Hydrodynamical Simulations of Strongly Irradiated Planets

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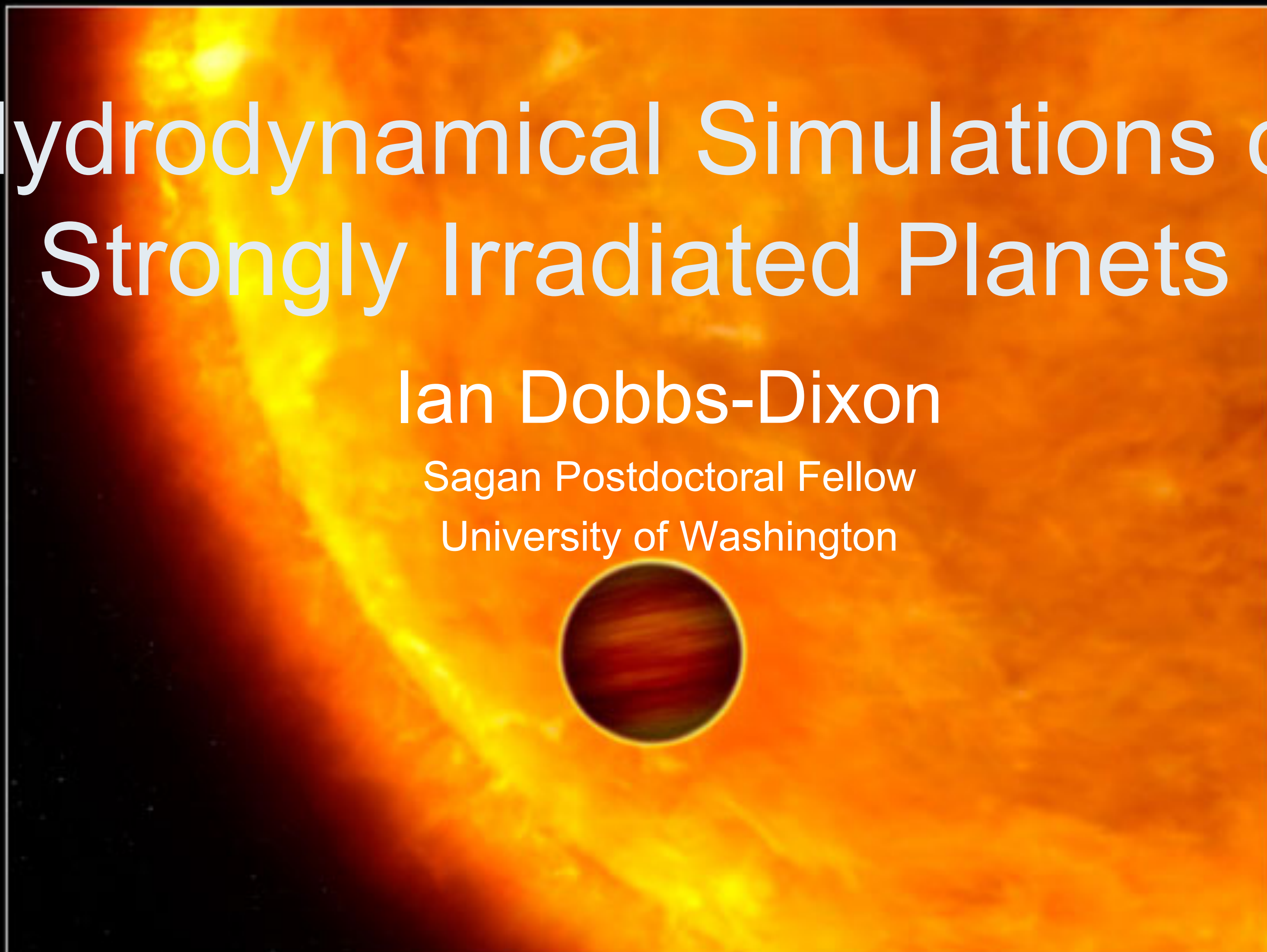


Artist's View of a Transiting Extrasolar Planet

NASA, ESA, and G. Bacon (STScI) ▪ STScI-PRC06-34b

Dynamical Methods

- 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)

Radiation Transfer Methods

- 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)

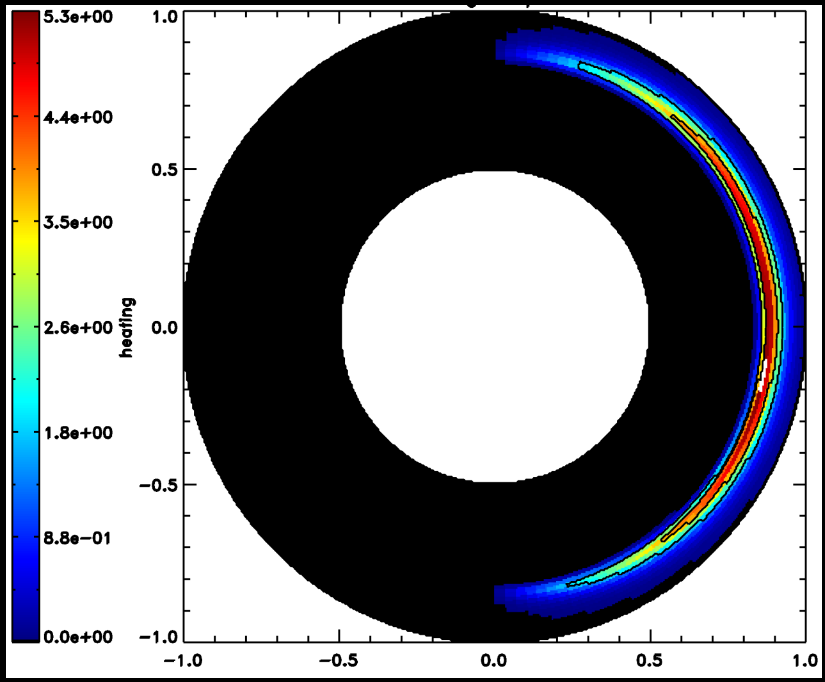
3D Navier-Stokes, flux limited diffusion and decoupled thermal and radiative components

