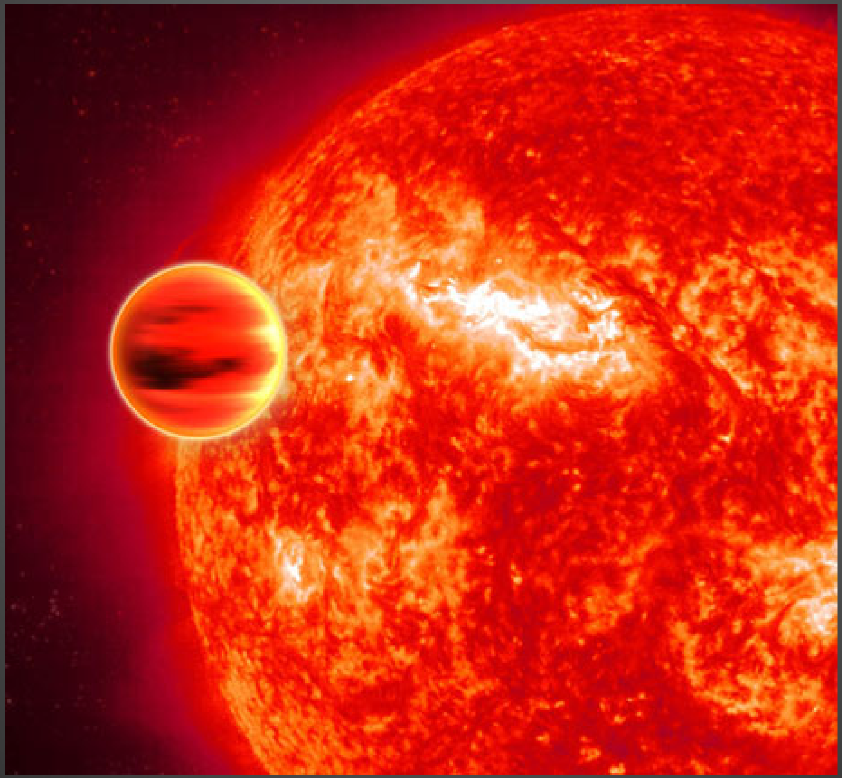
Non-Hydrostatic Dynamical Models of Giant Planet Atmospheres



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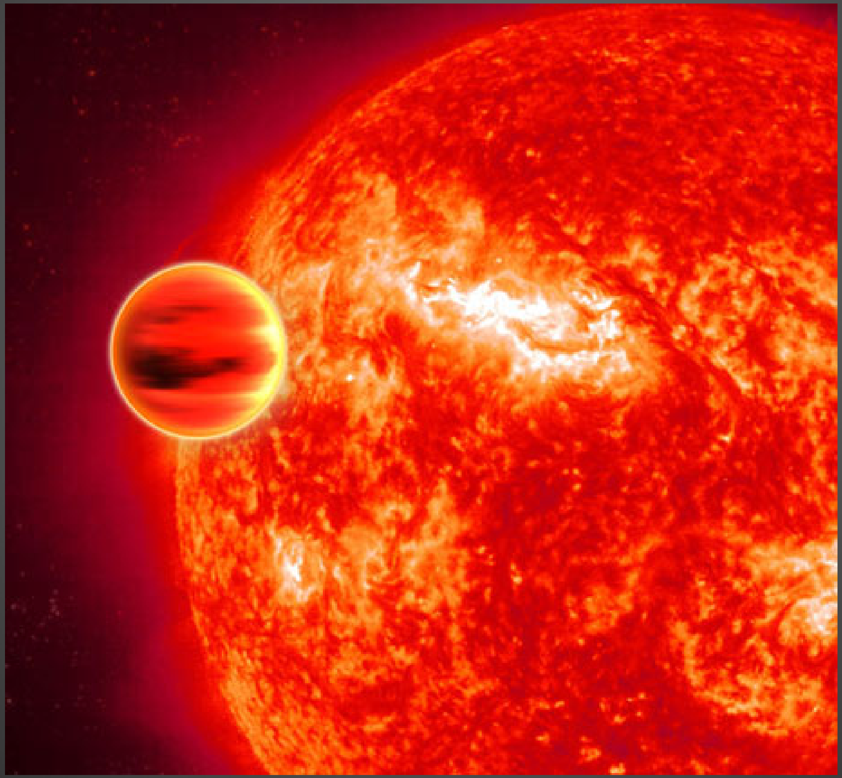
Outline

- Dynamical/Radiative Modeling Methodologies
- General Properties/Thermal Inversions (x2)
- Variations of Viscosity
- Changing Jets
- Shocks/ Potential Vorticity Generation
- Weather
- Observable Consequences
- Eccentric Planets

Dynamical Modeling Methodologies



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Dynamical Methods

Completeness

- Equivalent Barotropic and Shallow Water (2D)
  - Cho et al (2003,2008) Langton and Laughlin (2007,2008) Rauscher et al (2007, 2008)
- Navier-Stokes equation (2D)
  - Burkert et al. 2007
- Primitive equations (~3D)
  - Showman et al. (2002, 2005, 2006, 2008, 2009), Menou and Rauscher (2009)
- Eulers equations (3D)
  - Dobbs-Dixon and Lin (2008)
- Navier-Stokes equations (3D)
  - Dobbs-Dixon et al (2010)

Resolution

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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)

East-West

$$\rho\frac{\partial u}{\partial t}+u\frac{\partial \rho}{\partial t}=-\frac{1}{r\cos\phi}\frac{\partial p}{\partial\lambda}+\rho\left(2\Omega+\frac{u}{r\cos\phi}\right)(\sin\phi)v-\rho\left(2\Omega\cos\phi+\frac{u}{r}\right)w$$
$$-\left[\frac{1}{r\cos\phi}\frac{\partial}{\partial\lambda}(\rho u^2)+\frac{1}{r\cos\phi}\frac{\partial}{\partial\phi}(\rho uv\cos\phi)+\frac{1}{r^2}\frac{\partial}{\partial r}(\rho uwr^2)\right]+\rho F_\lambda,$$

North-South

$$\rho\frac{\partial v}{\partial t}+v\frac{\partial \rho}{\partial t}=-\frac{1}{r}\frac{\partial p}{\partial\phi}-\rho\left(2\Omega+\frac{u}{r\cos\phi}\right)(\sin\phi)u-\rho\frac{vw}{r}$$
$$-\left[\frac{1}{r\cos\phi}\frac{\partial}{\partial\lambda}(\rho uv)+\frac{1}{r\cos\phi}\frac{\partial}{\partial\phi}(\rho v^2\cos\phi)+\frac{1}{r^2}\frac{\partial}{\partial r}(\rho r^2 vw)\right]+\rho F_\phi,$$

Radial

$$\rho\frac{\partial w}{\partial t}+w\frac{\partial \rho}{\partial t}=-\frac{\partial p}{\partial r}-\rho g+\rho\left(2\Omega\cos\phi+\frac{u}{r}\right)u+\rho\frac{v^2}{r}$$
$$-\left[\frac{1}{r\cos\phi}\frac{\partial}{\partial\lambda}(\rho uw)+\frac{1}{r\cos\phi}\frac{\partial}{\partial\phi}(\rho vw\cos\phi)+\frac{1}{r^2}\frac{\partial}{\partial r}(\rho r^2 w^2)\right]+\rho F_r.$$

Gilman and Glatzmaier 1981

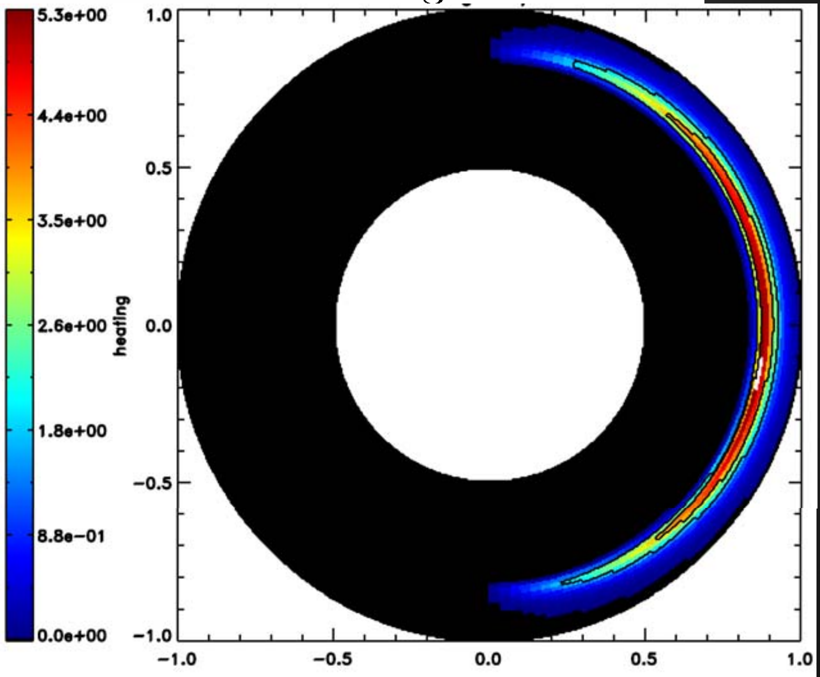
3D Navier-Stokes, flux limited diffusion and decoupled thermal and radiative components

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

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

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

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



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

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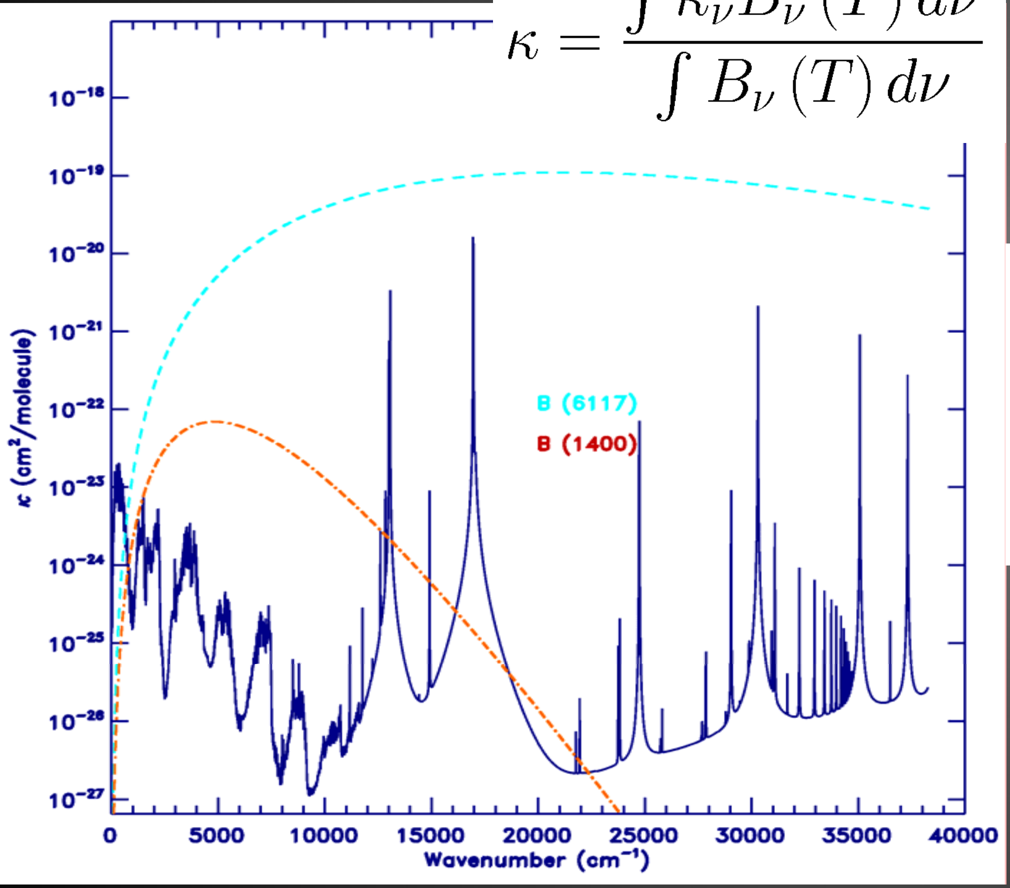
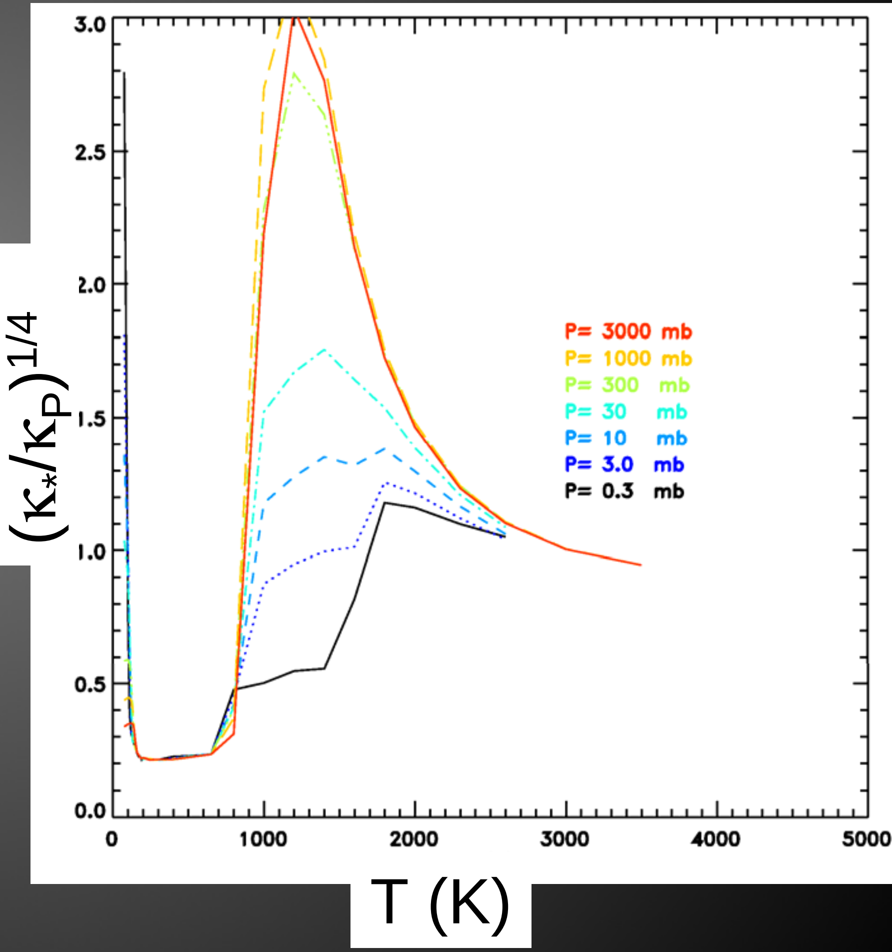
Absorption vs. Emission Opacities

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





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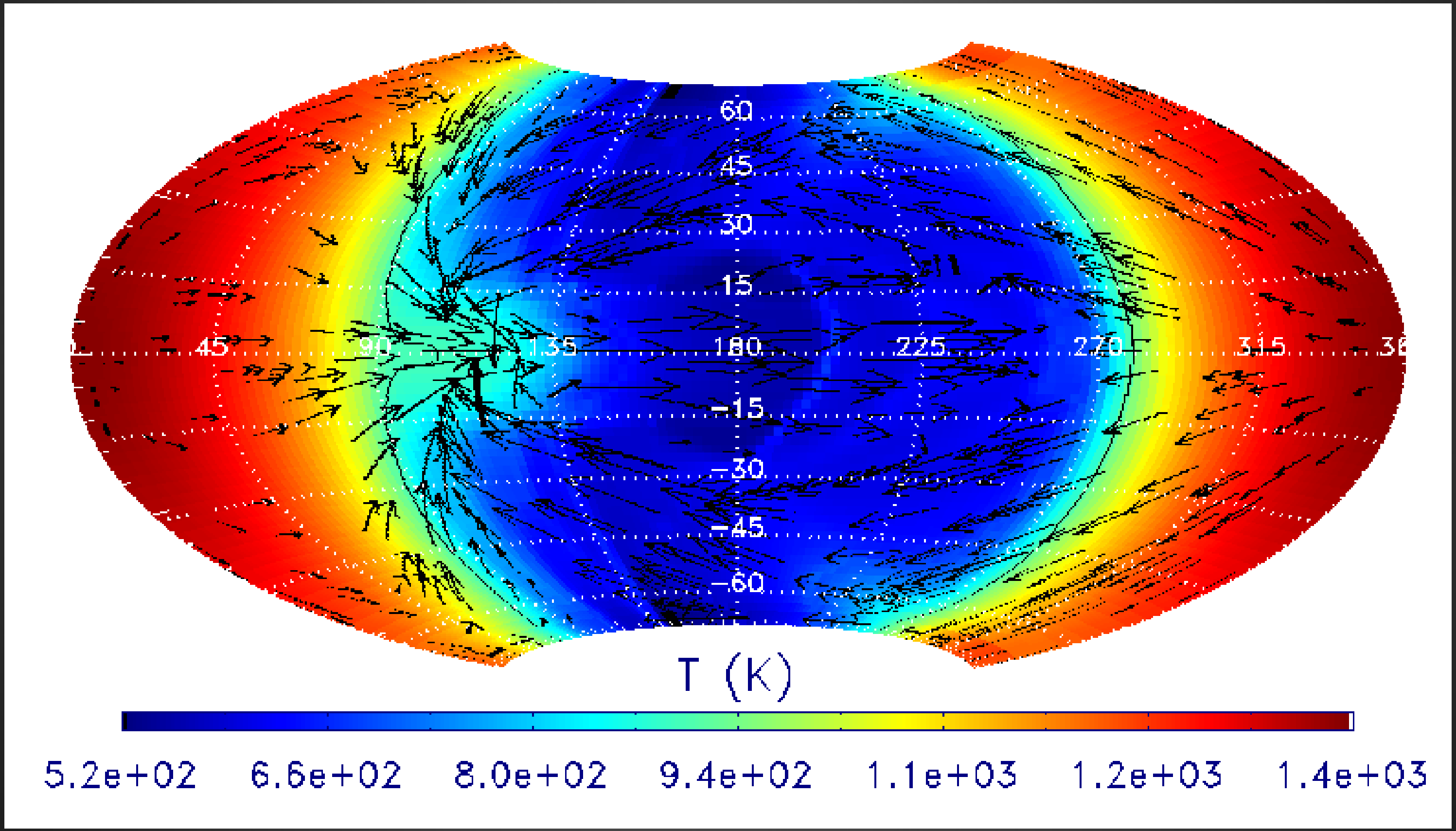
$P_{rot}=P_{orb}=3.52d$, $T_{\star}=6117K$
$M_p=0.69M_J$, $R_p = 1.3R_J$



