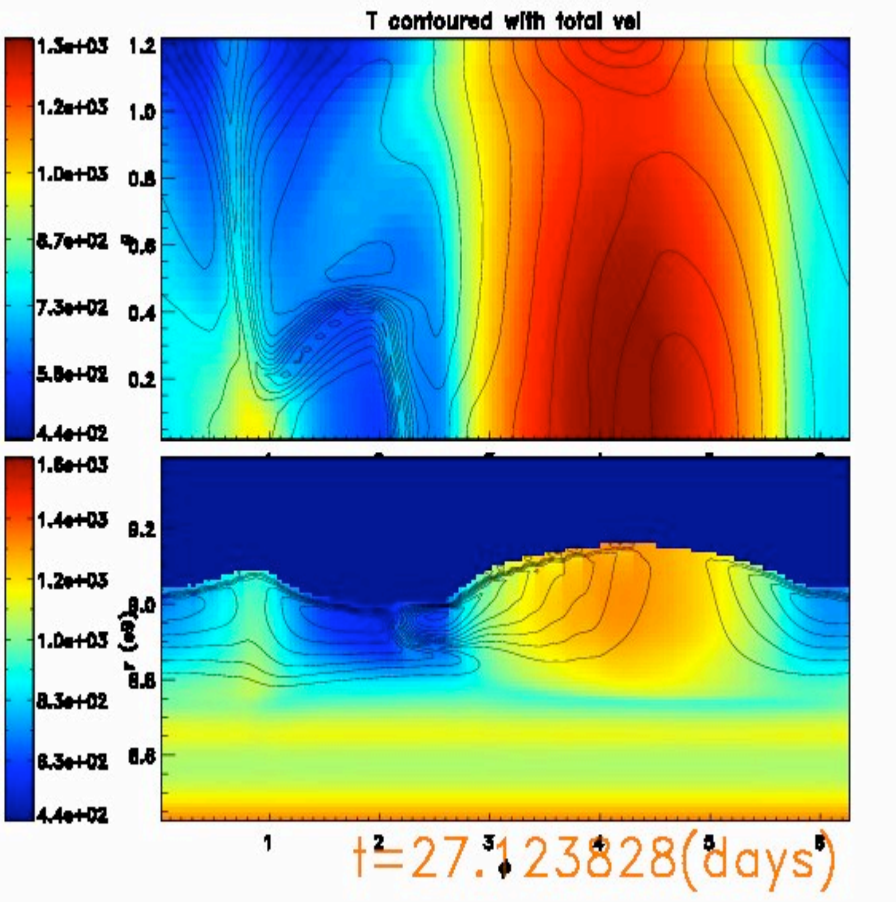
Spiegel et al (2007)

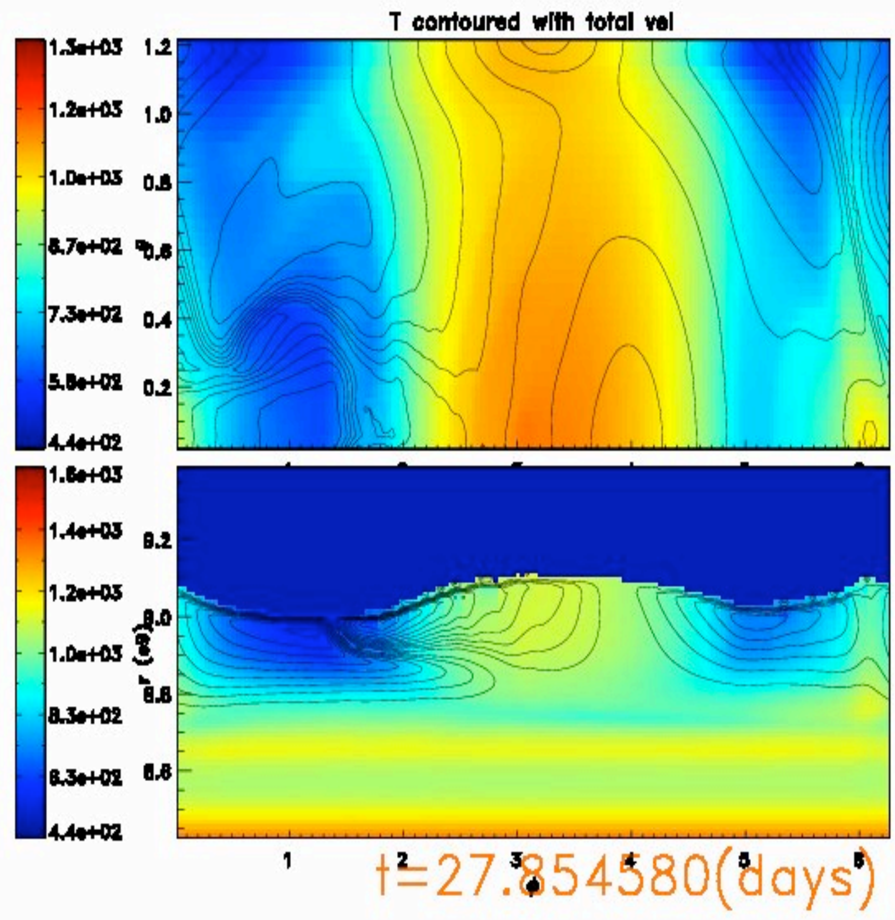
Ian Dobbs-Dixon, University of Washington,
Seattle, WA