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

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

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

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



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

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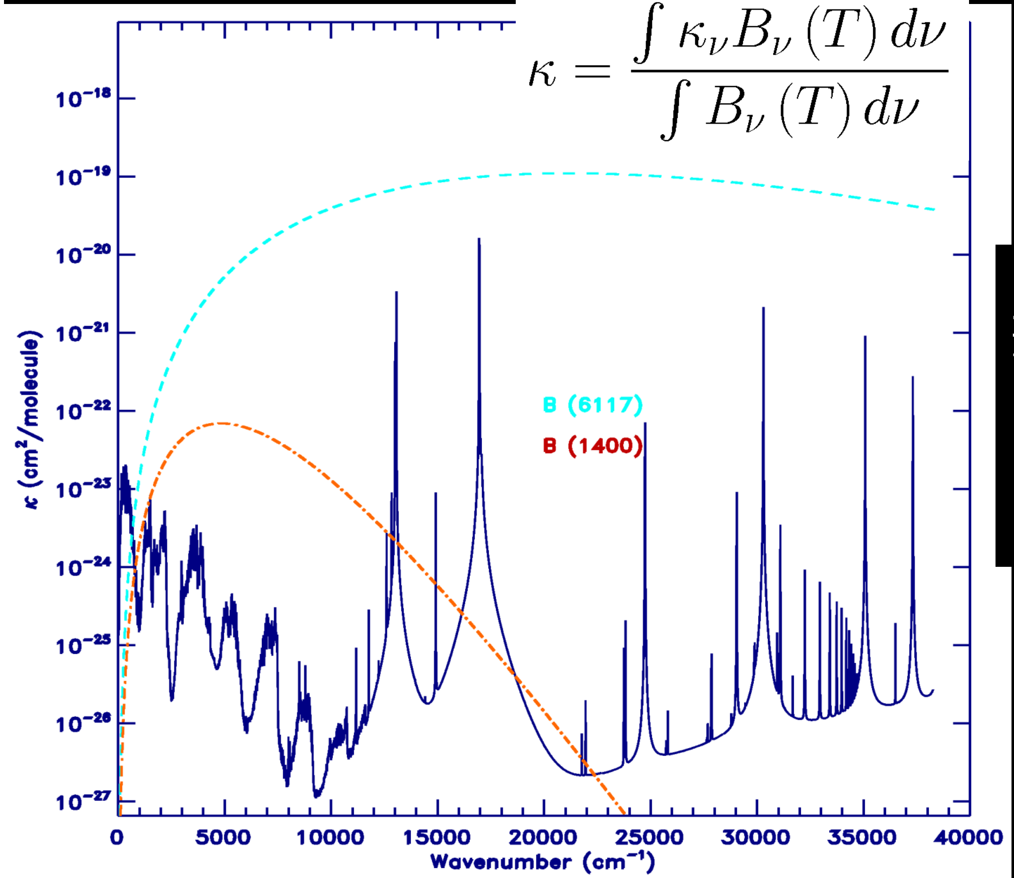
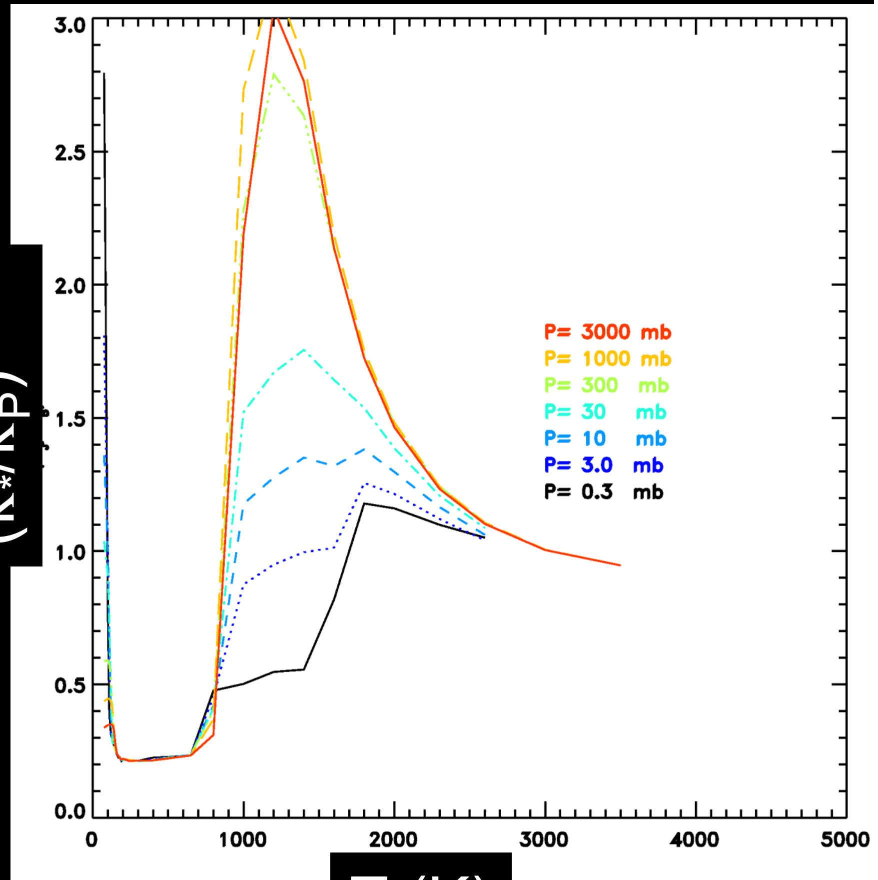
Absorption vs. Emission Opacities

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





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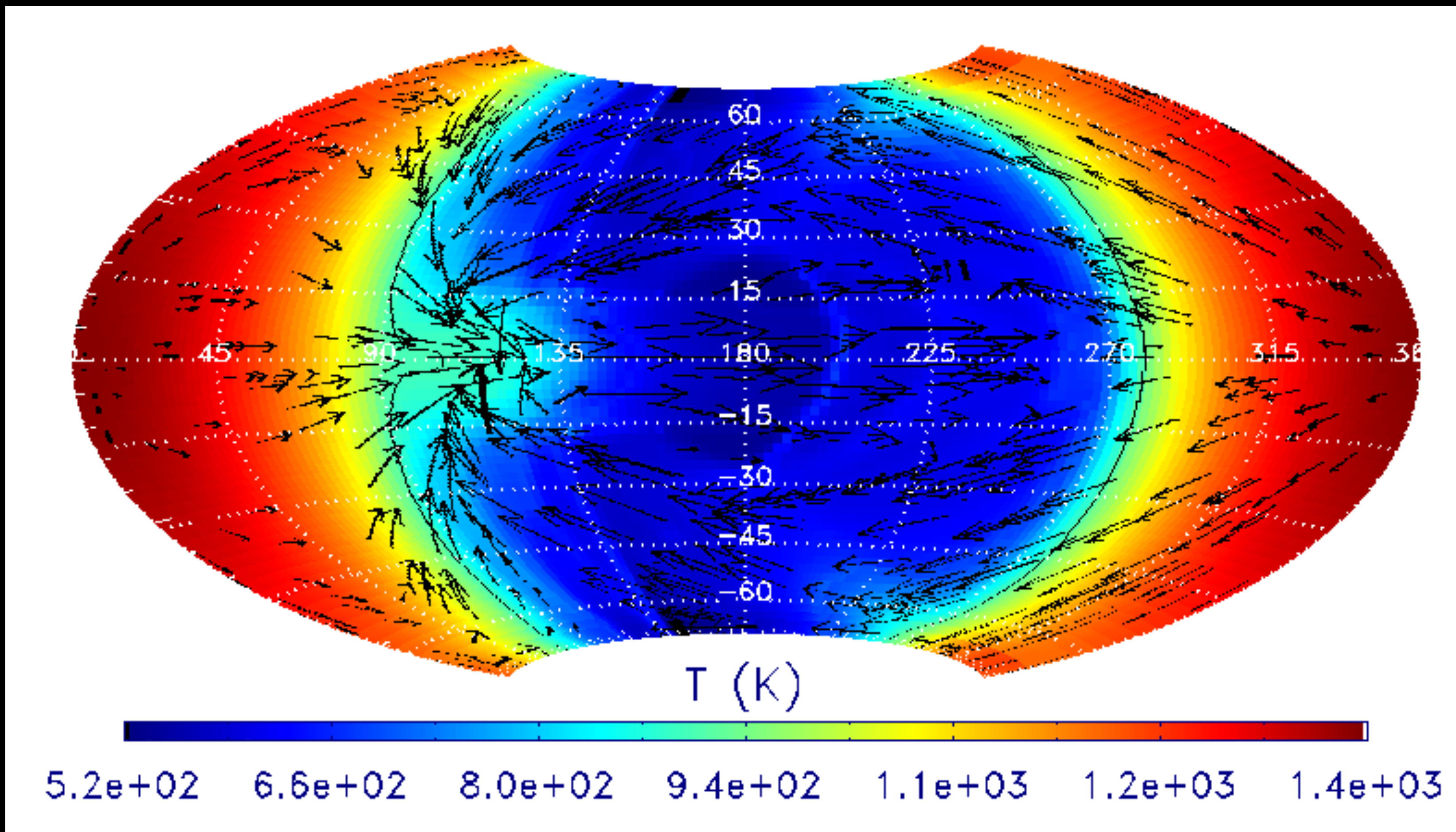
$P_{rot}=P_{orb}=3.52d,\ T_{star}=6117K$