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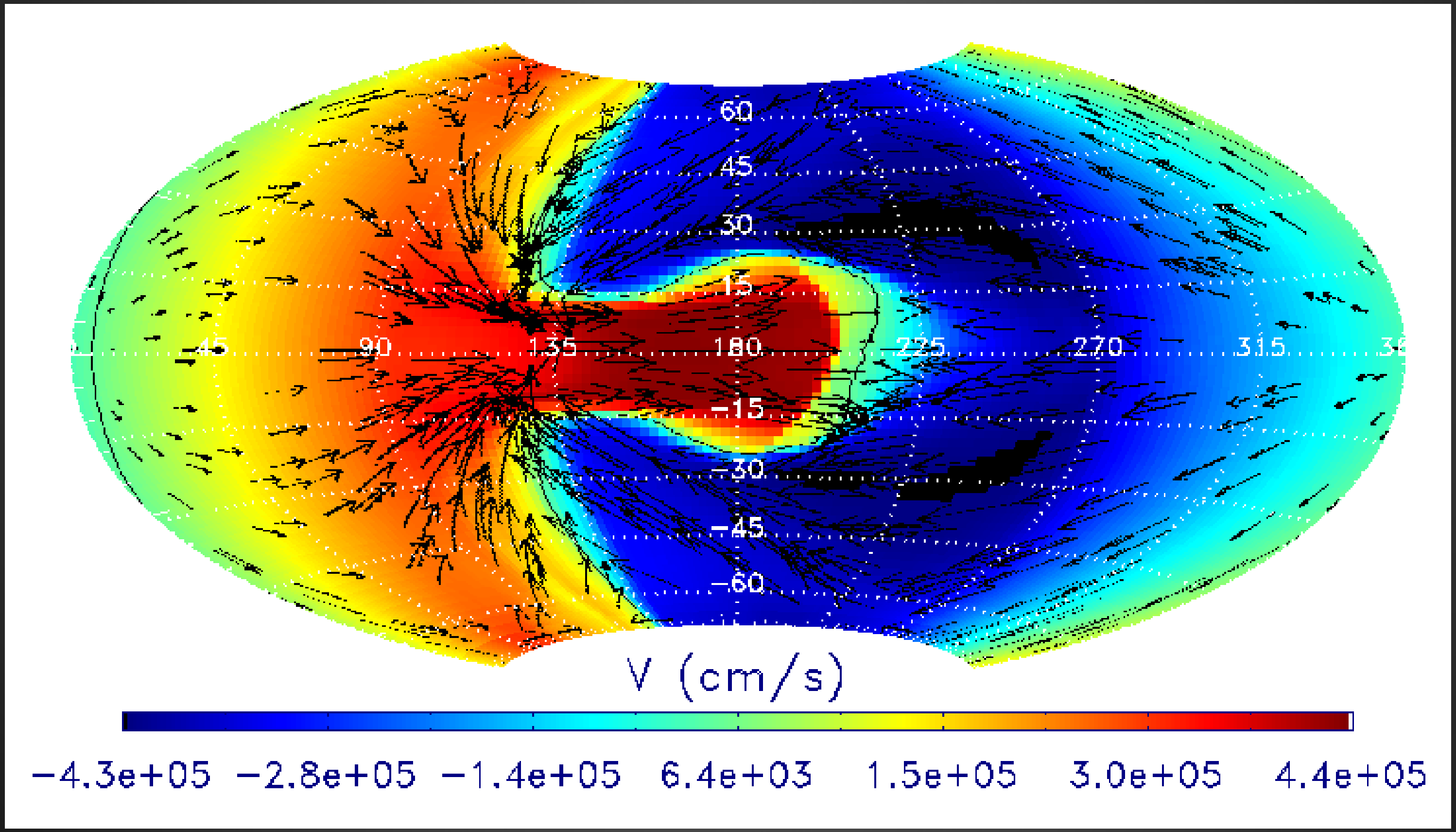
Photospheric Velocities



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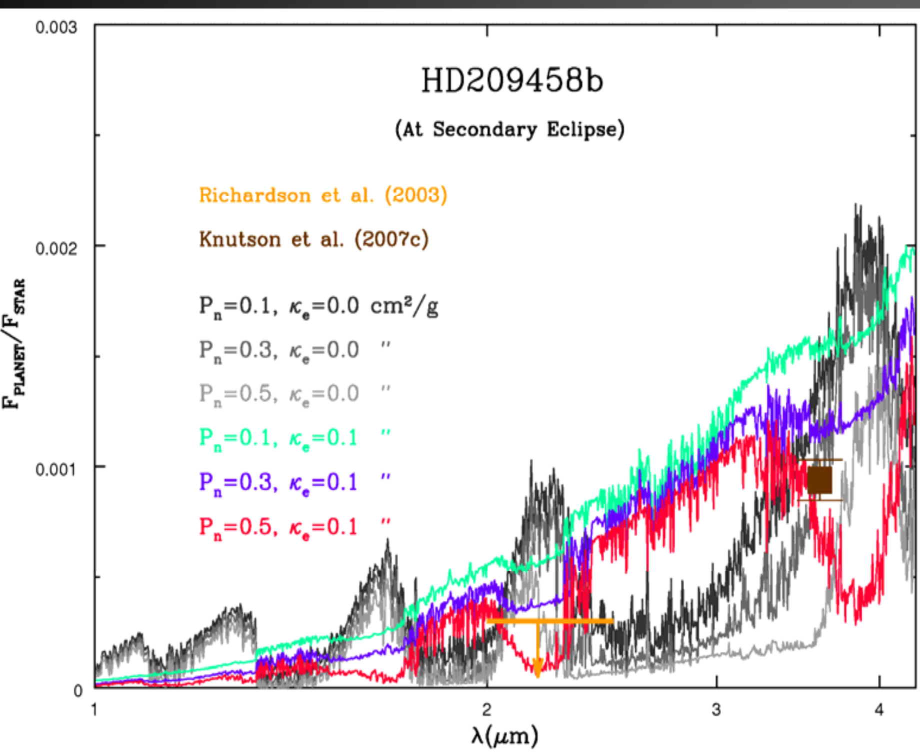
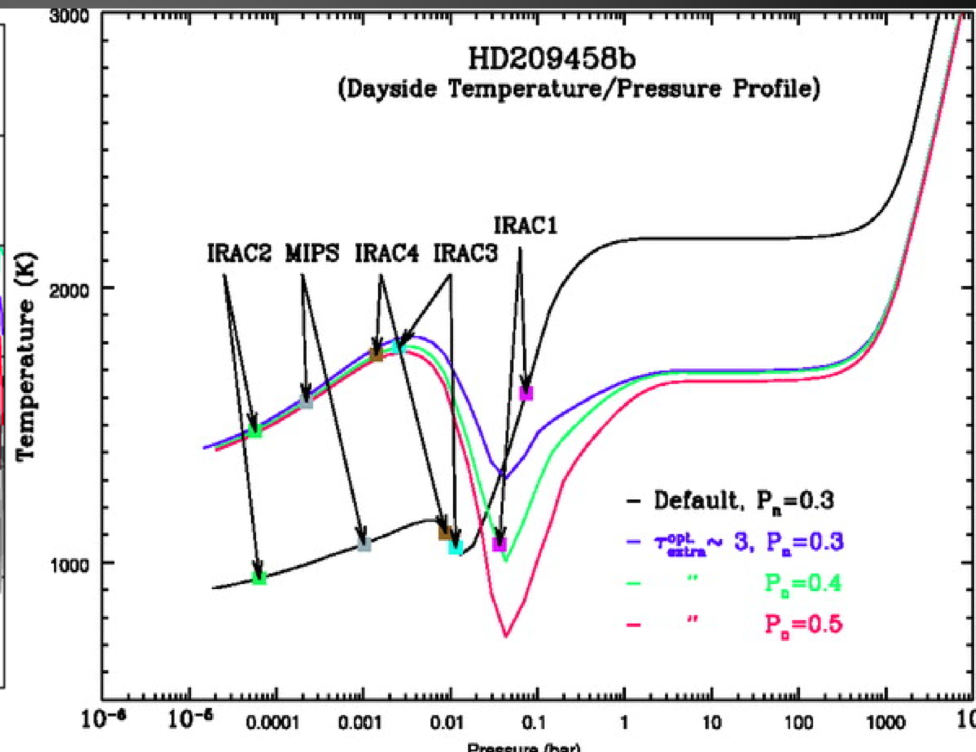
Observed Inversion (HD 209458b)





Burrows et al (2007)

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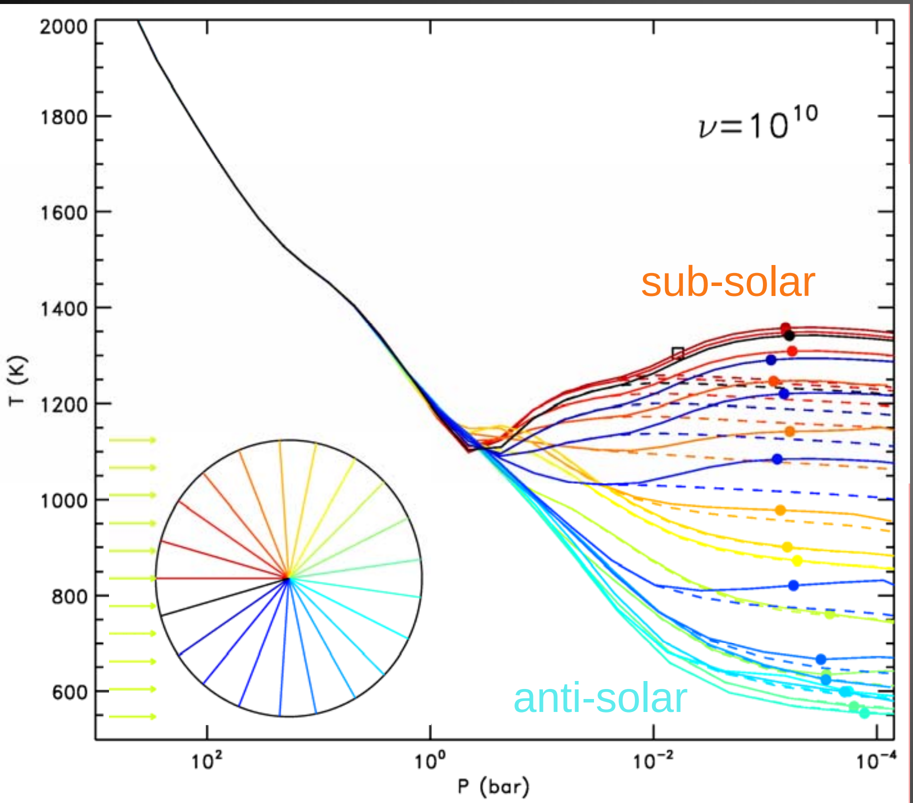
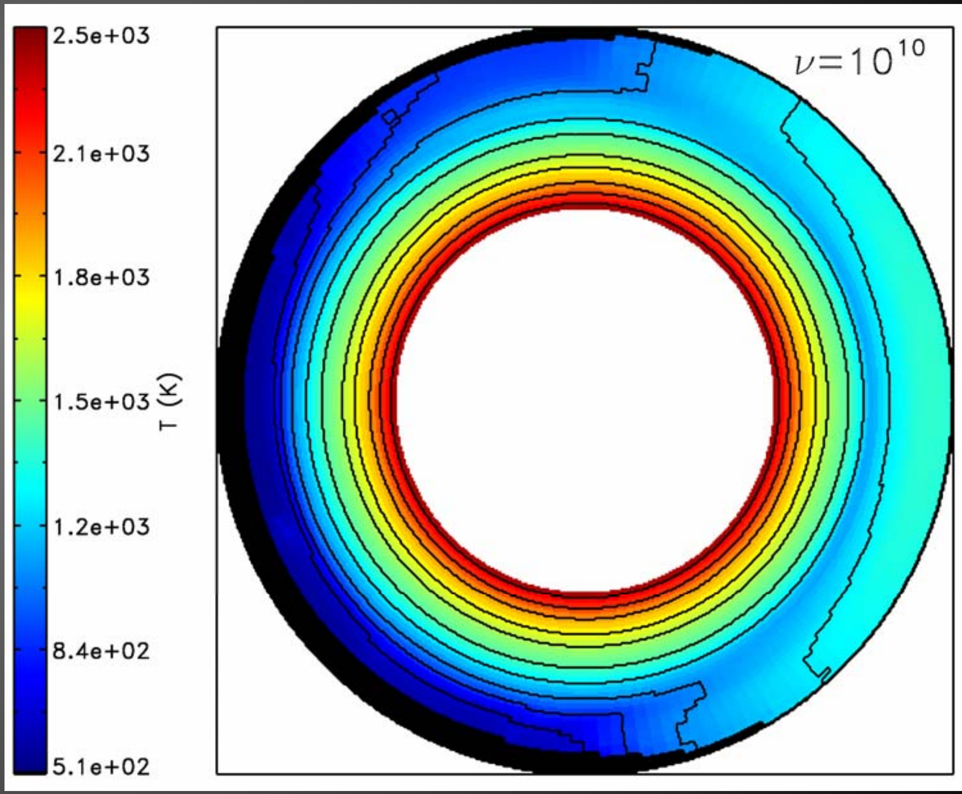
HD209458b