Eccentric Planets



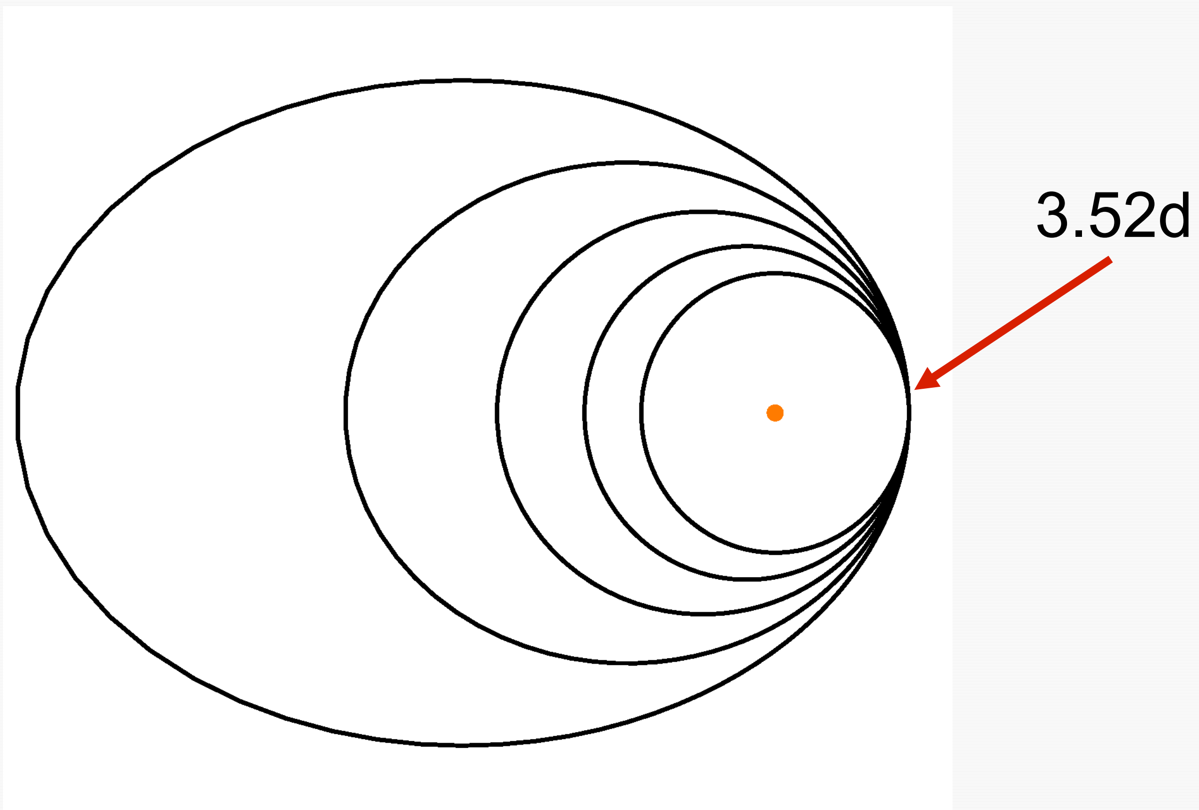
Eccentric Planets

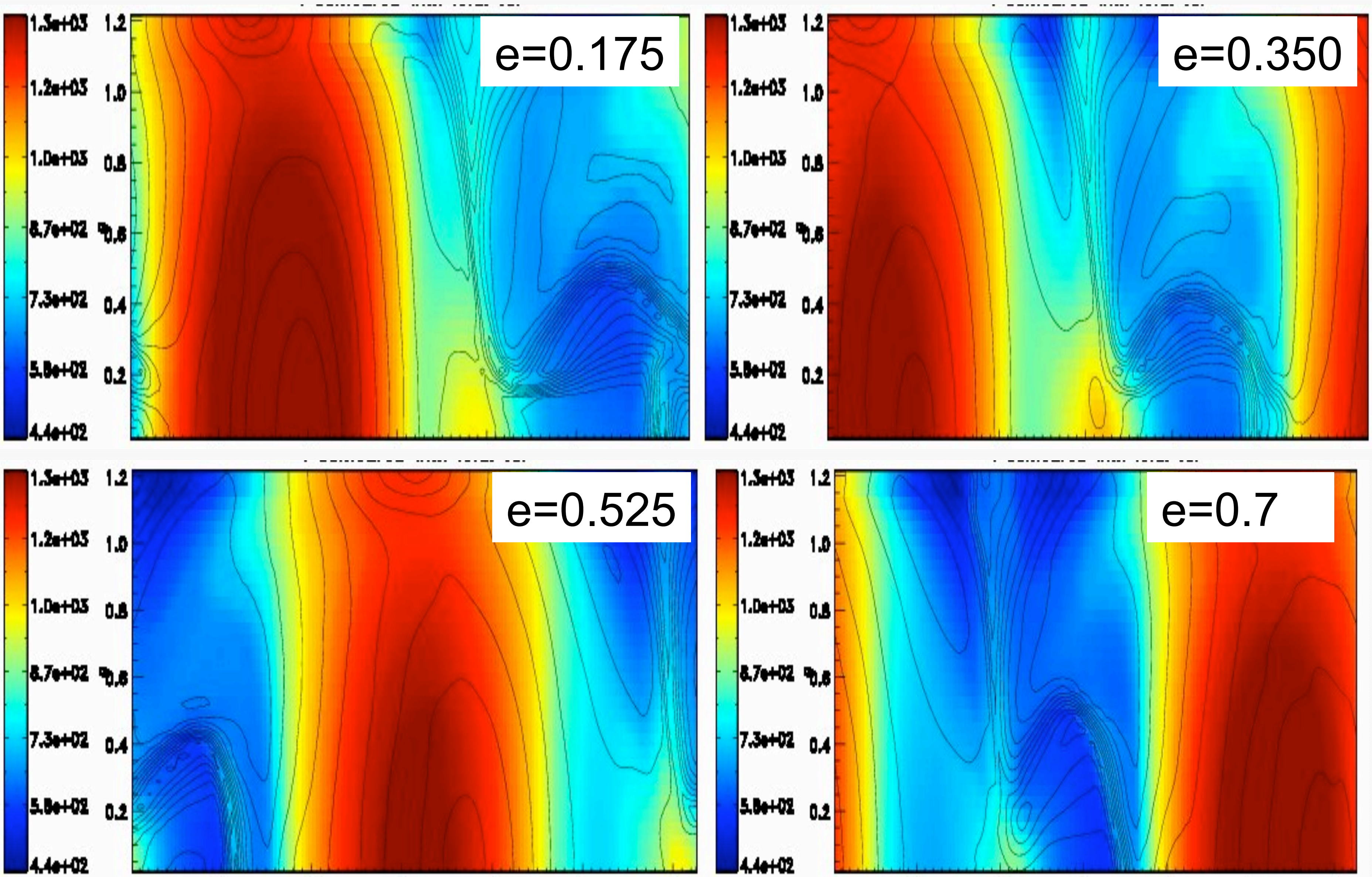




Ian Dobbs-Dixon, University of Washington,
Seattle, WA

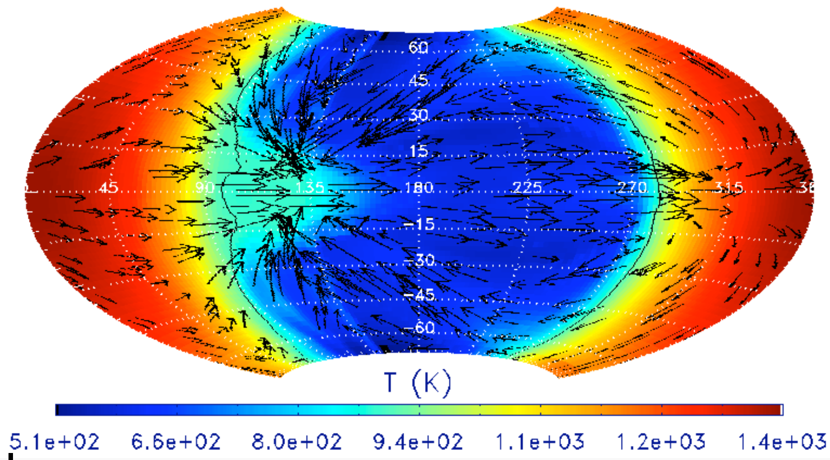
Eccentric Planets





Ian Dobbs-Dixon, University of Washington,
Seattle, WA

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

Ian Dobbs-Dixon, University of Washington,
Seattle, WA