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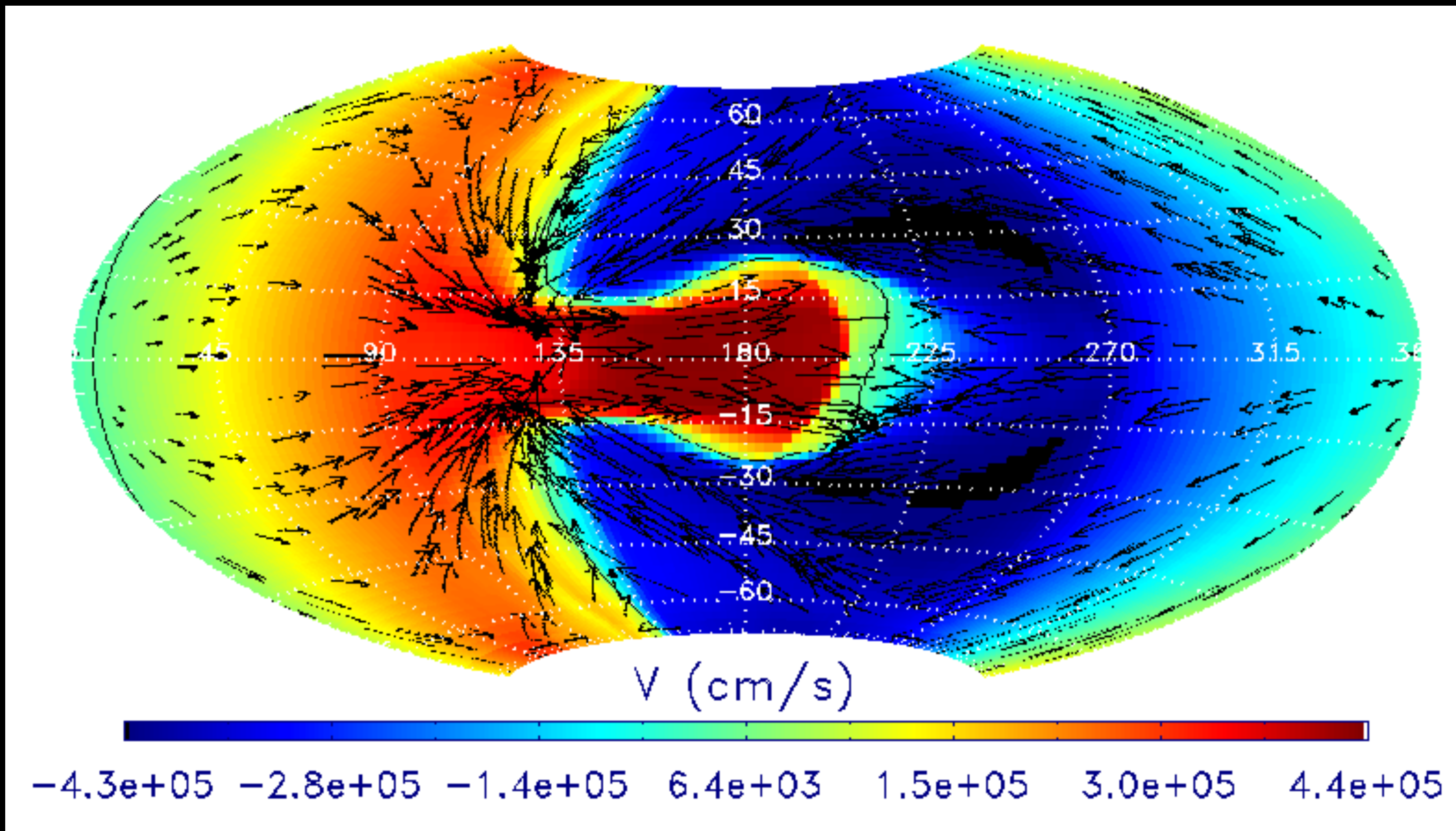
Photospheric Velocities



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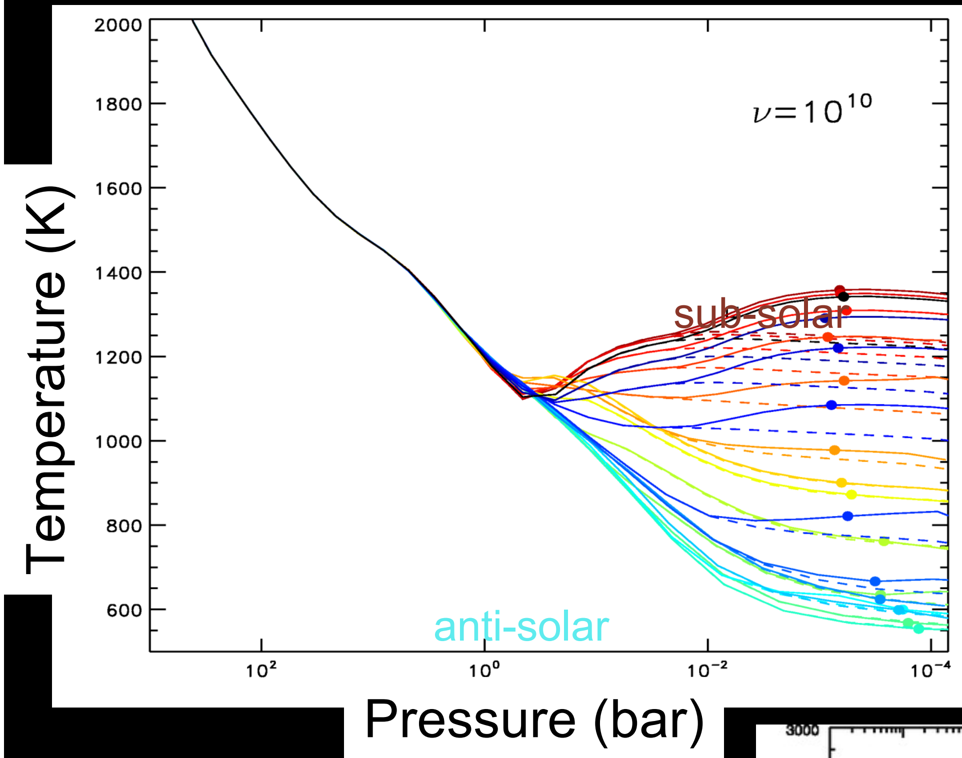
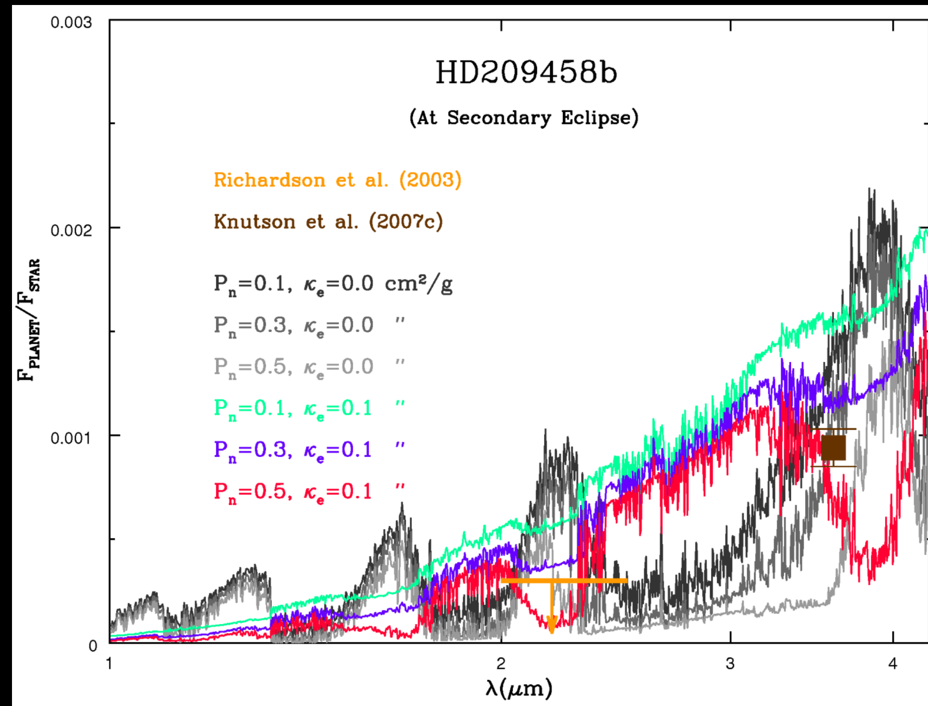
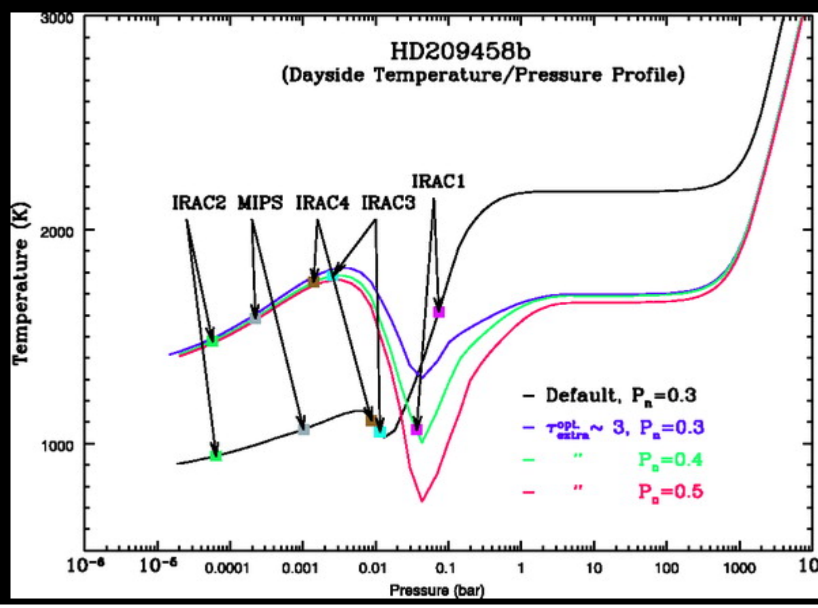
HD209458b