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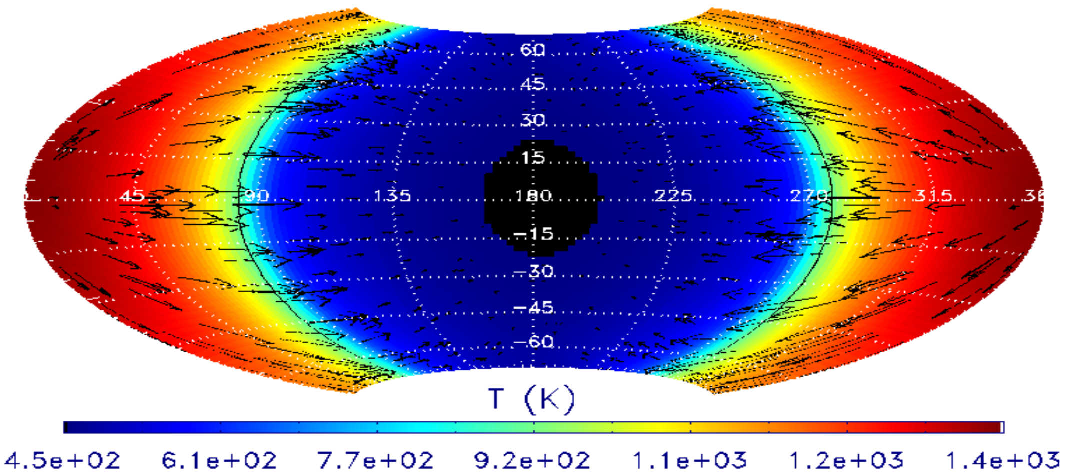
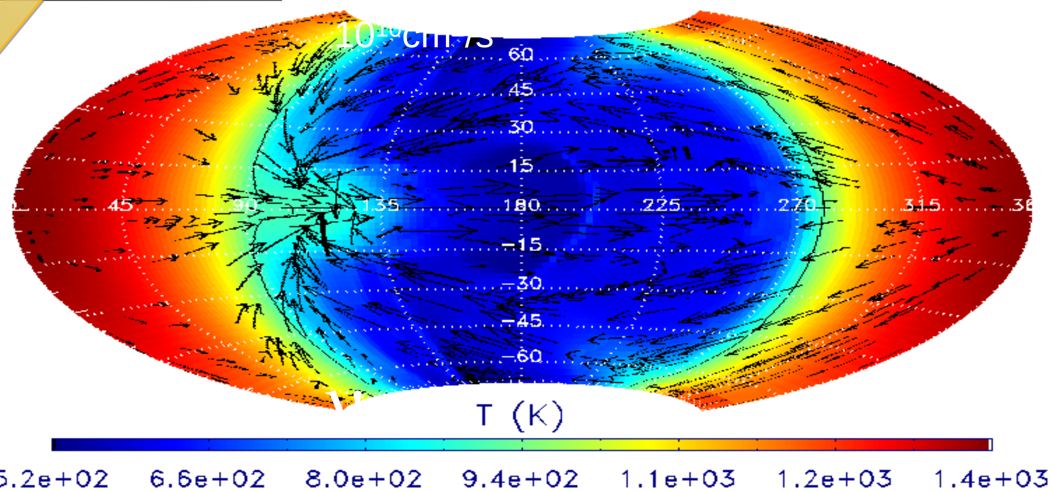
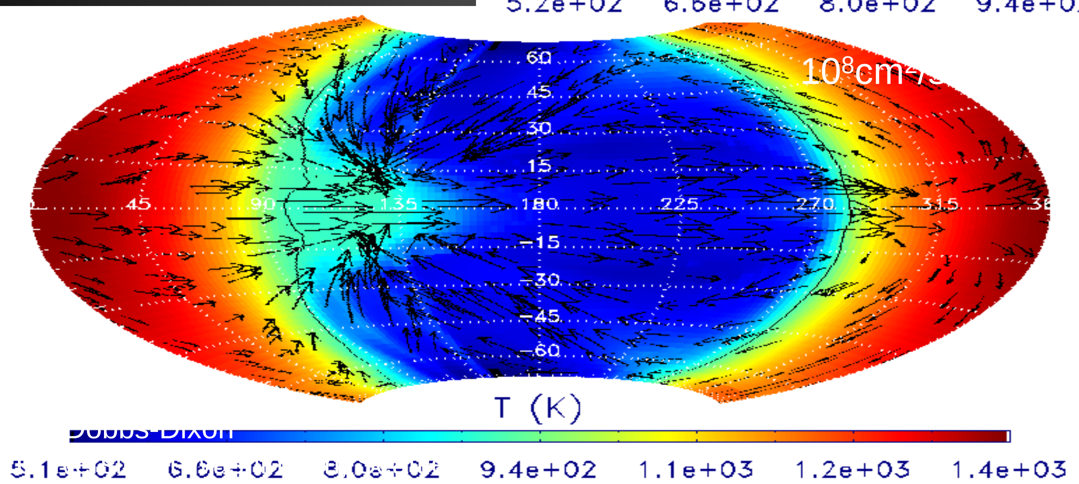
Varying Viscosity

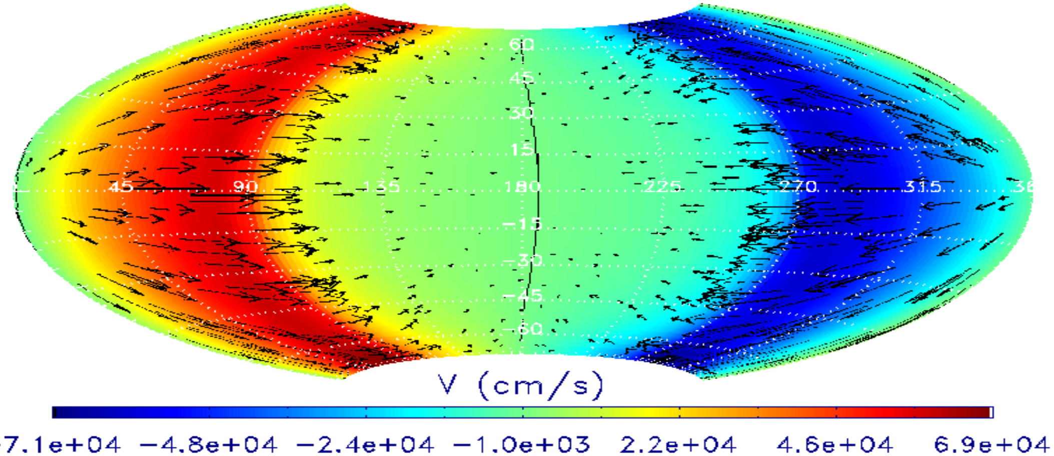


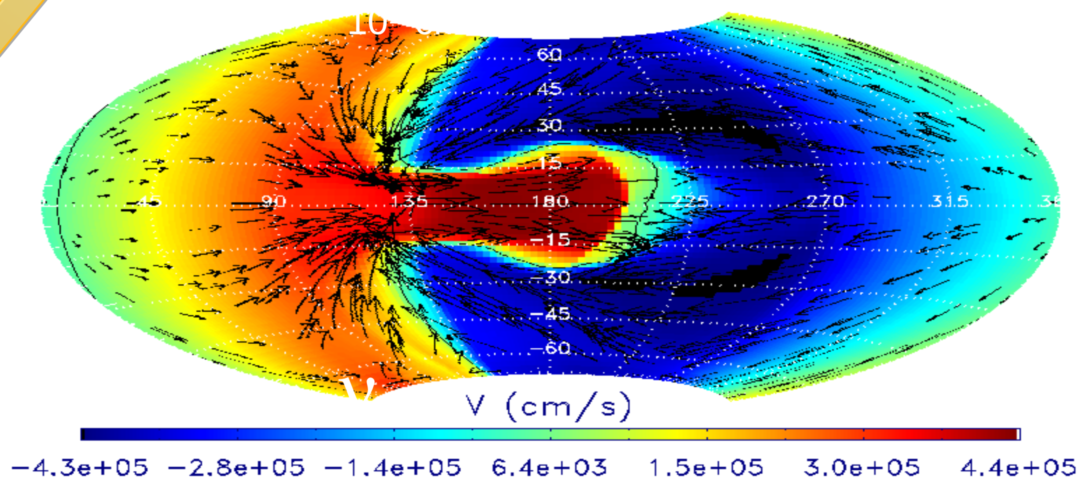


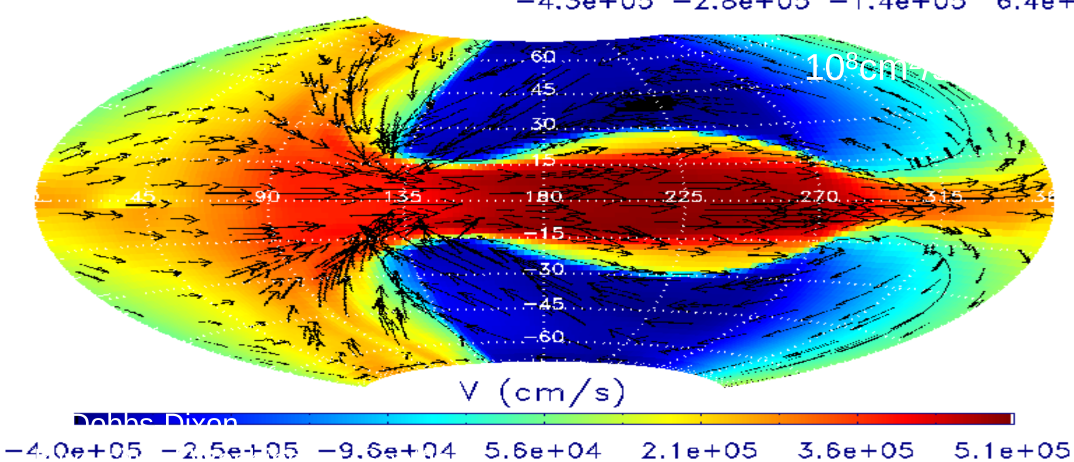


Varying Viscosity

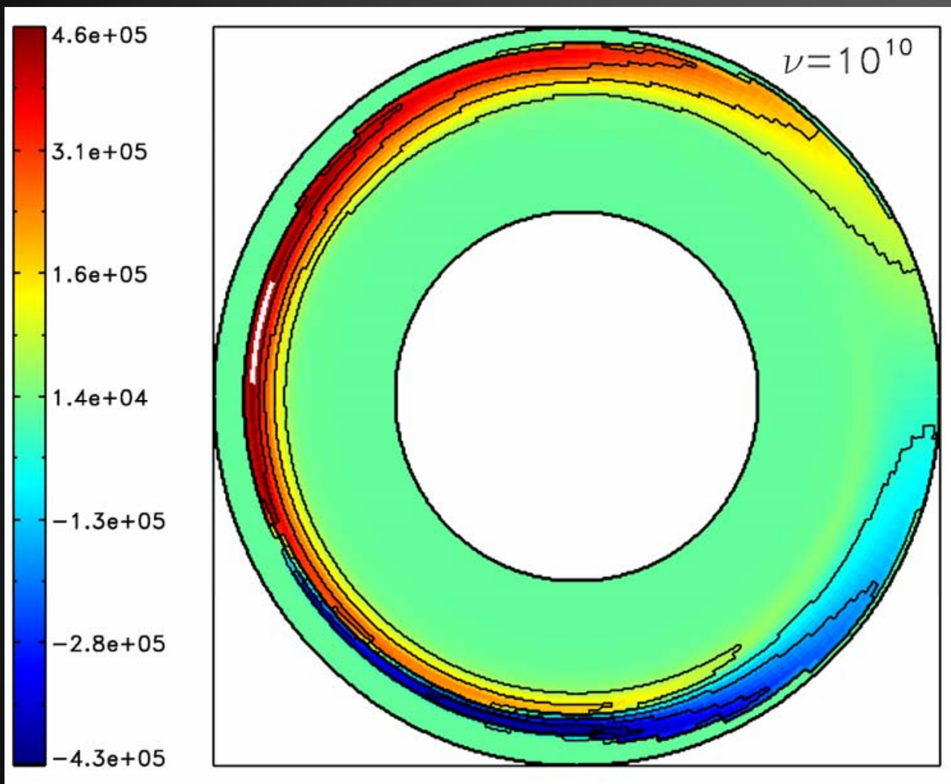
Viscosity



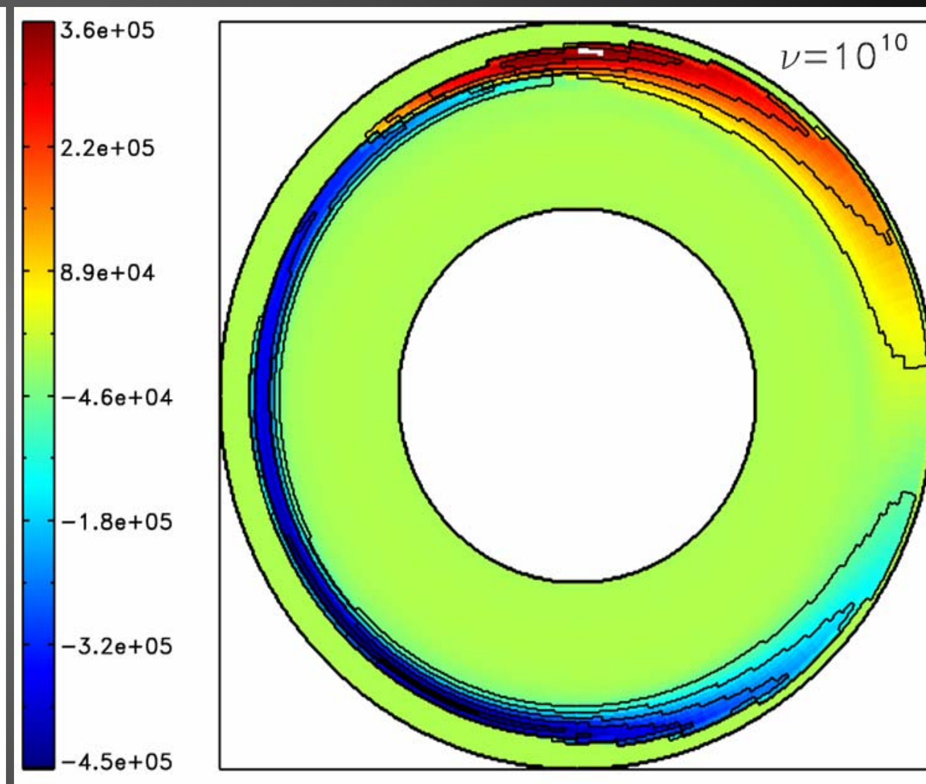




Velocity Structure with Radius



Equator



Mid-Latitude

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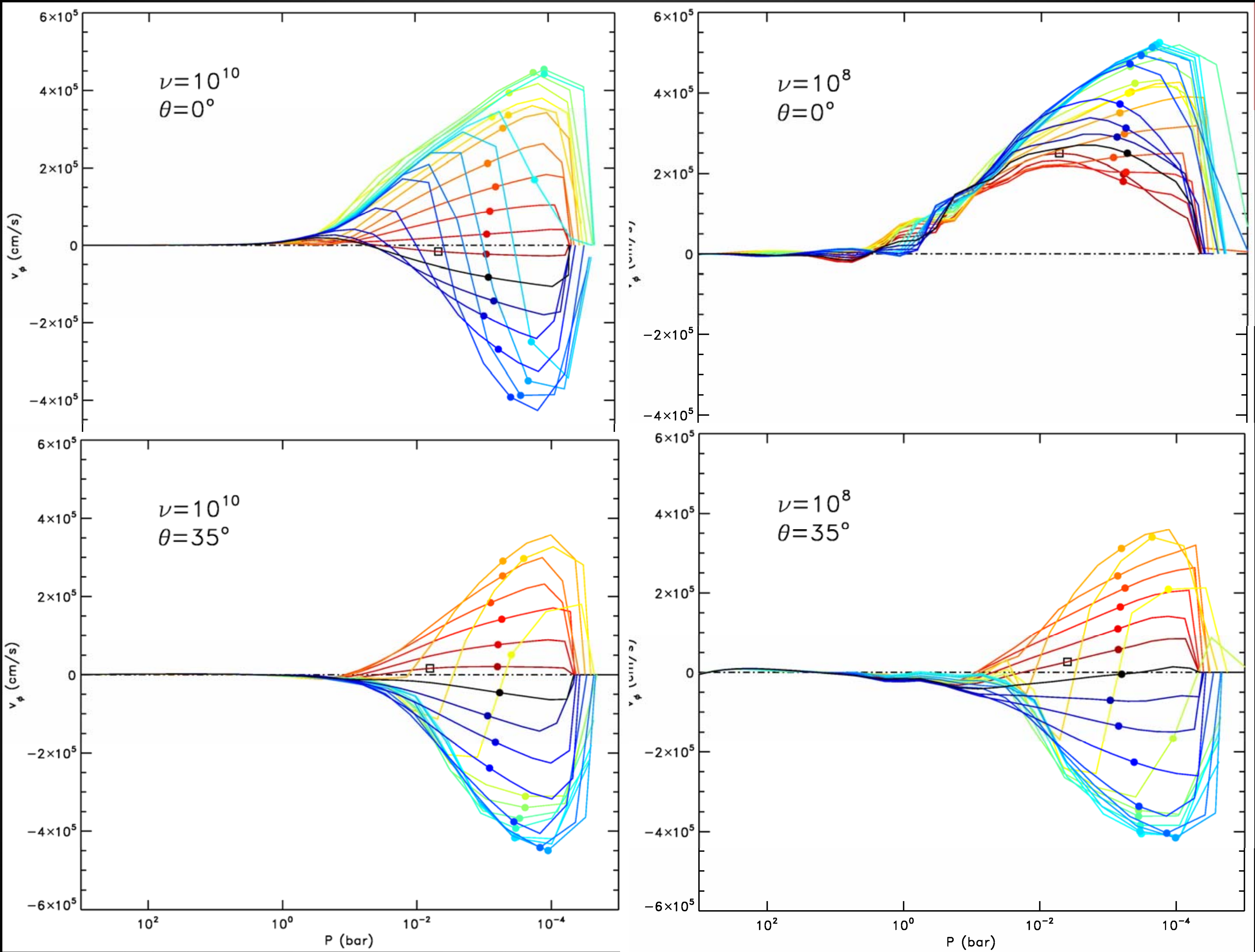
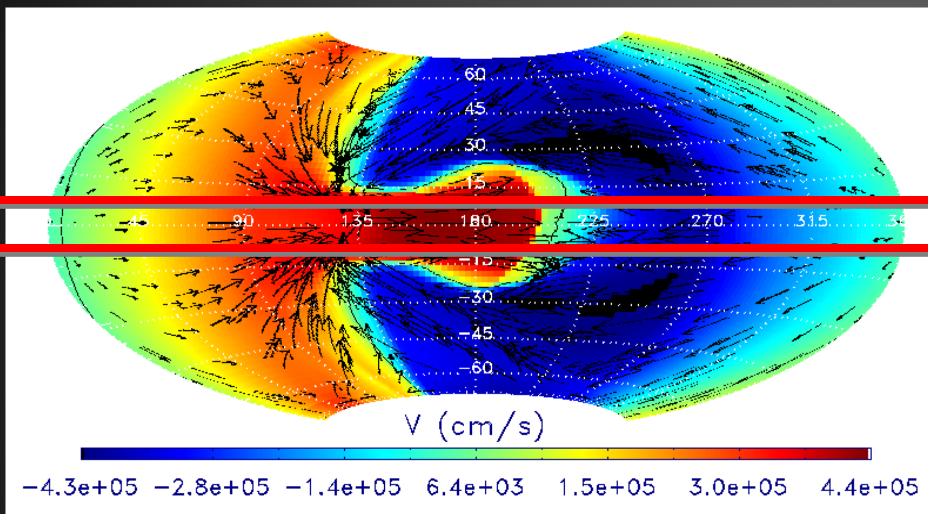
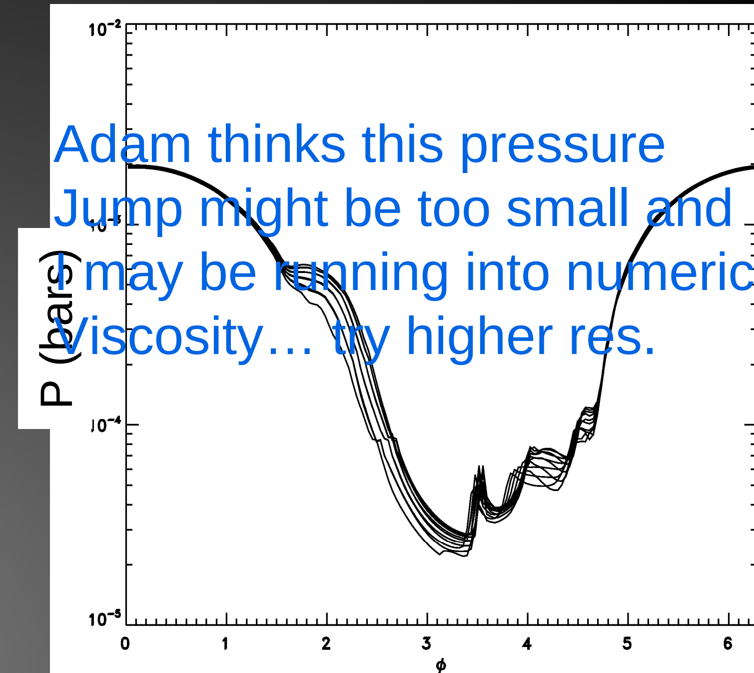