Burrows et al (2007)



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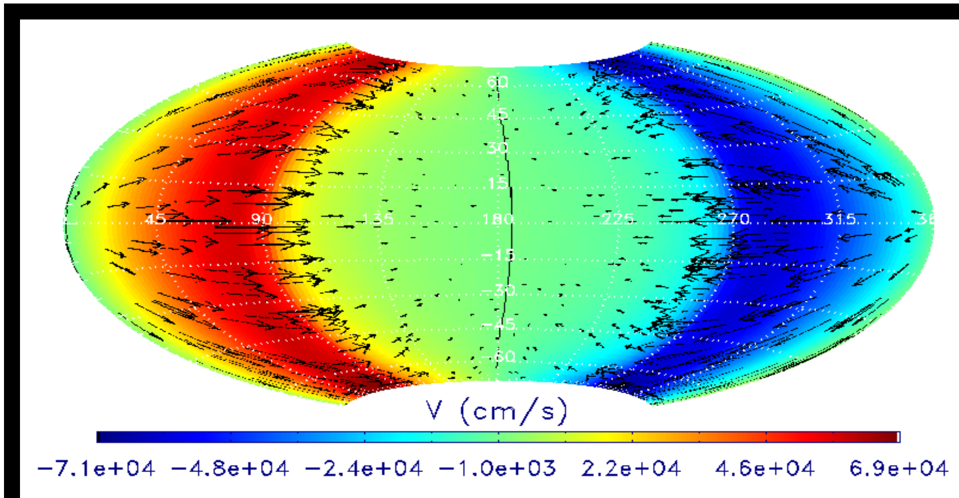
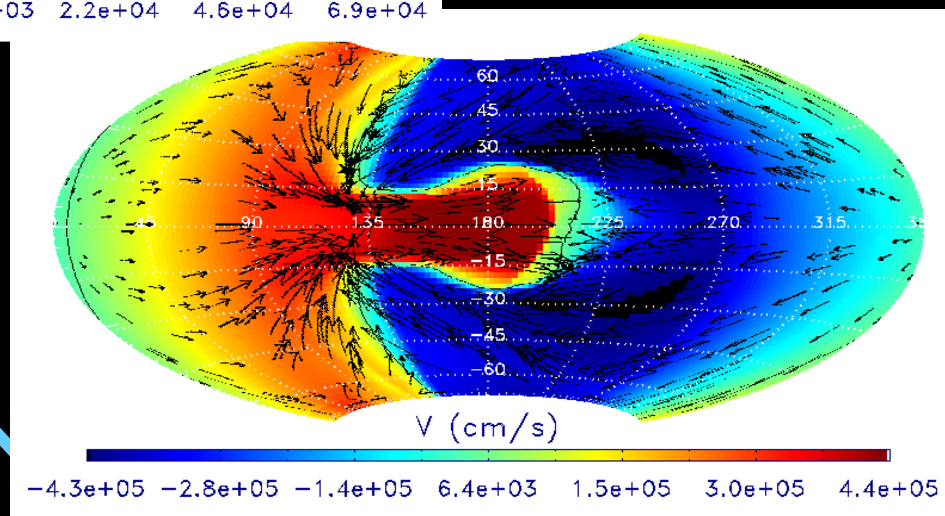
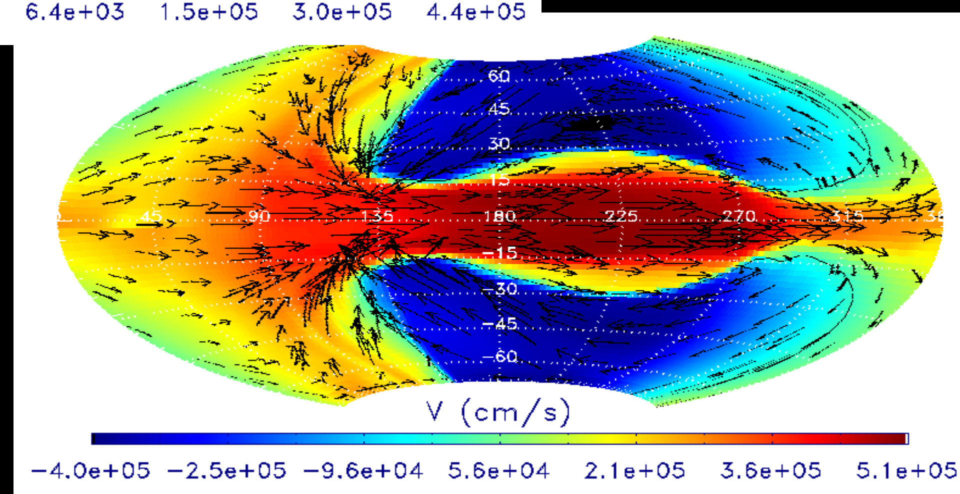
Velocity Structure







10^{12}cm^2/s

ν

10^{10}cm^2/s

10^{8}cm^2/s

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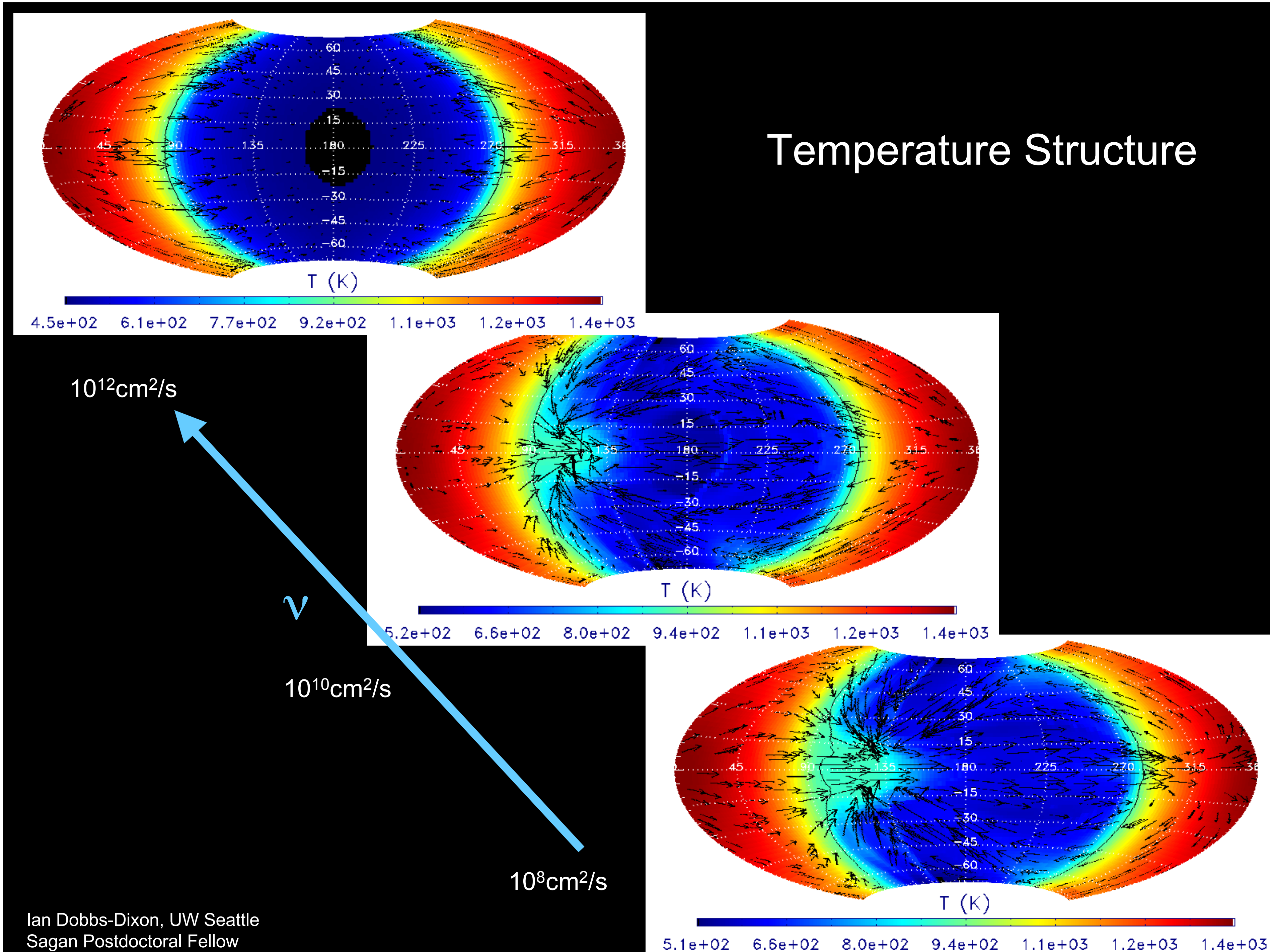
Temperature Structure



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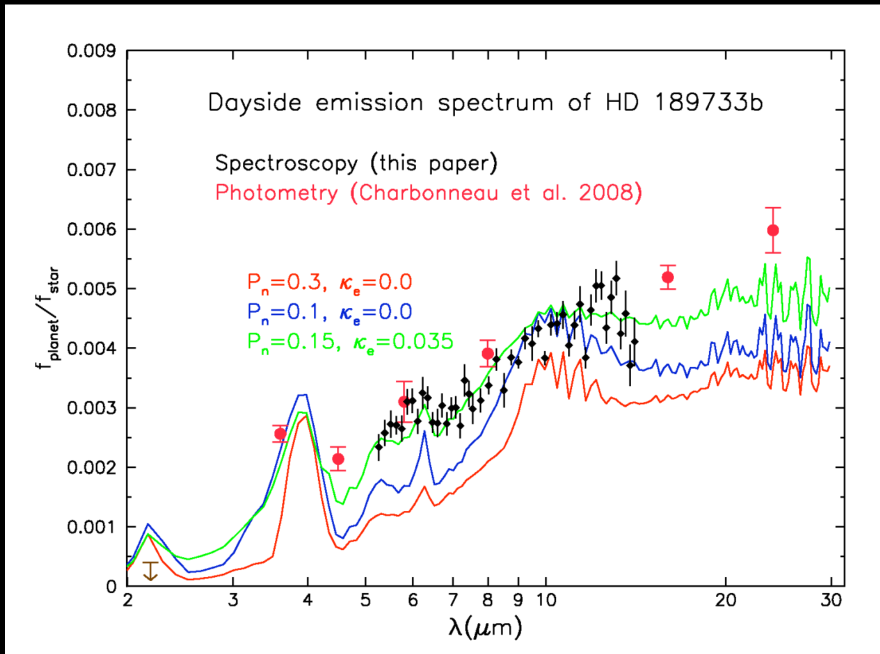
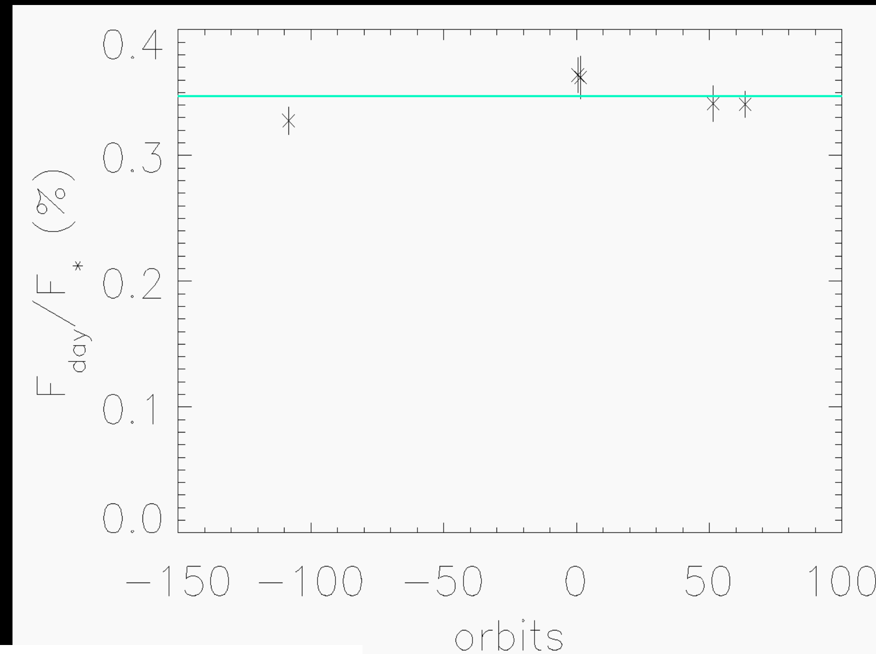
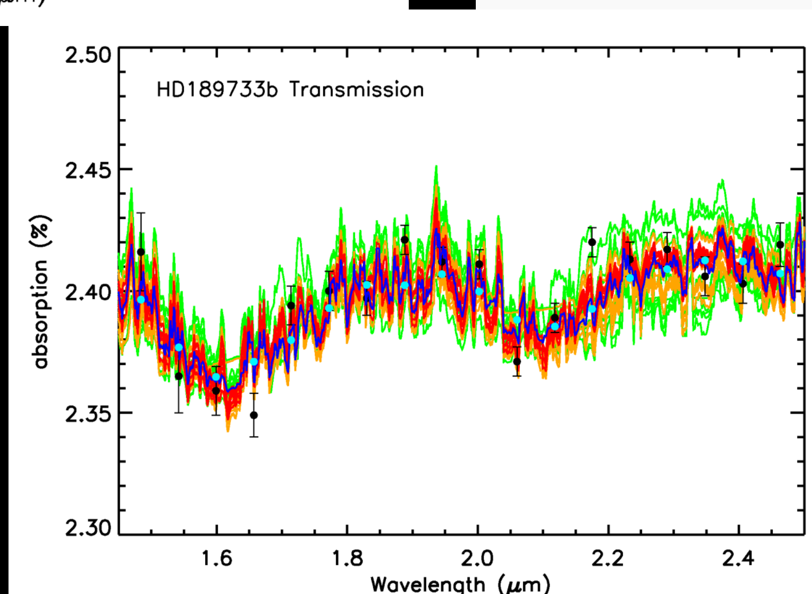
Variability