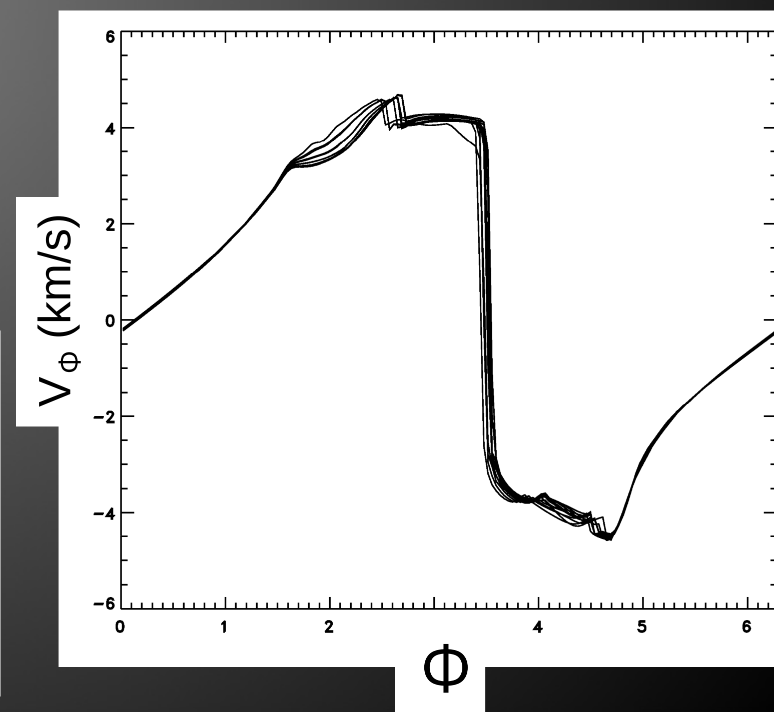
$\nu=10^{10}$
$\theta=0°$
$\nu=10^{8}$
$\theta=0°$
$\nu=10^{10}$
$\theta=35°$
$\nu=10^{8}$
$\theta=35°$
v_ϕ (cm/s)
P (bar)
6×10^5
4×10^5
2×10^5
0
-2×10^5
-4×10^5
-6×10^5
10^2
10^0
10^{-2}
10^{-4}

Horizontal Equatorial Shock Structure

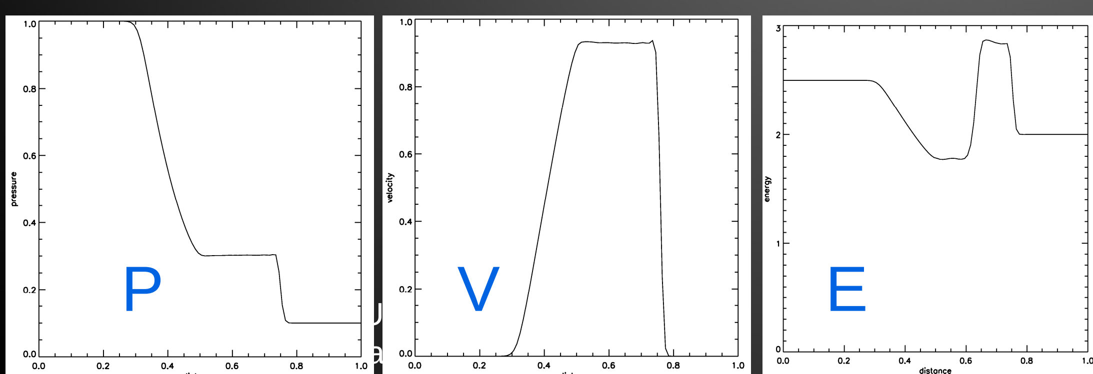




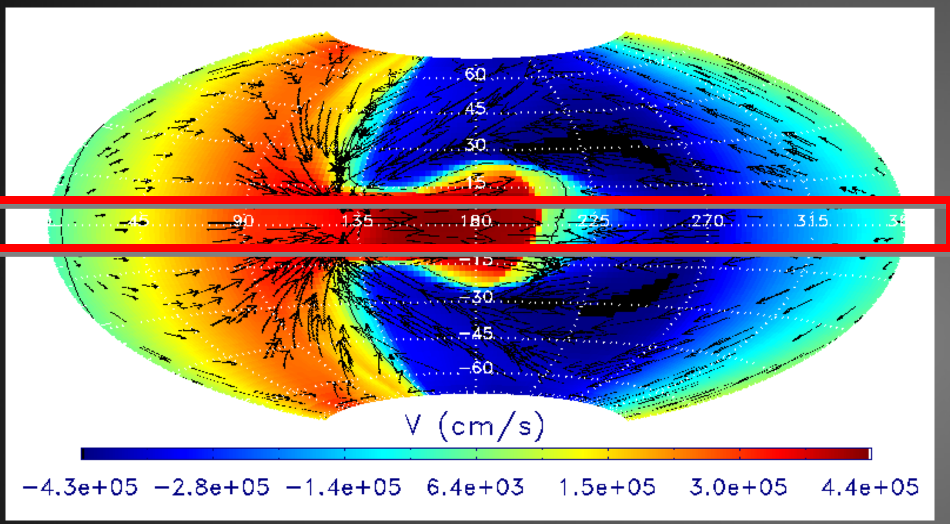
Adam thinks this pressure Jump might be too small and I may be running into numerical Viscosity… try higher res.

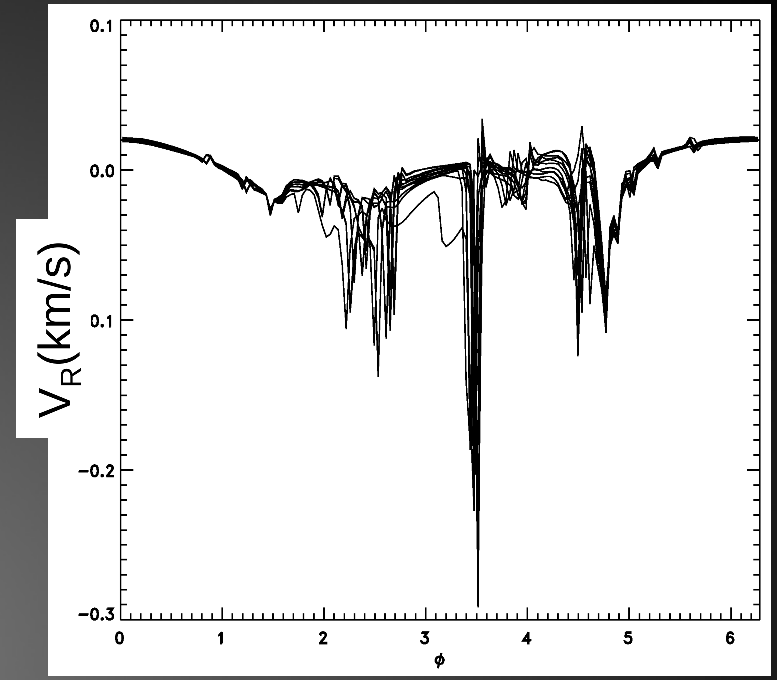


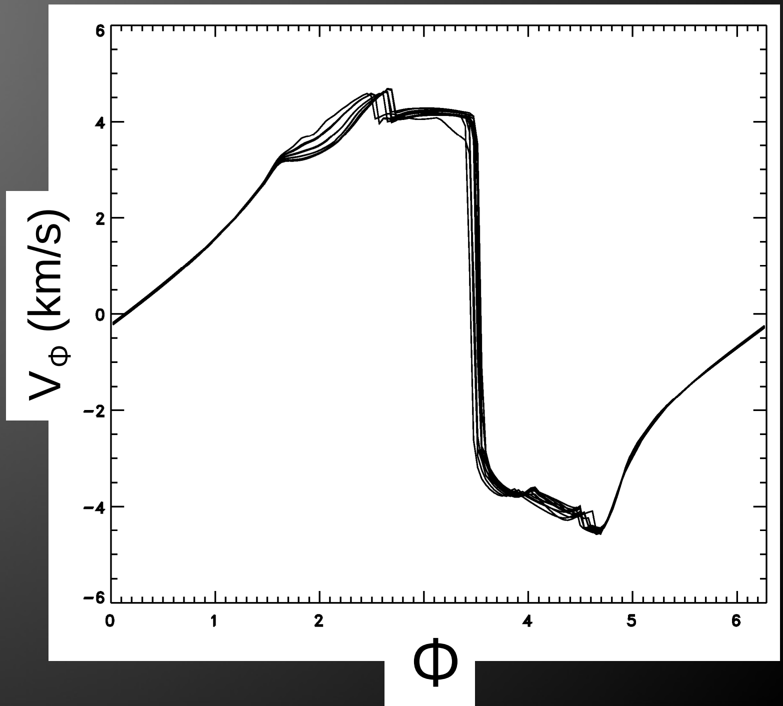
1D Riemann shock tube



Horizontal Equatorial Shock Structure







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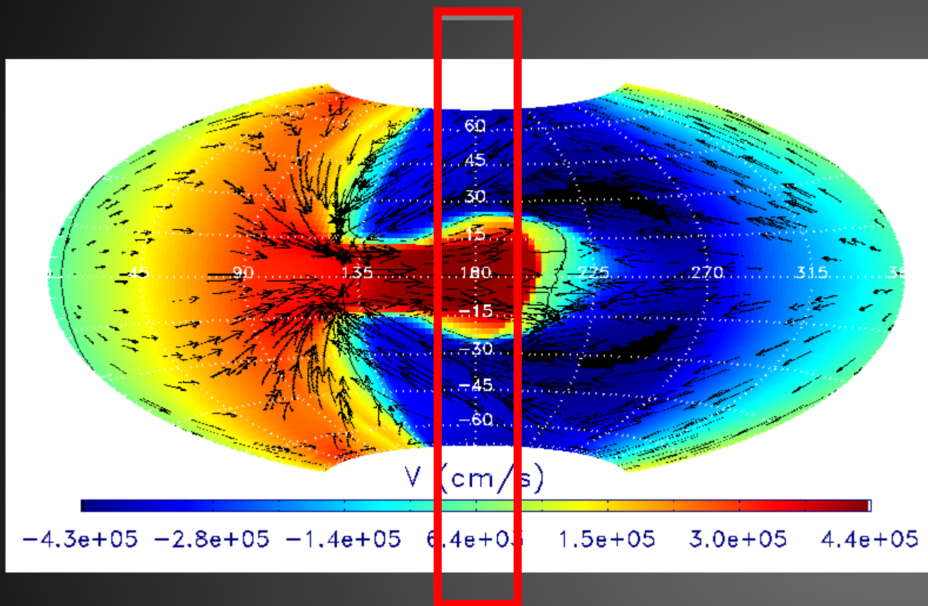
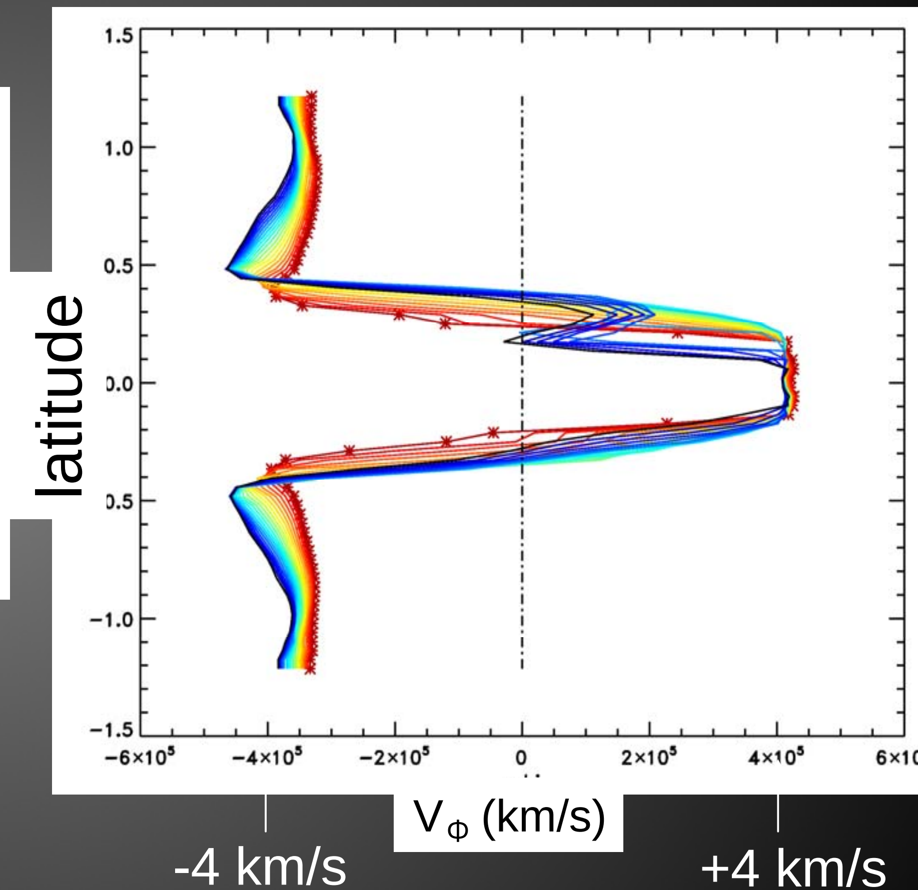
Horizontal Latitudinal Shearing