Grillmair et al 2009



Agol et al 2008



Madhusudhan and Seager 2009

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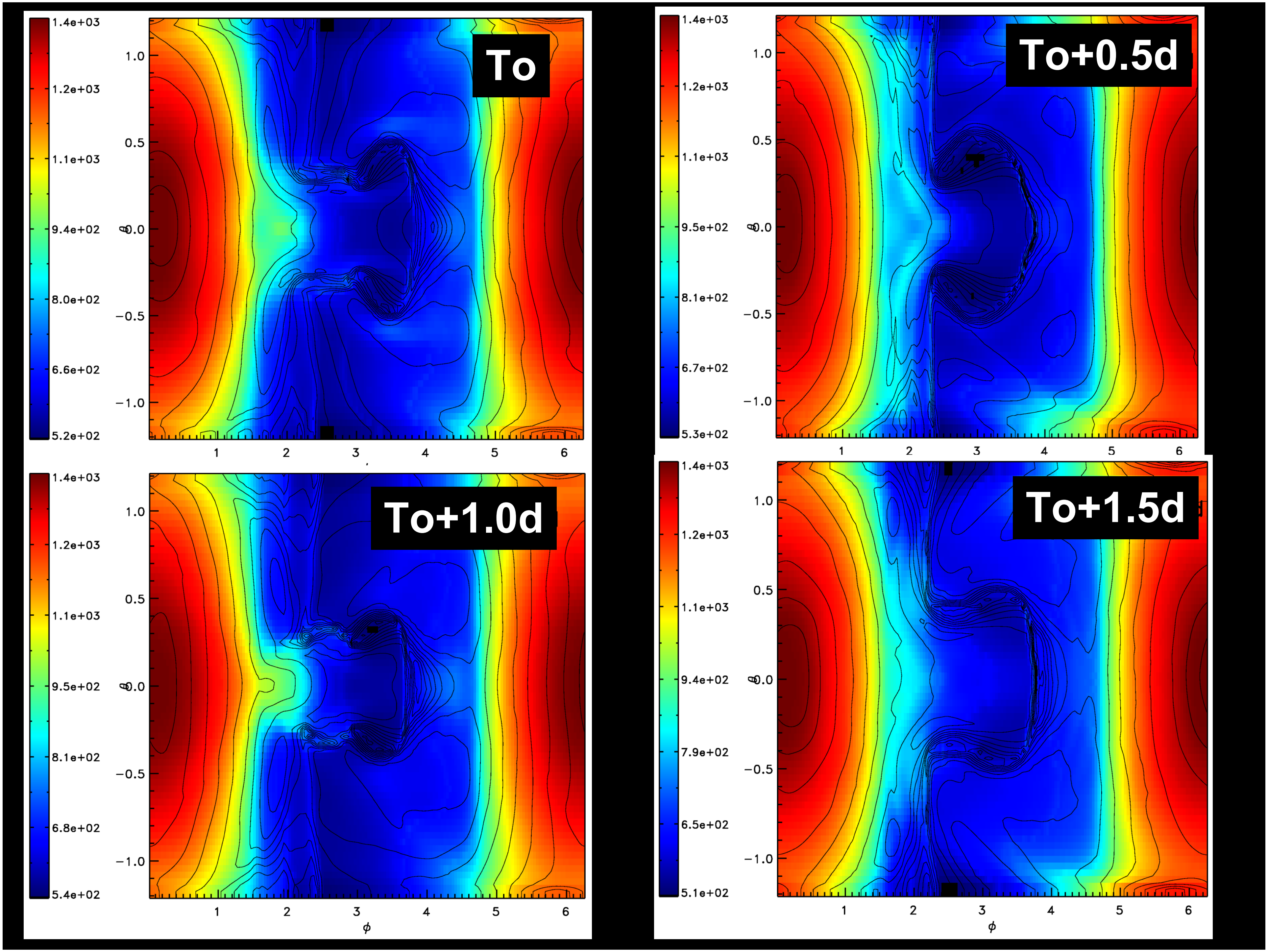
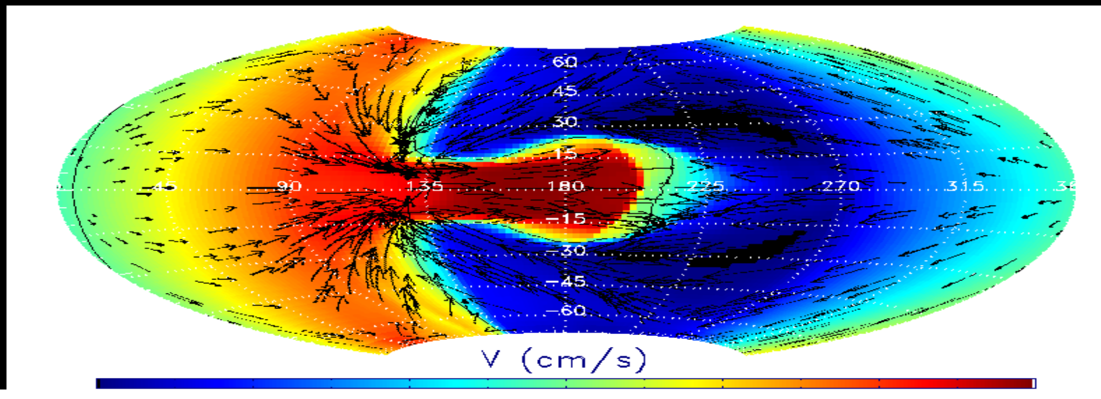
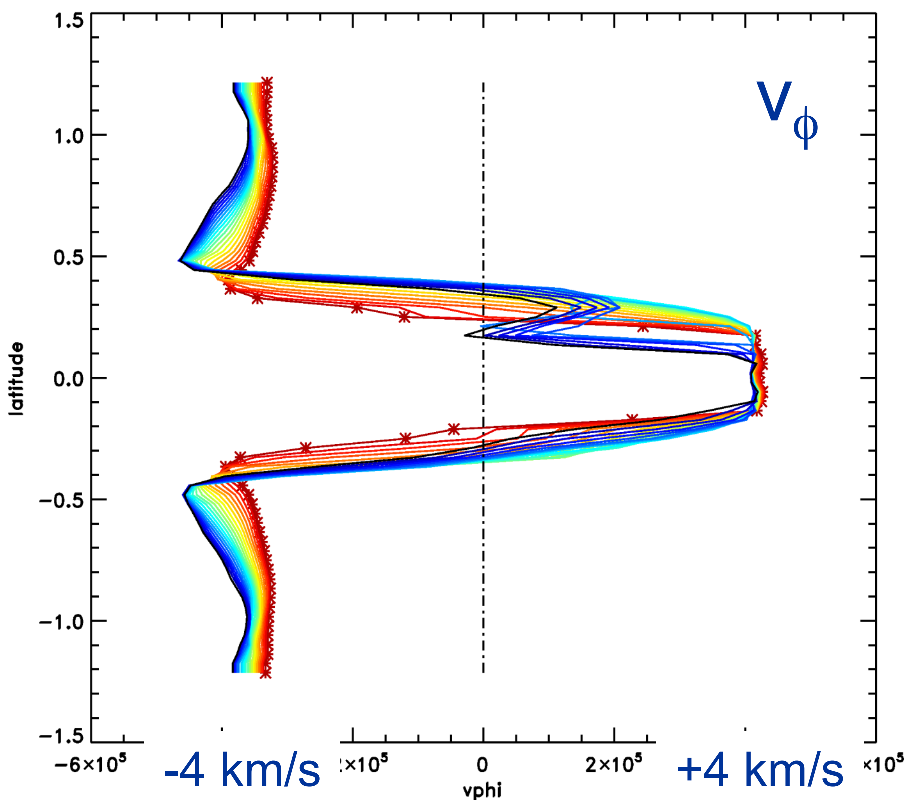
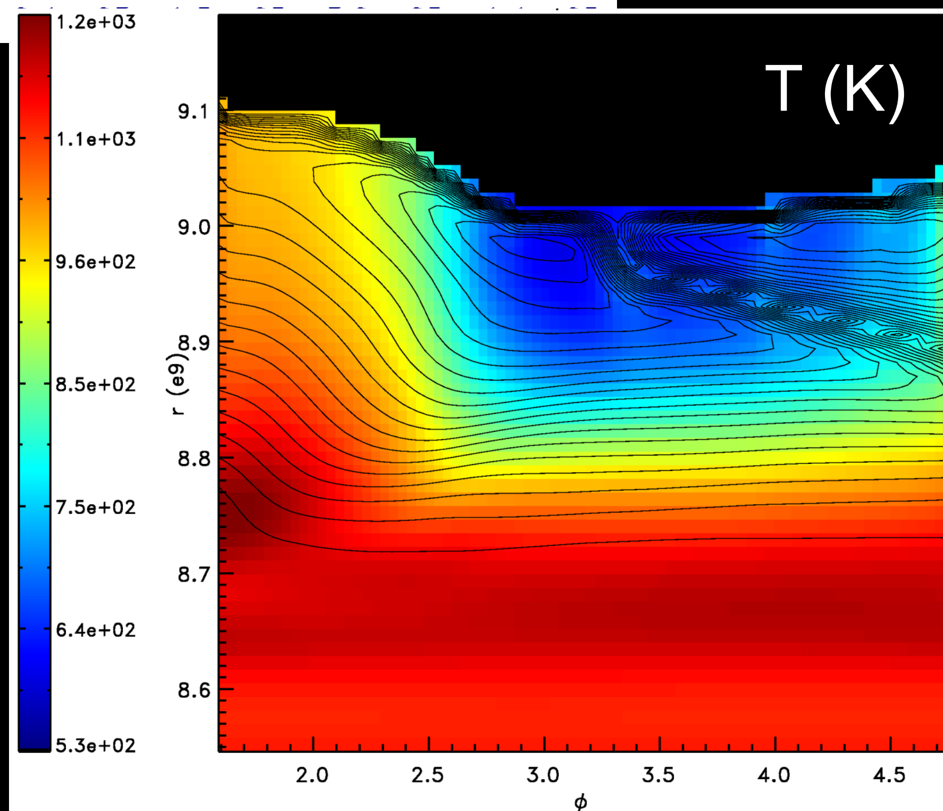