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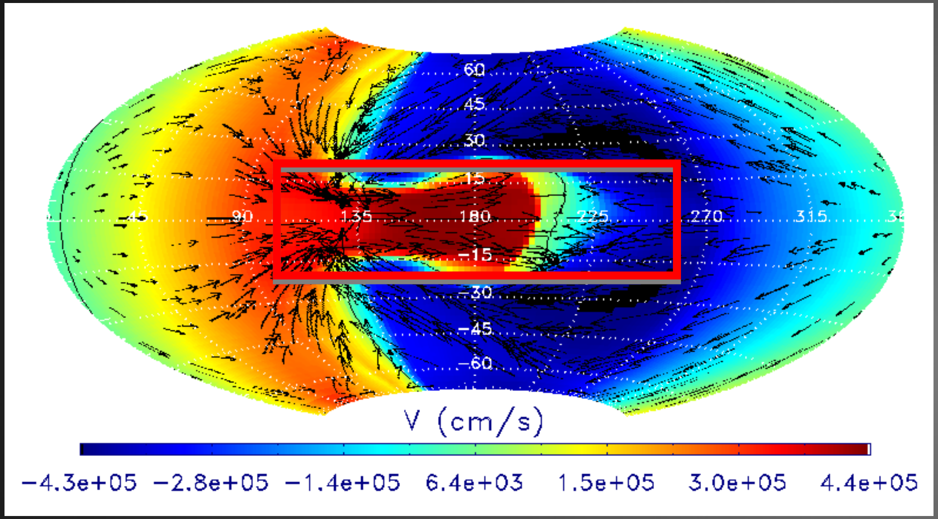
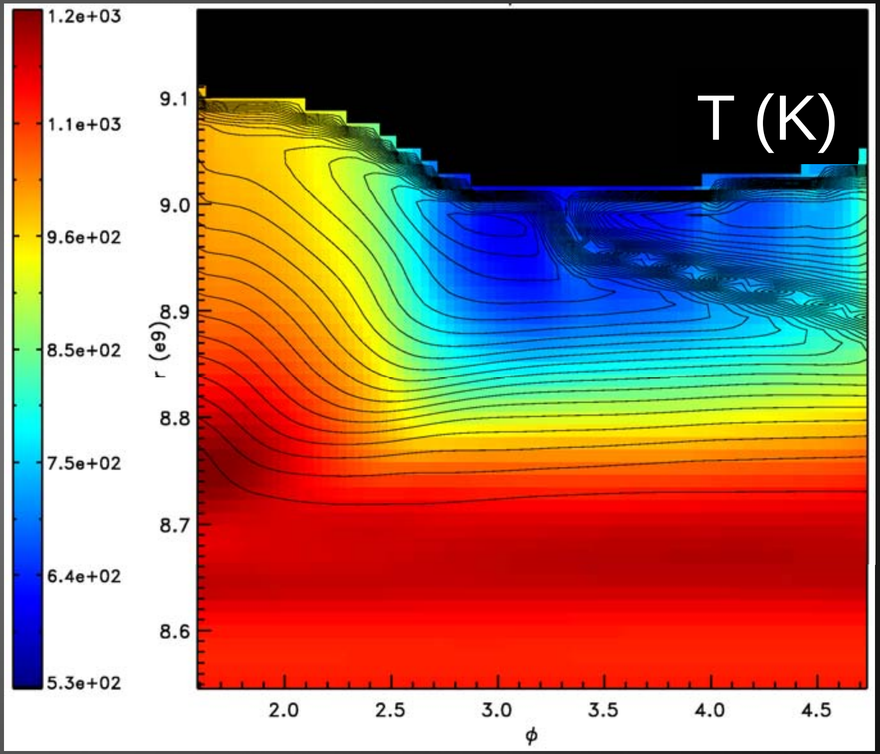
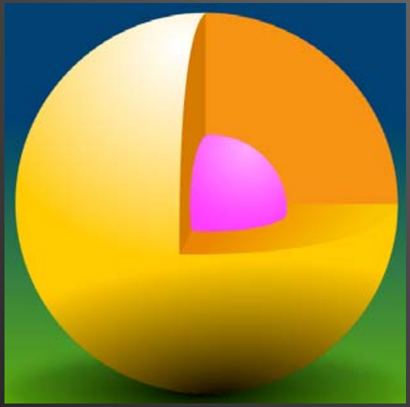
Radial Shearing







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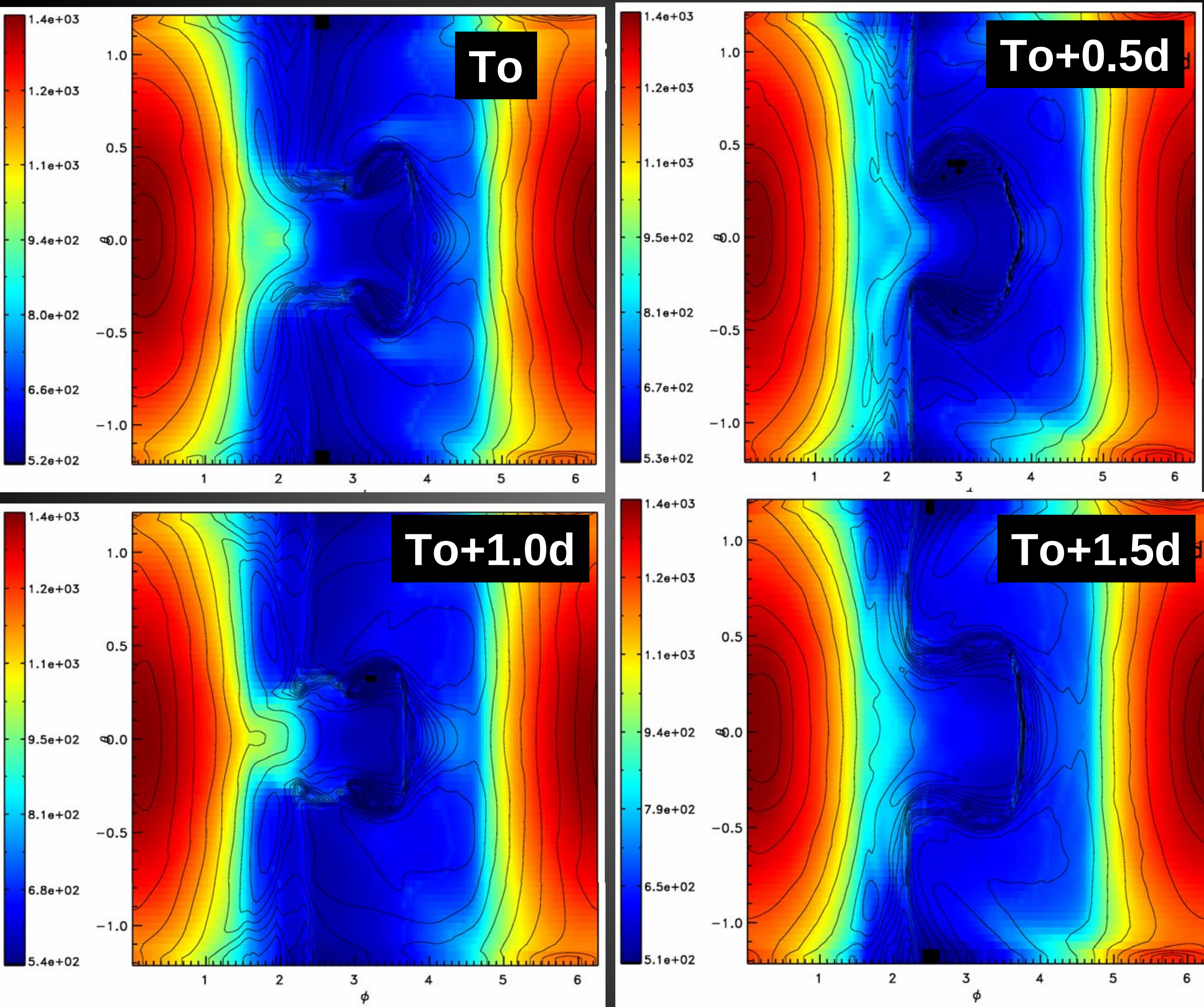
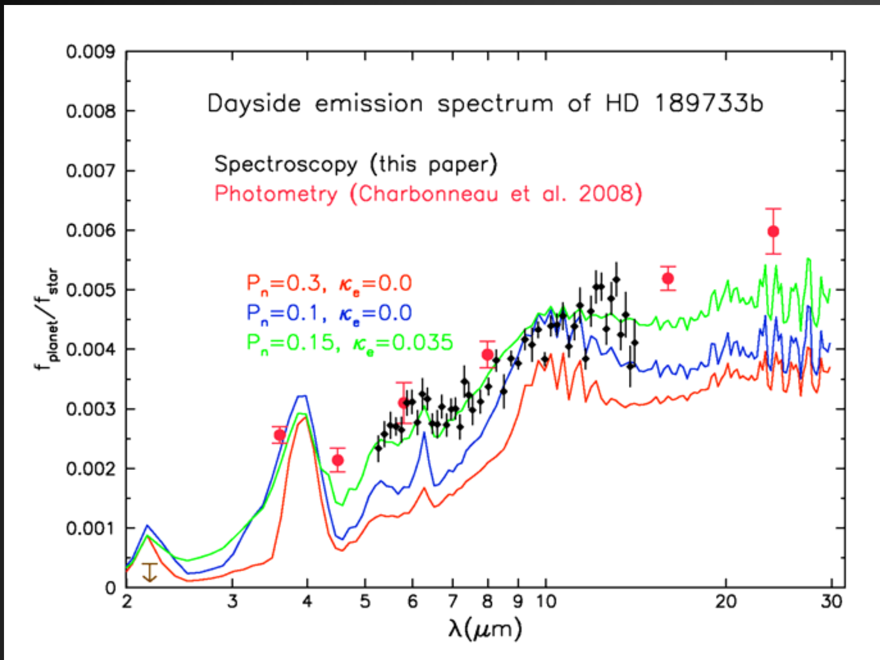
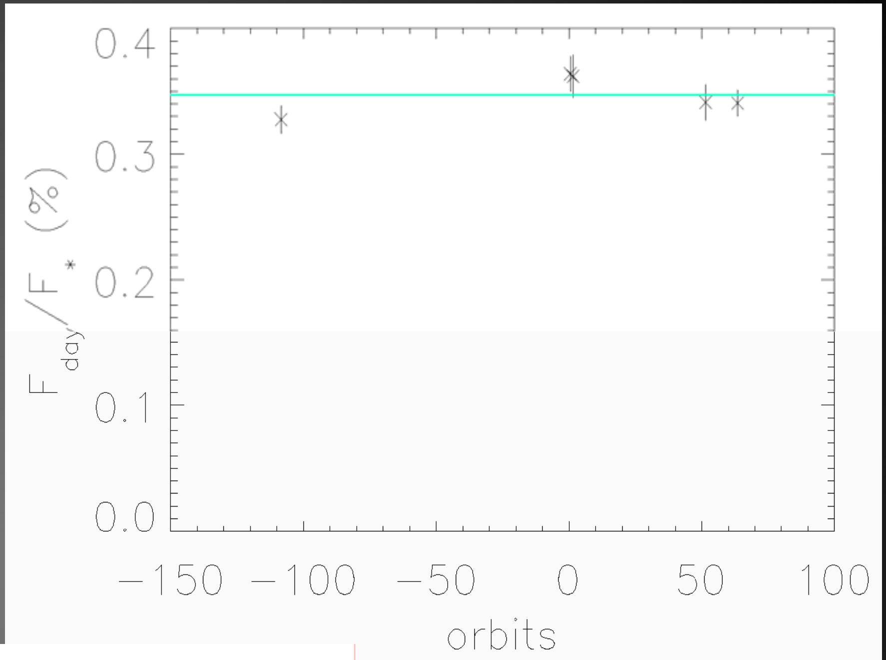

To
To+0.5d
To+1.0d
To+1.5d
1.4e+03
1.2e+03
1.1e+03
9.4e+02
8.0e+02
6.6e+02
5.2e+02
5.3e+02
9.5e+02
8.1e+02
6.7e+02
6.8e+02
5.4e+02
7.9e+02
6.5e+02
5.1e+02
θ
ϕ

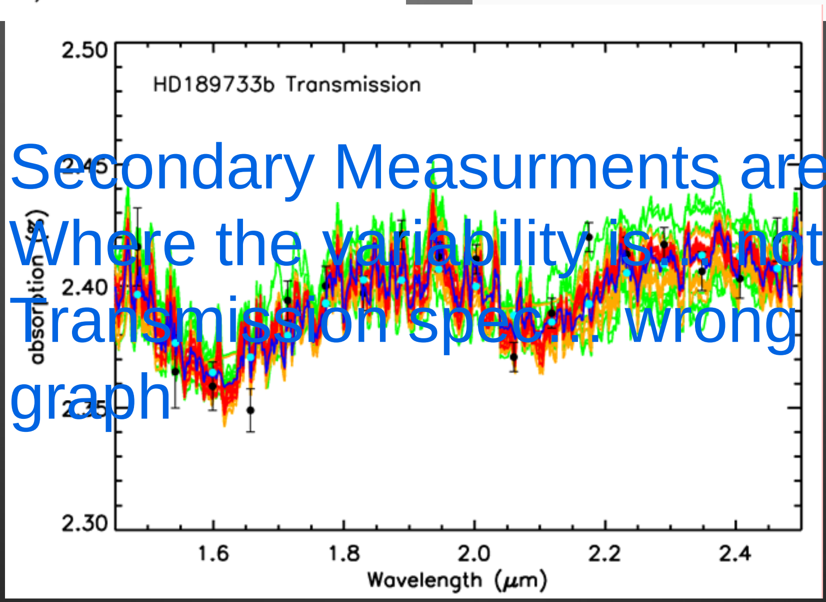
Observed Variability?



Grillmair et al 2008



Agol et al 2009



Secondary Measurments are Where the variability is… not Transmission spec… wrong graph

Madhusudhan and Seager 2009

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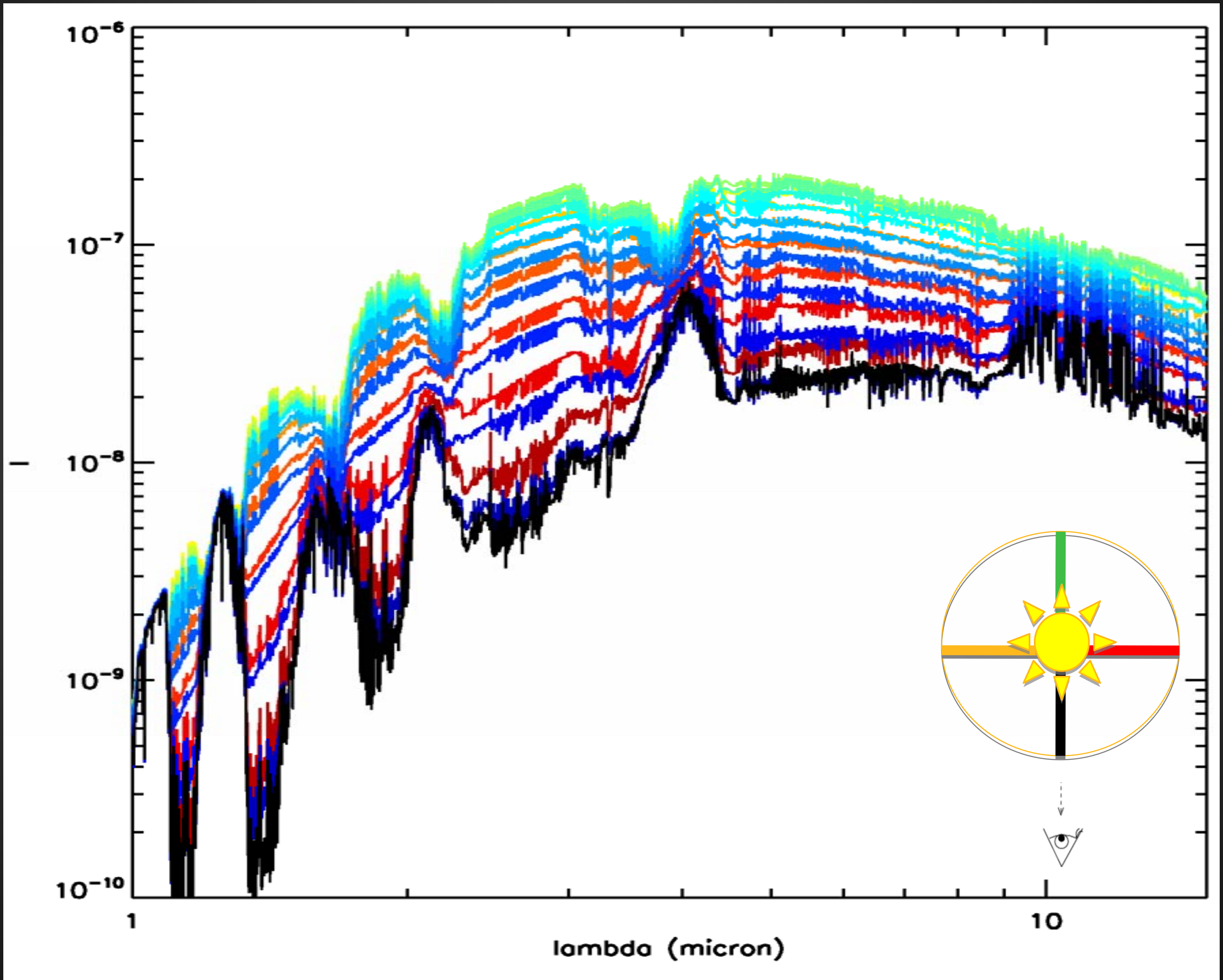
Emission Spectra



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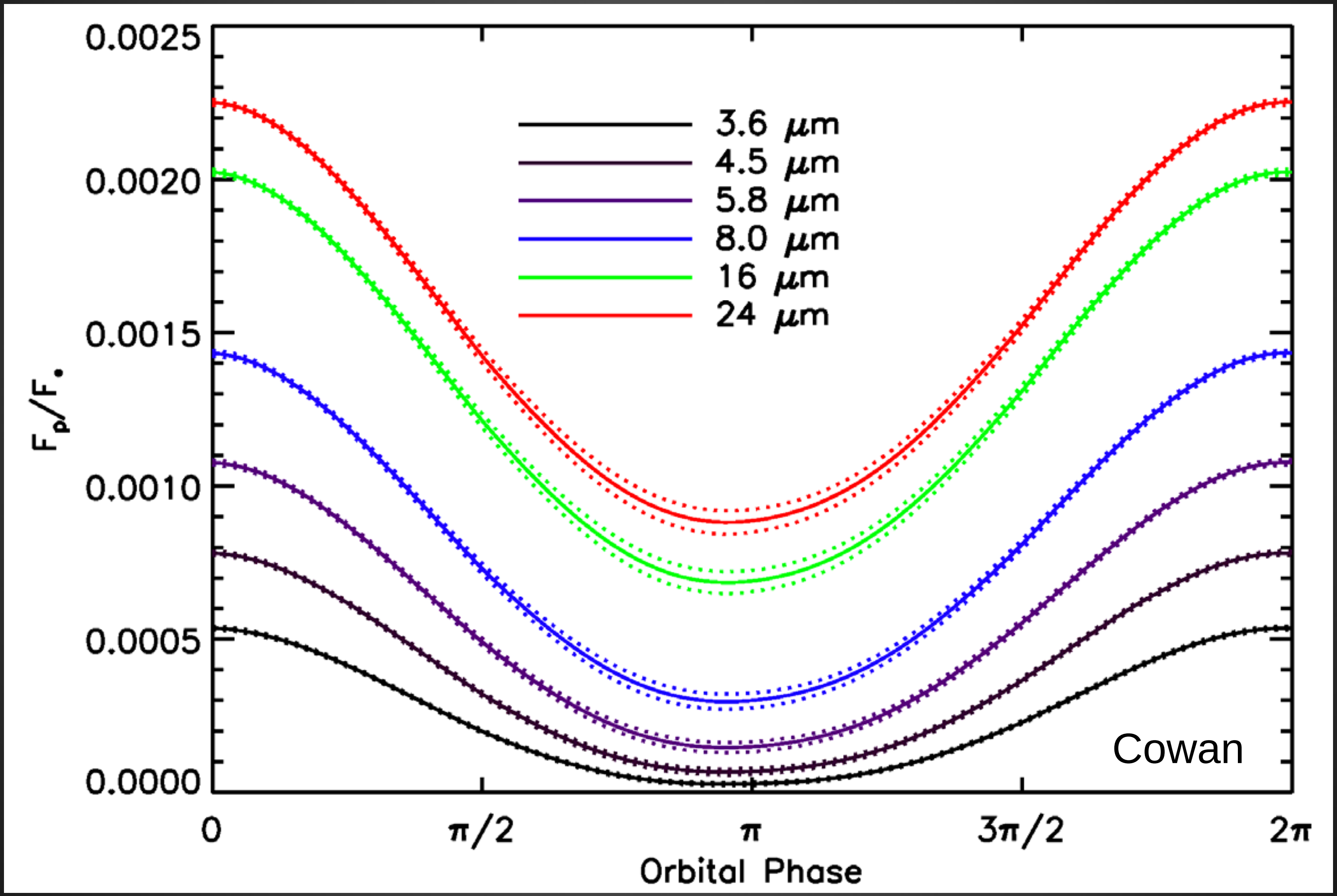
Emission Spectra



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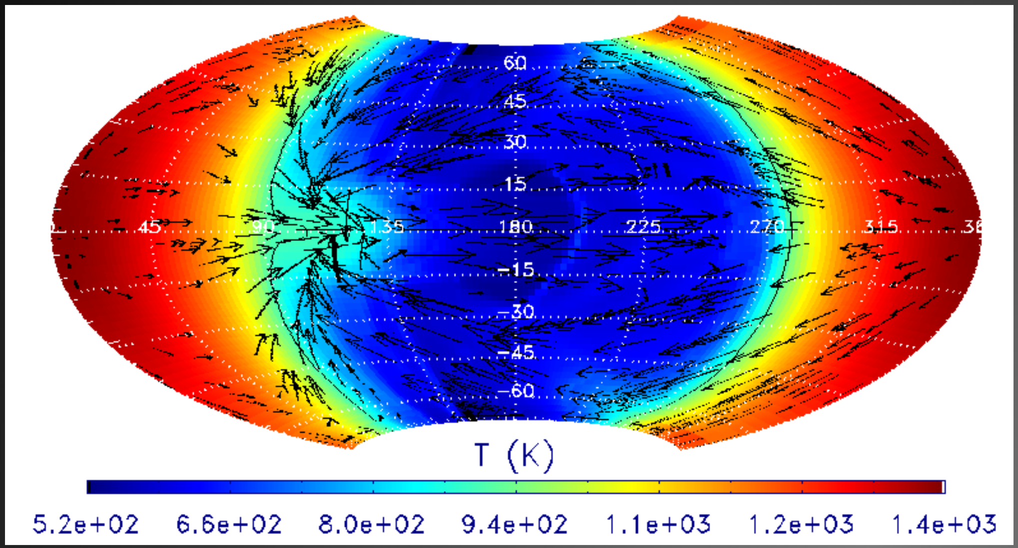
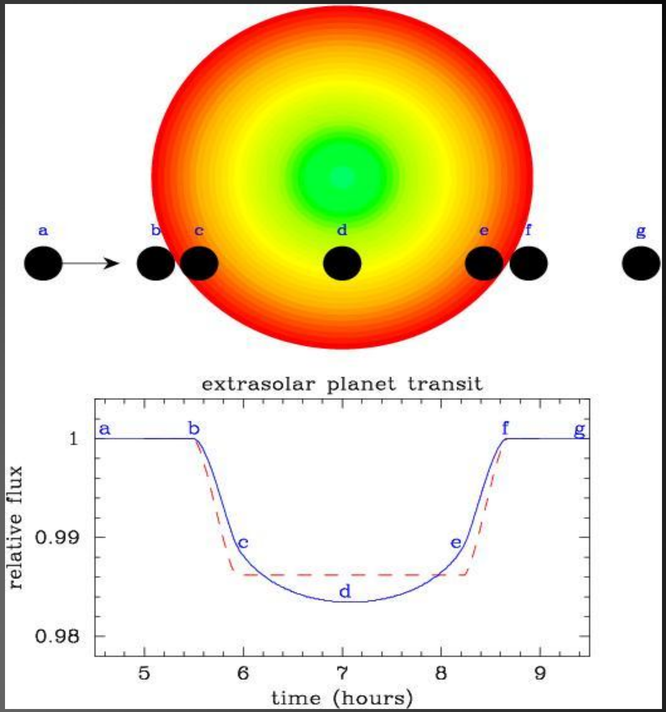
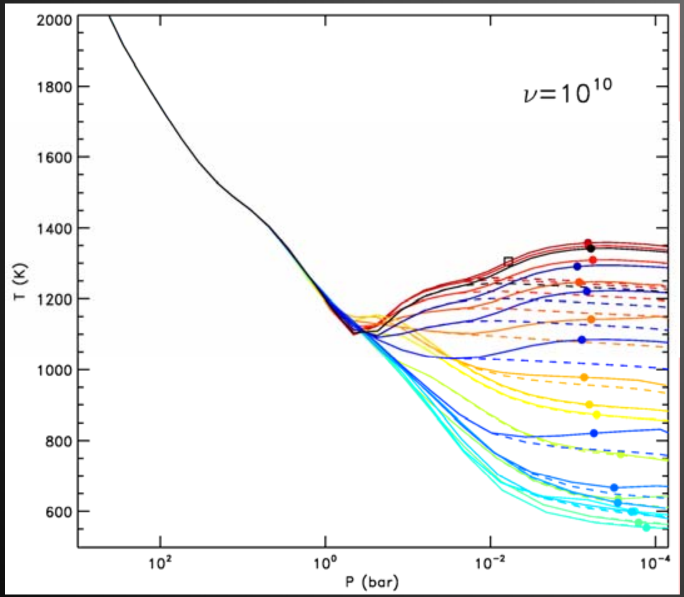
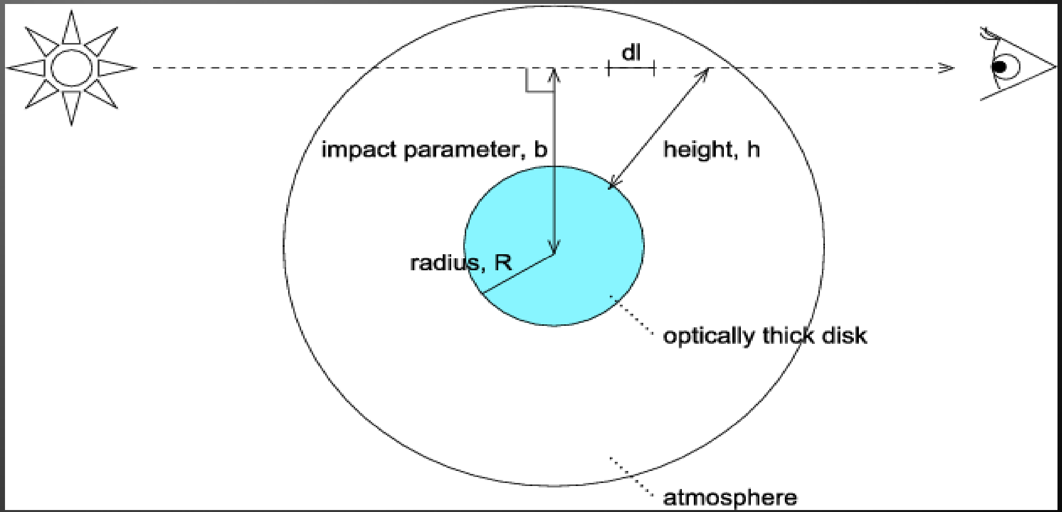
Transmission Spectra









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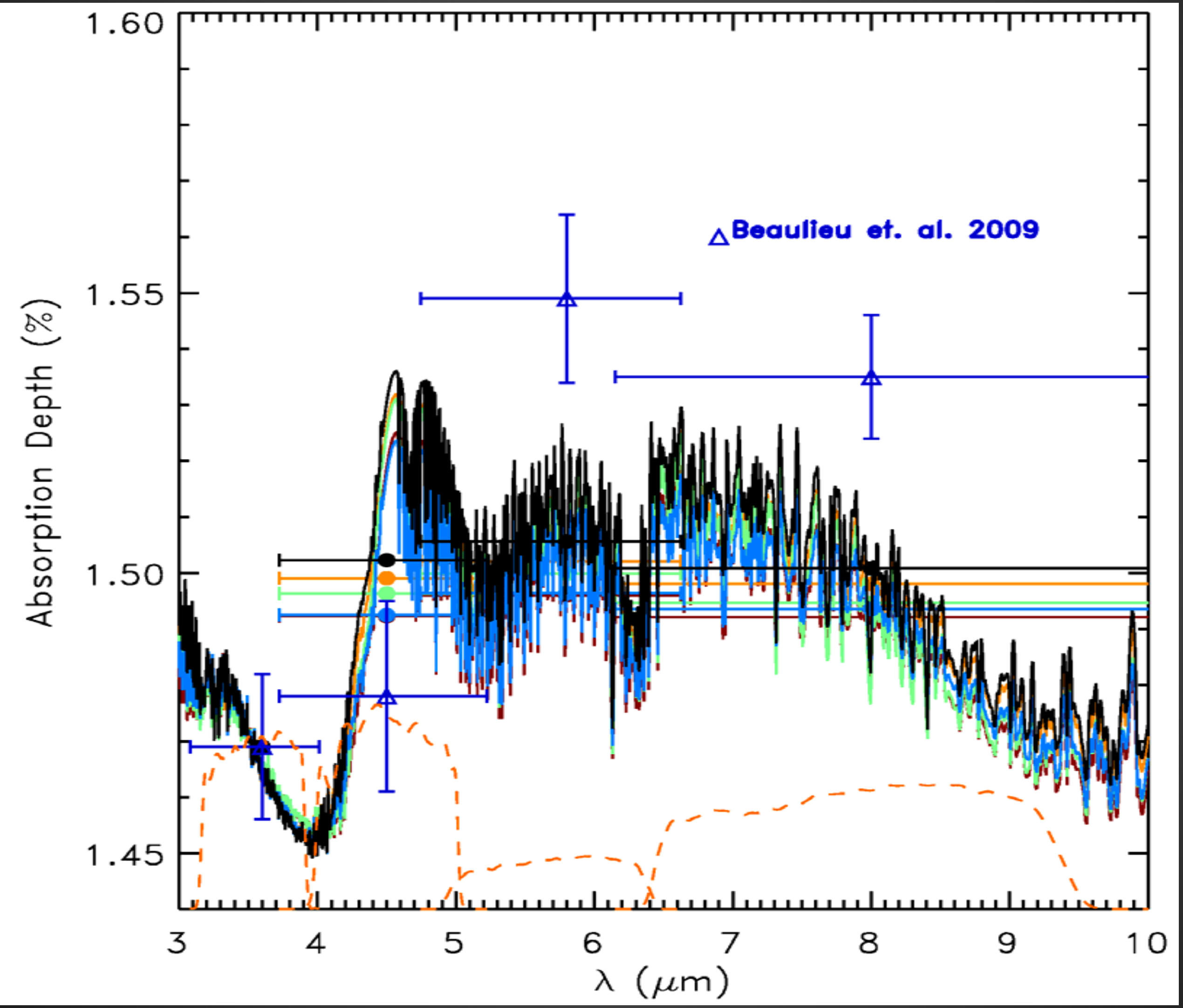
Transmission Spectra: temporal variations