To
To+0.5d
To+1.0d
To+1.5d
1.4e+03
1.2e+03
1.1e+03
9.4e+02
8.0e+02
6.6e+02
5.2e+02
1.4e+03
1.2e+03
1.1e+03
9.5e+02
8.1e+02
6.7e+02
5.3e+02
1.4e+03
1.2e+03
1.1e+03
9.5e+02
8.1e+02
6.8e+02
5.4e+02
1.4e+03
1.2e+03
1.1e+03
9.4e+02
7.9e+02
6.5e+02
5.1e+02
1.0
0.5
0.0
−0.5
−1.0
1
2
3
4
5
6
ϕ

Surface and radial shear







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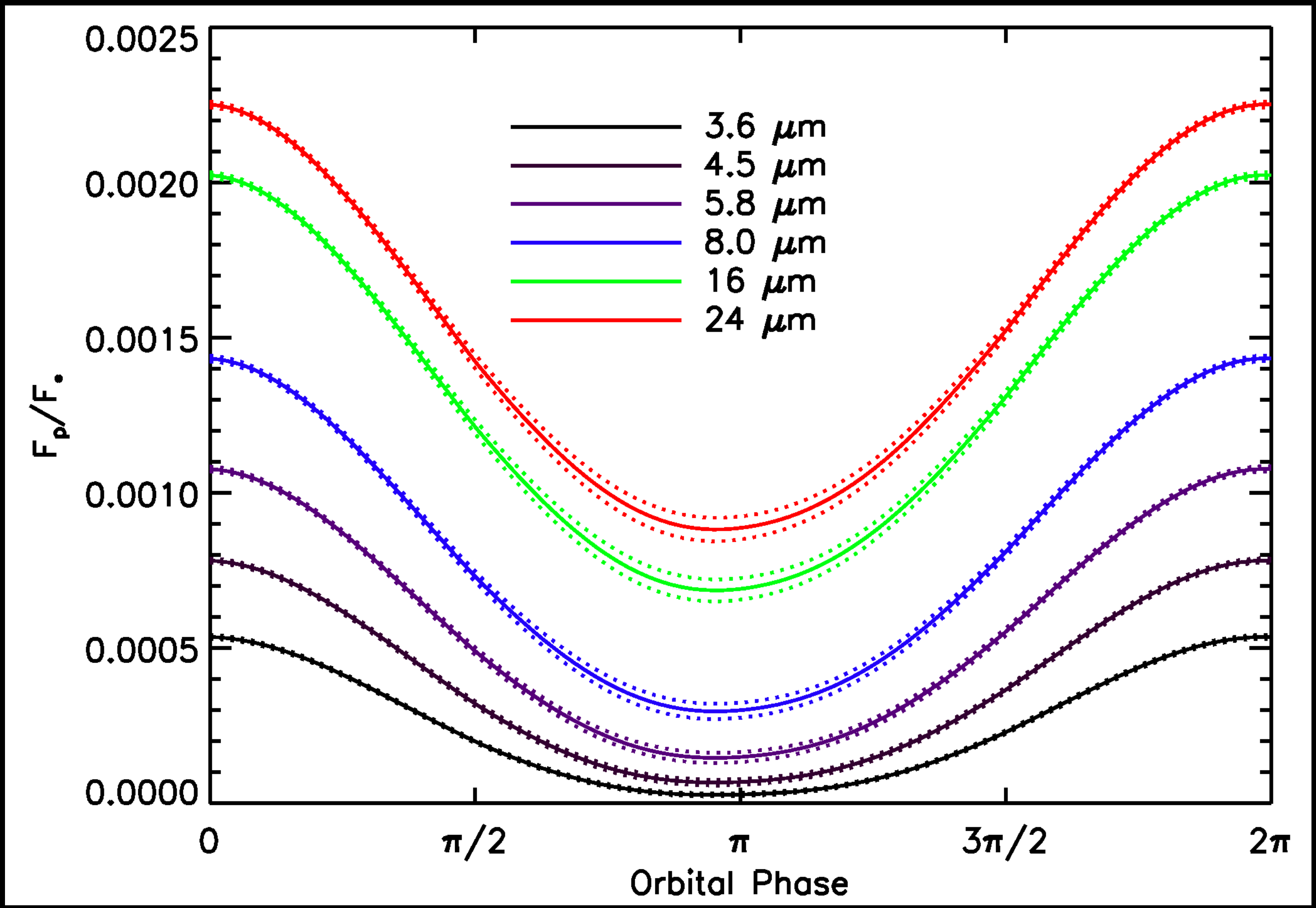
Hemispherically averaged phase curves (approximate)