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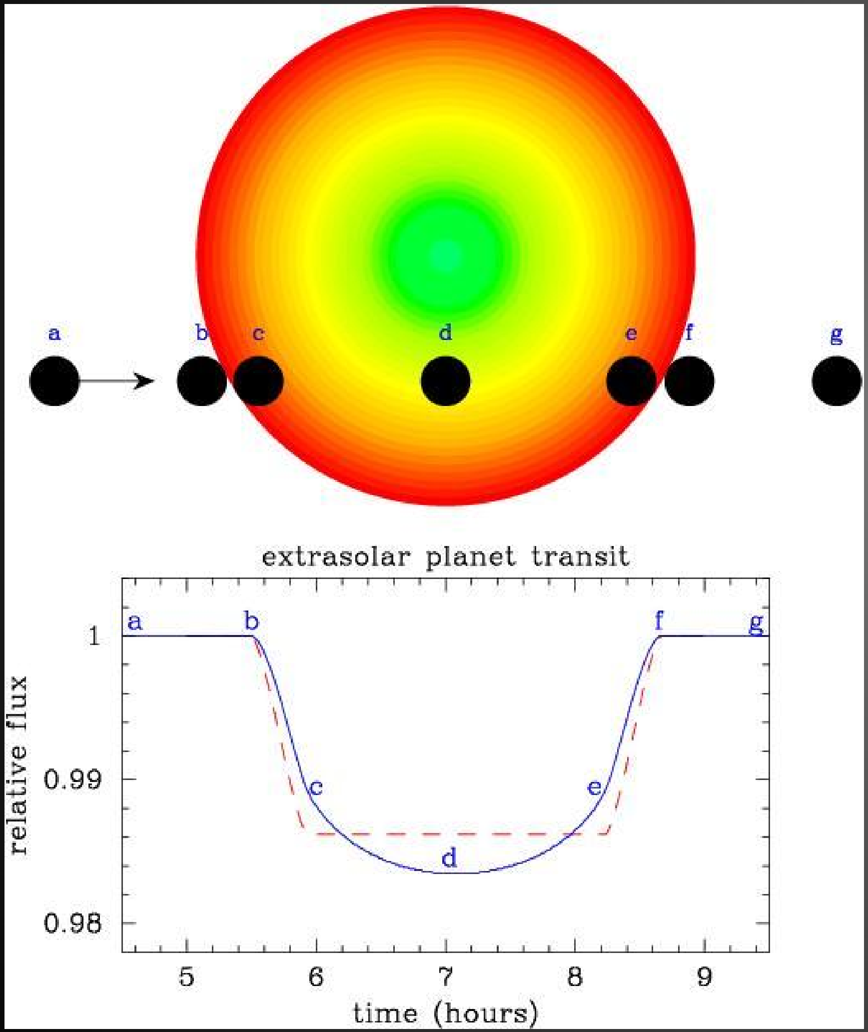
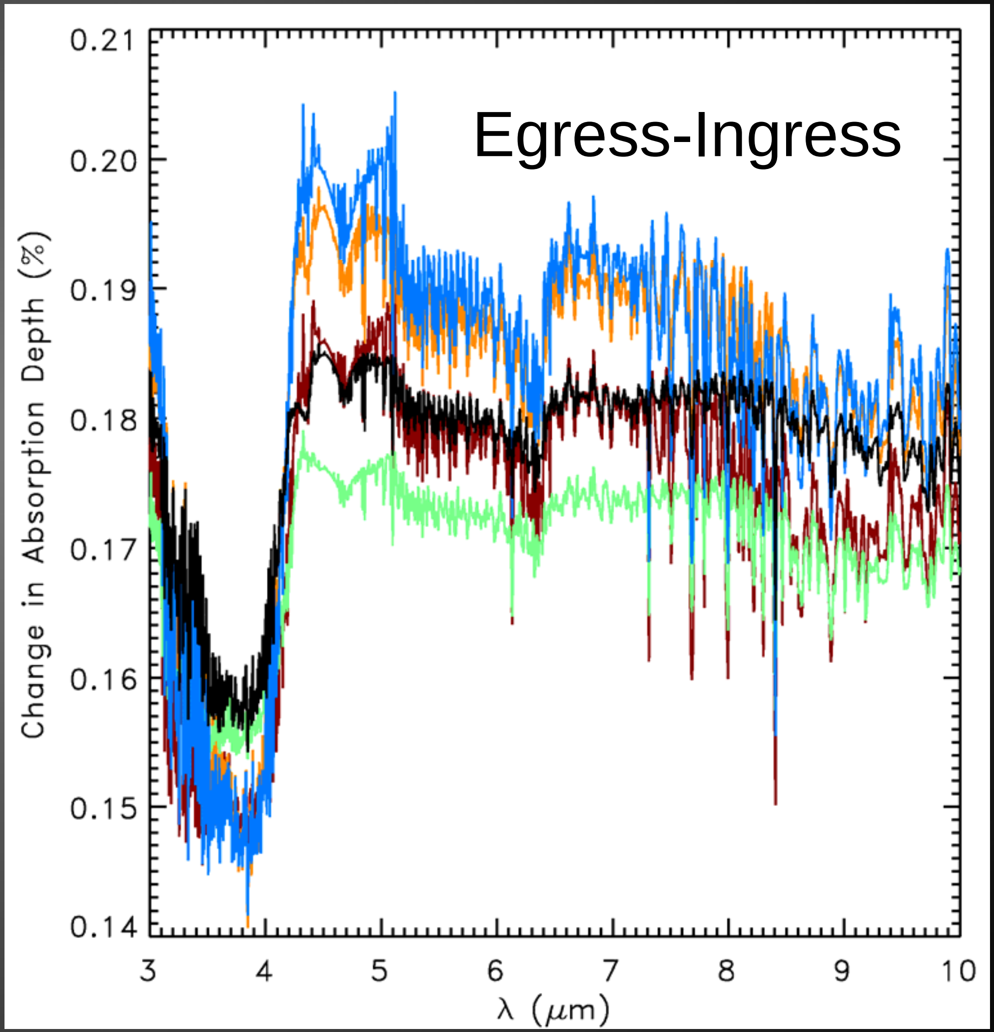
Transmission Spectra: temporal variations





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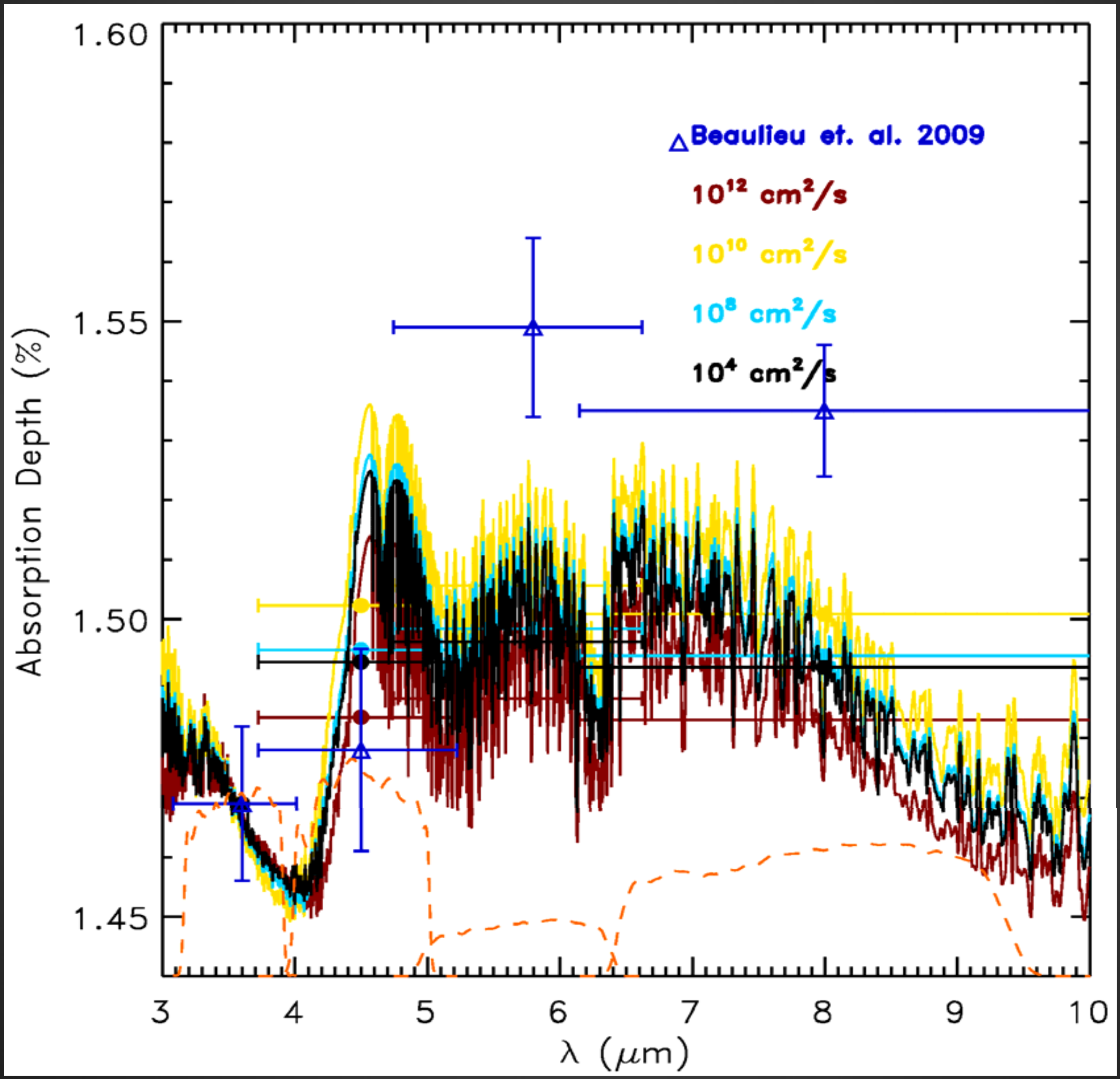
Transmission Spectra: viscous effects



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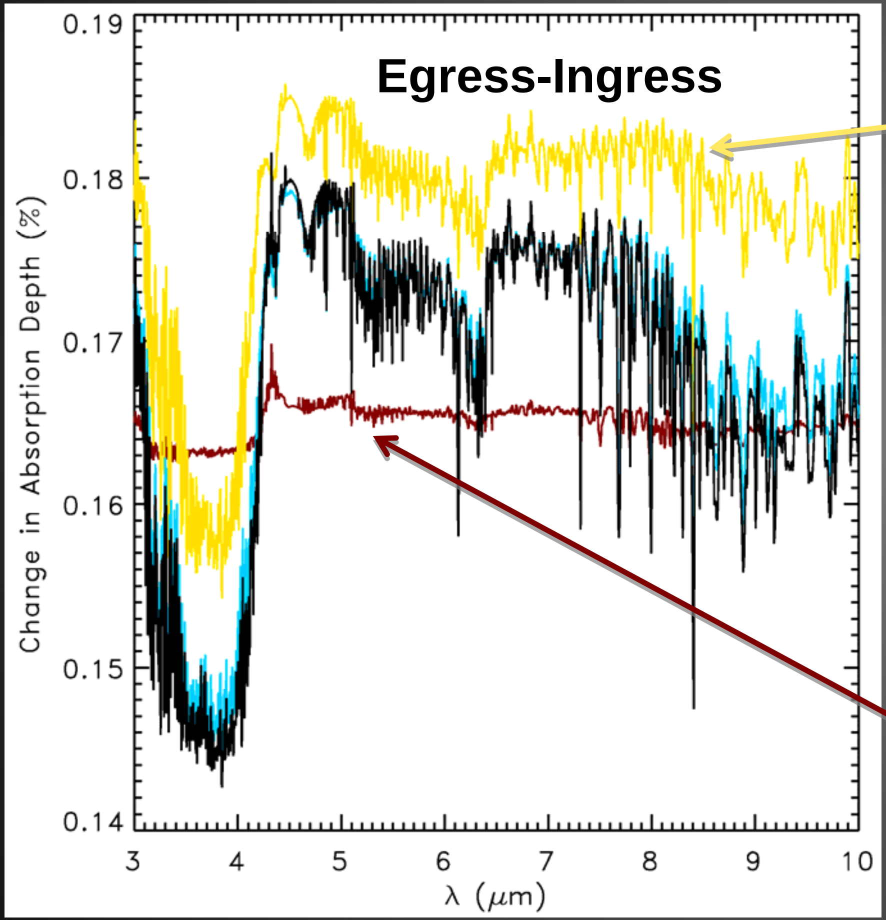
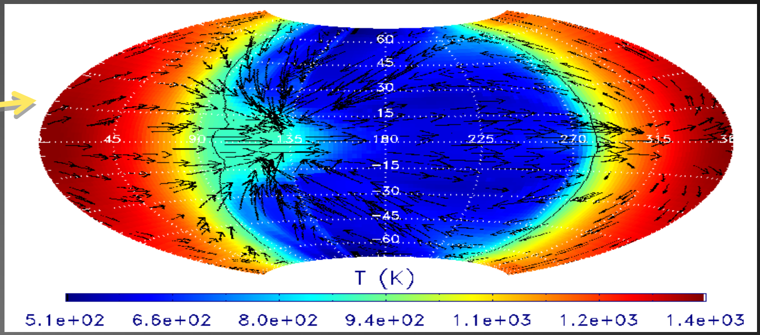
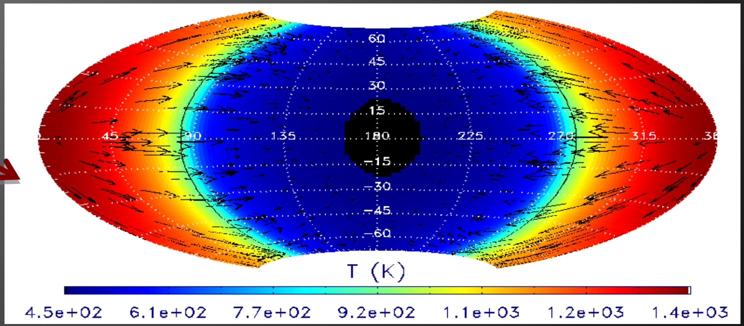
Transmission Spectra: Viscous Variations







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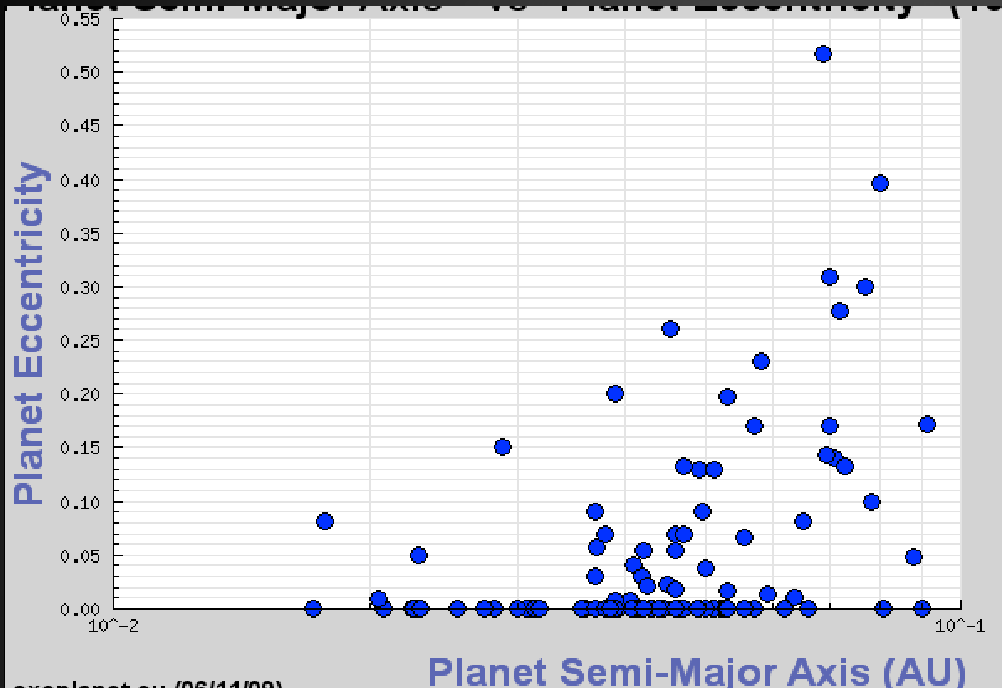
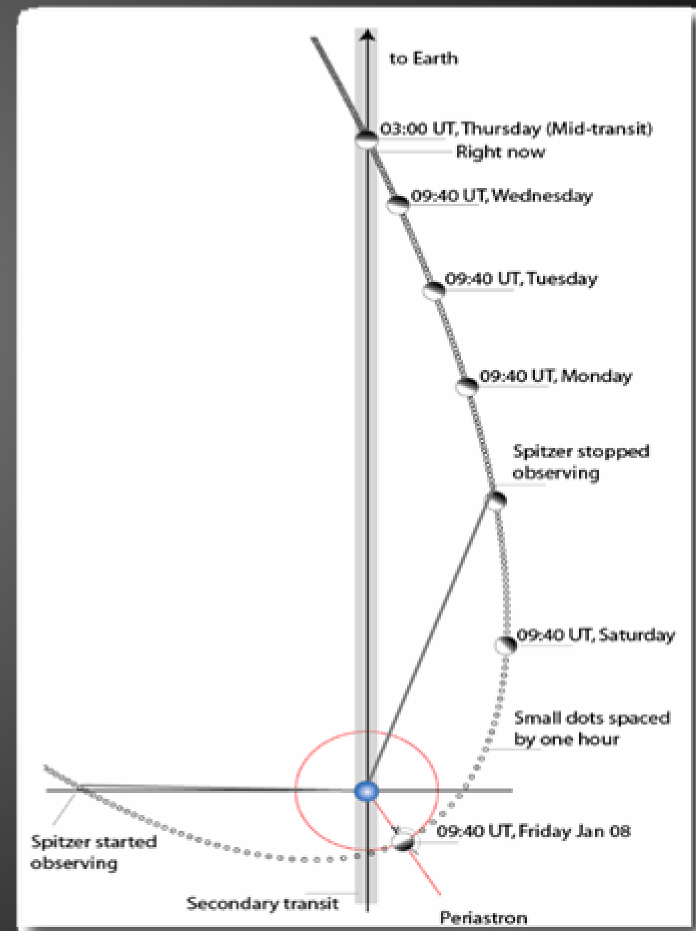
Eccentric Planets