Nick Cowan

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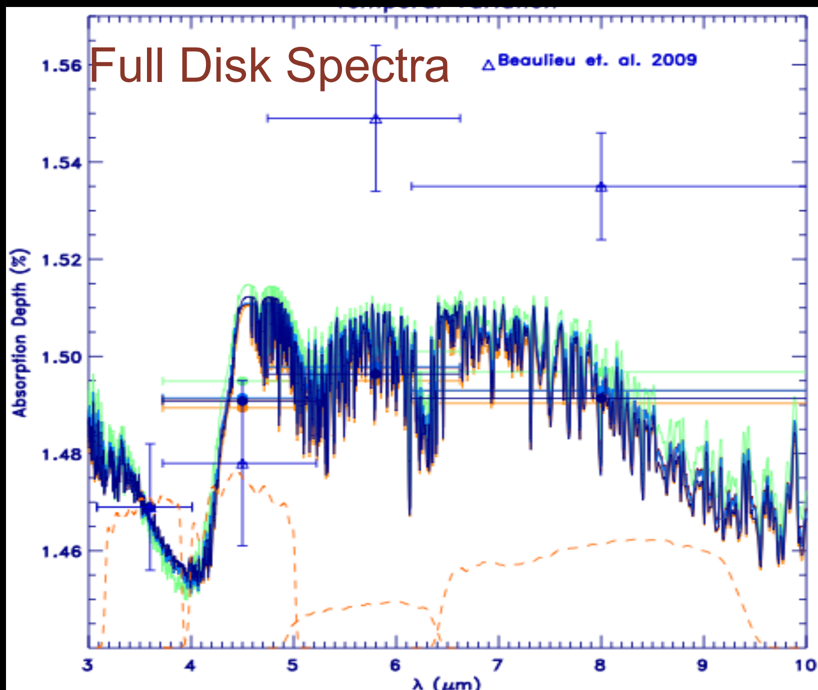
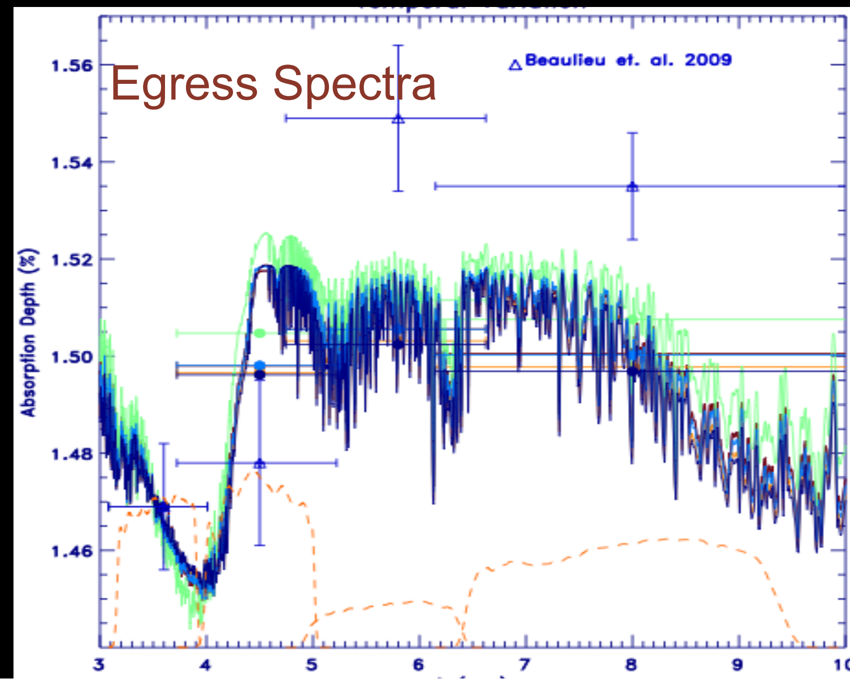
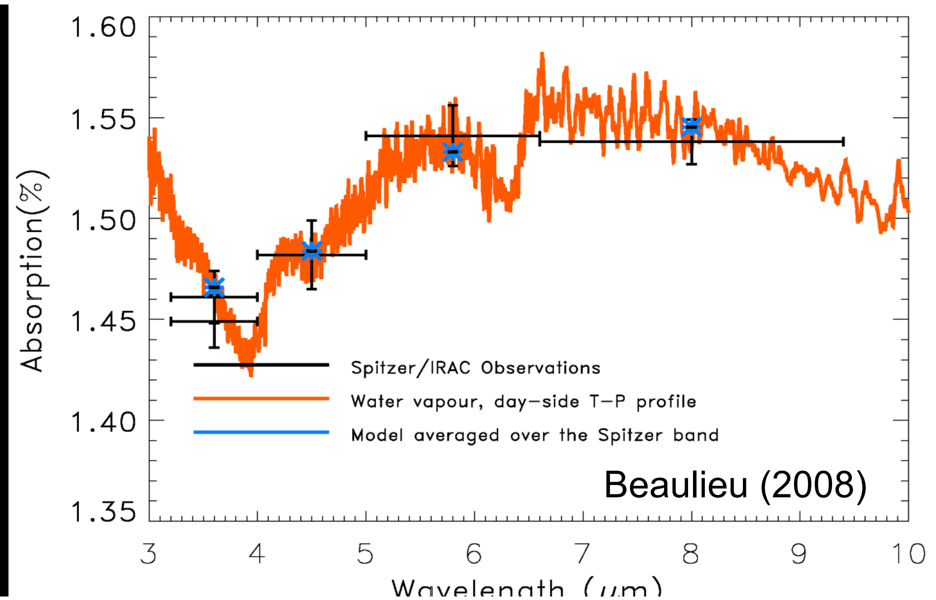
Transmission Spectra





Opacities from
Sharp and Burrows (2007)



H_20 opacities from
Barber *et al* (2006)

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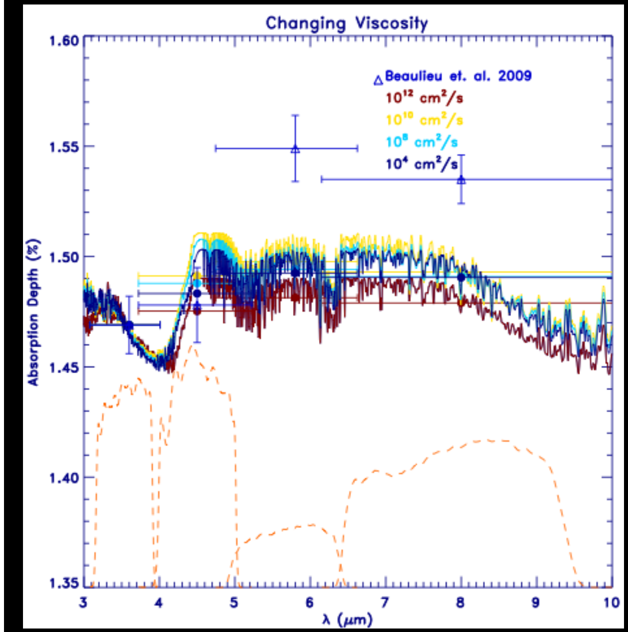
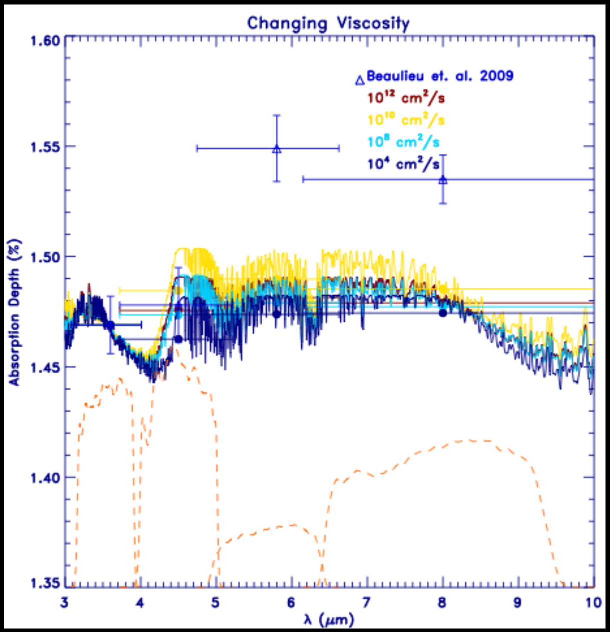
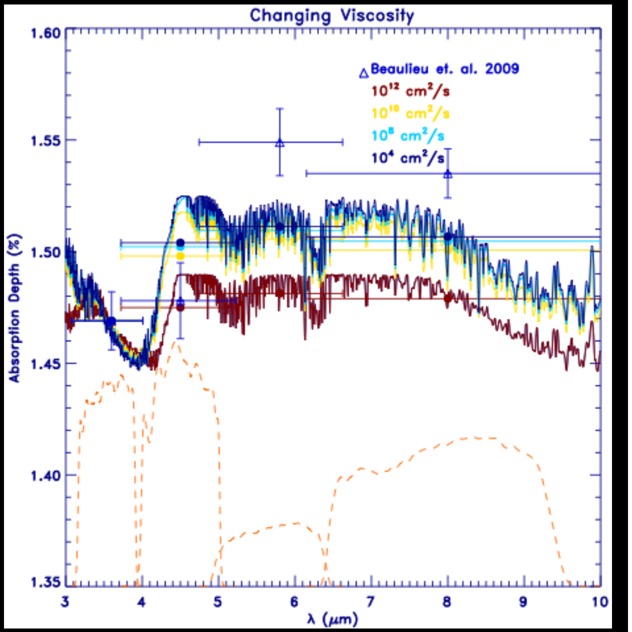
Viscous Variations



V5, whole disk



V5 western



V5 eastern

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Conclusions

- Numerical treatment of radiation and dynamics must be included as coupled model
- Opacity and dynamical temperature inversions play roles in dynamics and spectra
- Three quasi-jets (one equatorial and two mid-lat.) are common features, with width decreasing with increased planetary rotation period
- Optical and IR opacities both are important in determining location of stellar energy deposition and efficiency of redistribution to the night-side
- 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