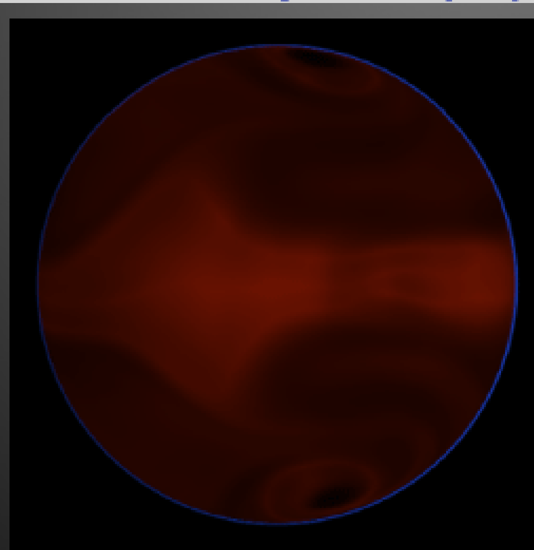


HD80606b
P=111days, e=0.9



G. Laughlin

Langton and Laughlin



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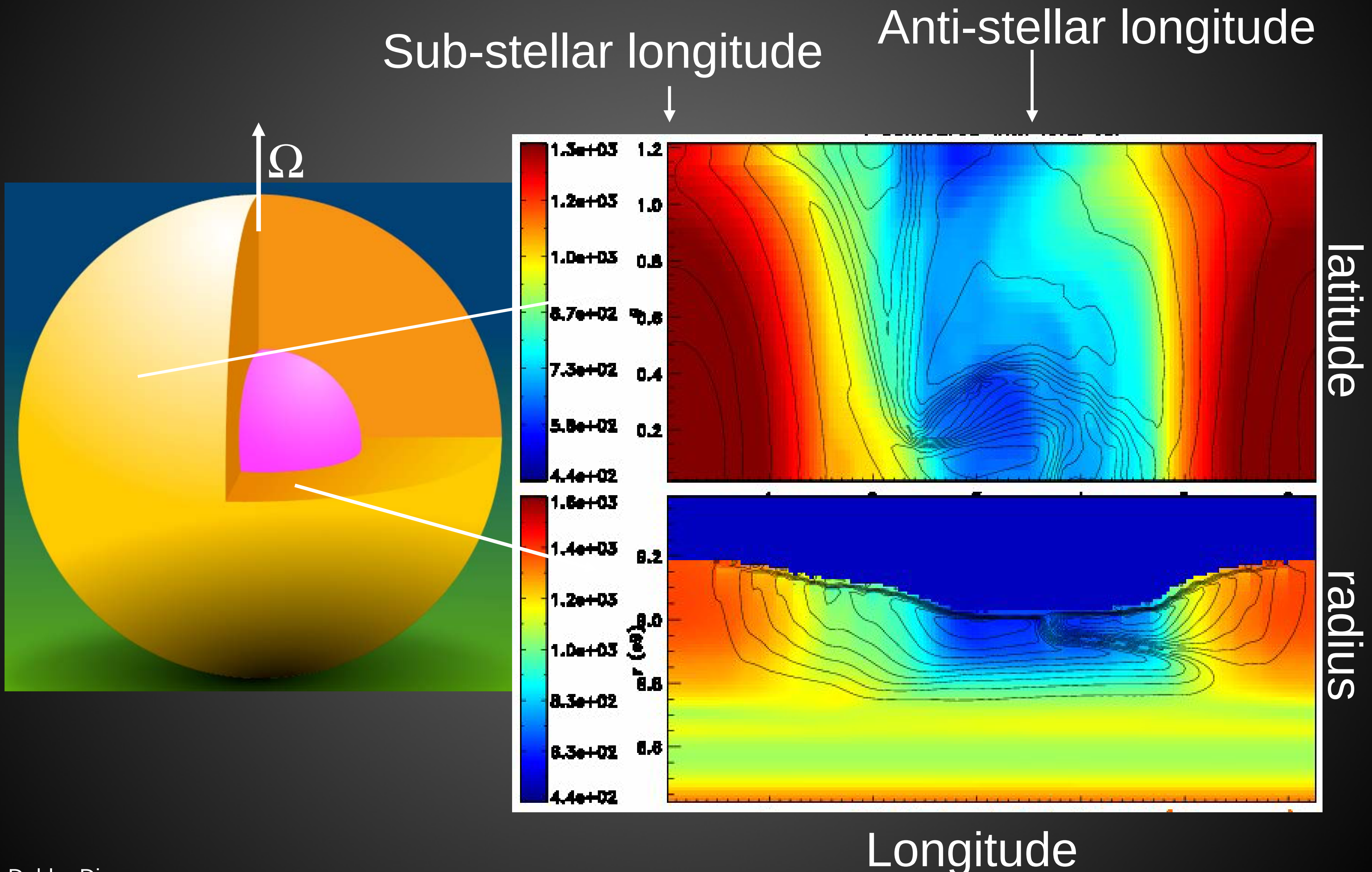
Eccentric Planets



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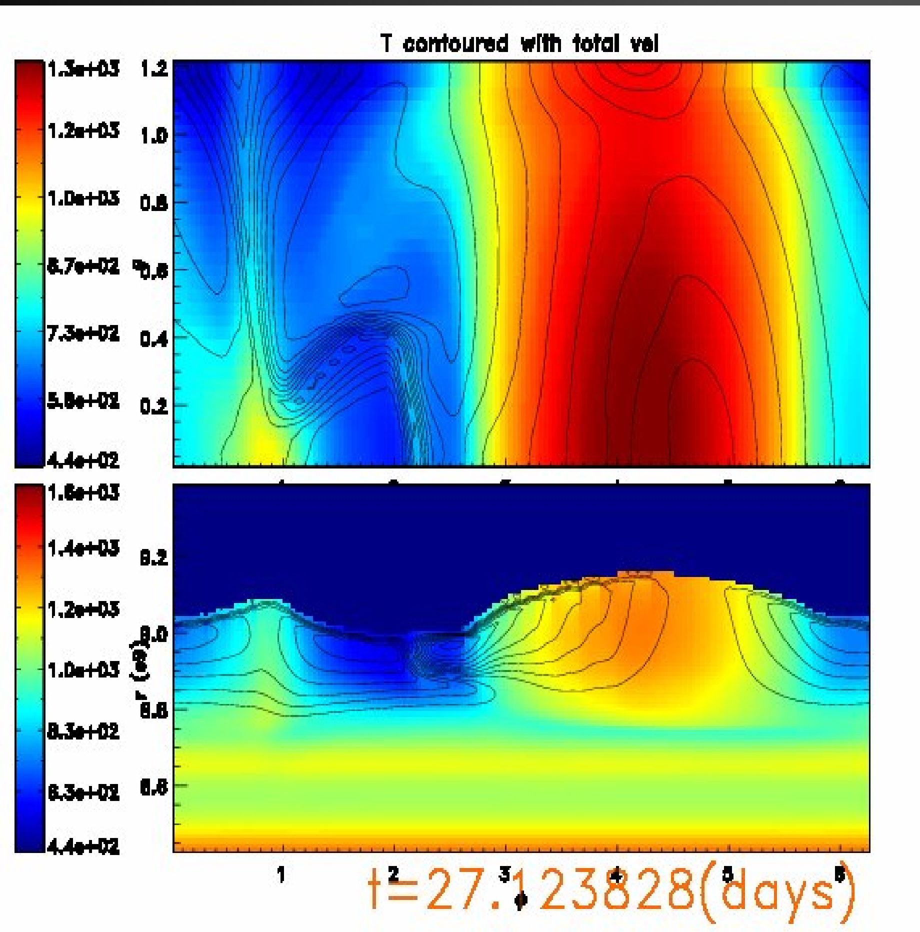
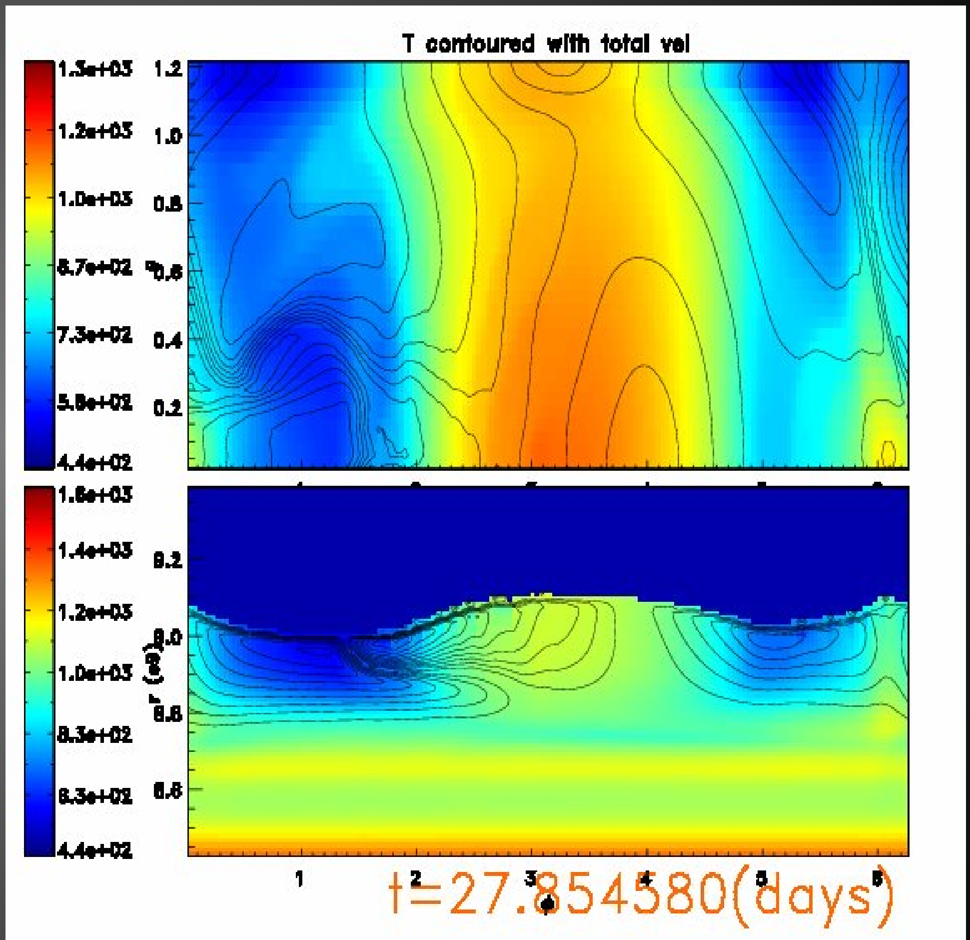
Eccentric Planets (e=0.5)



T_{peri}



T_{peri}+15hr

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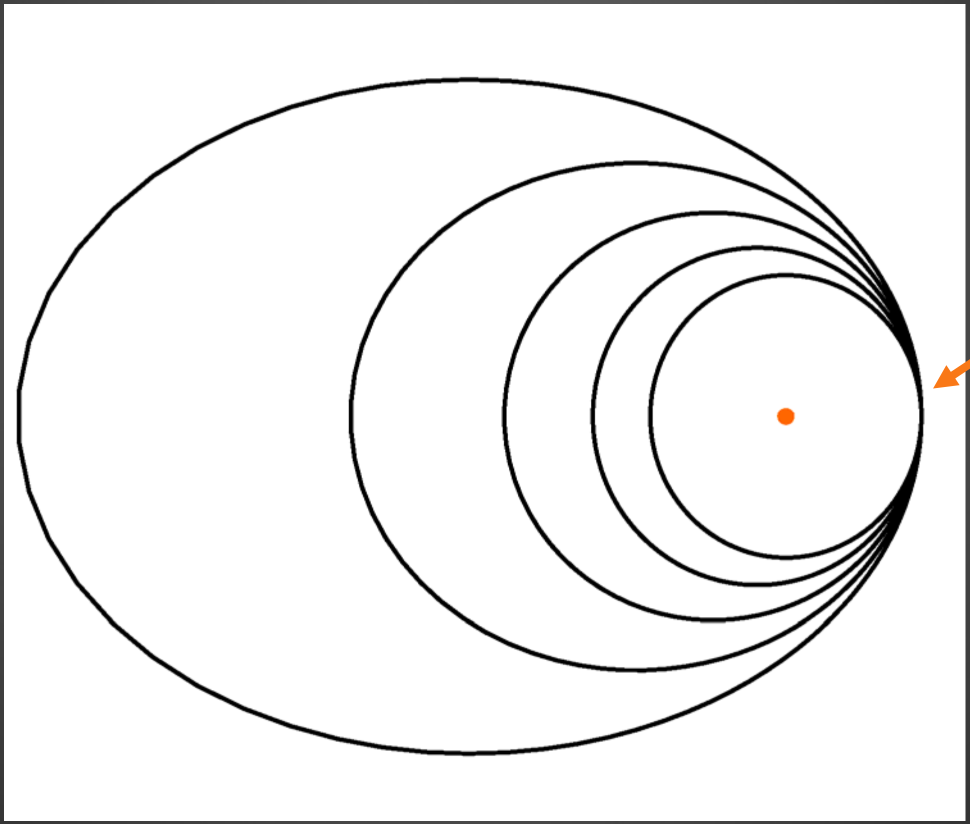
Eccentric Planets



3.52d

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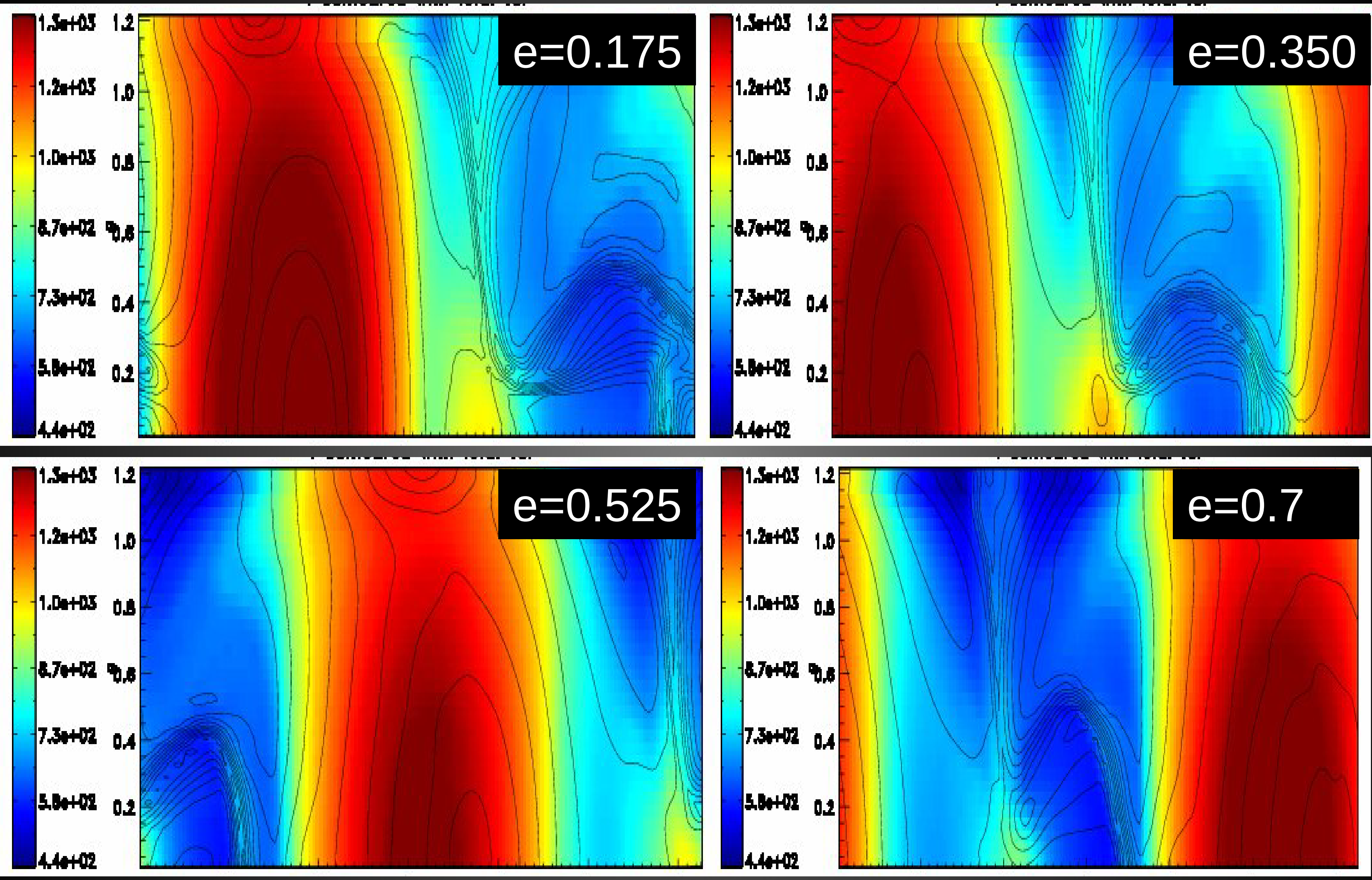

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Conclusions

- Numerical treatment of radiation and dynamics must be included as coupled model.
- Three (pseudo) jets (one equatorial and two mid-lat.) are common features, with width decreasing with increased planetary rotation.
- 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
- Caution must be exercised in regions where material passes through strong shocks. Radial velocity becomes very important
- Dynamically driven variability causes variations transit spectra, but variation in hemispherically averaged phase curves will be difficult.
- Differences between ingress and egress transmission spectra may prove to be powerful tools for model diagnostics.
- Continuing observational programs, and coupling of dynamical and spectral models should allow tighter constraints on dynamical processes: eccentric planets, multiple wavelength (and continuous) observations, lower masses, younger planets.