Planetary Dynamos: A Brief Overview

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(with contributions and inspiration from Mark Miesch)
Geomagnetic Declination in 1701

[Edmond Haley, 1701]
History of Earth’s Magnetic Field

Movie:
Chris Finlay (DTU)

Geomagnetism is Dynamic
Something inside the Earth is causing this variation
Most Planets Possess Magnetic Fields

[Cao 2014]

Mercury

Earth

Jupiter

Saturn

Uranus

Neptune
Where are we going?

- Quick review of dynamo fundamentals
- A closer look at rotating convection
- Survey of magnetism in the solar system
- The triumphs and troubles of simulations
MHD Magnetic Induction equation

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (v \times \mathbf{B} - \eta \nabla \times \mathbf{B}) \]

Comes from Maxwell’s equations (Faraday’s Law and Ampere’s Law)

\[ \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \]

\[ \nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J} \quad \text{(Assumes } v \ll c) \]

And Ohm’s Law

\[ \mathbf{J} = \sigma \mathbf{E} \]

Magnetic diffusivity

\[ \eta = \frac{c^2}{4\pi \sigma} \]

electrical conductivity
Creation and destruction of magnetic fields

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \nabla \times \mathbf{B}) \]

How would you demonstrate this?

(Hint: have a sheet handy with lots of vector identities!)

\[ E_m = \frac{B^2}{8\pi} \]
Creation and destruction of magnetic fields

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \nabla \times \mathbf{B}) \]

Source of Magnetic Energy

\[ \frac{\partial E_m}{\partial t} = -\nabla \cdot \mathbf{F}_P - \frac{\mathbf{v}}{c} \cdot (\mathbf{J} \times \mathbf{B}) - \Phi_o \]

Sink of Magnetic Energy

Poynting Flux

\[ \mathbf{F}_P = \mathbf{E} \times \mathbf{B} = \left[ \frac{\eta}{c} \mathbf{J} - \frac{1}{4\pi} (\mathbf{v} \times \mathbf{B}) \right] \times \mathbf{B} \]

Ohmic Heating

\[ \Phi_o = \frac{4\pi \eta}{c^2} J^2 \]
Creation and destruction of magnetic fields

\[ \frac{\partial B}{\partial t} = \nabla \times (v \times B - \eta \nabla \times B) \]

Source of Magnetic Energy
\[ \sim UB / D \]

Sink of Magnetic Energy
\[ \sim \eta B / D^2 \]

\[ Rm = \frac{UD}{\eta} \]

If \( Rm \gg 1 \) the source term is much bigger than the sink term

....Or is it???
Creation and destruction of magnetic fields

\[ \frac{\partial B}{\partial t} = \nabla \times (v \times B - \eta \nabla \times B) \]

\( \delta \) can get so small that the two terms are comparable

It’s not obvious which term will “win” - it depends on the subtleties of the flow, including geometry & boundary conditions
Creation and destruction of magnetic fields

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \nabla \times \mathbf{B}) \]

Source of Magnetic Energy
\( \sim U B / D \)

Sink of Magnetic Energy
\( \sim \eta B / \delta^2 \)

What is a Dynamo? (A corollary)

A dynamo must sustain the magnetic energy (through the conversion of kinetic energy) against Ohmic dissipation
The need for a Dynamo

If \( v = 0 \) and \( \eta = \text{constant} \) then the induction equation becomes

\[
\frac{\partial B}{\partial t} = -\eta \nabla \times \nabla \times B = \eta \nabla^2 B
\]

The field will diffuse away (dissipation of magnetic energy) on a time scale of

\[
\tau_d \approx \frac{D^2}{\eta}
\]

A more careful calculation for a planet gives

\[
\tau_d \approx \frac{R^2}{\pi^2 \eta}
\]

Earth: \( \tau_d \sim 80,000 \text{ yrs} \)

Jupiter: \( \tau_d \sim 30 \text{ million yrs} \)

Planetary fields must be maintained by a dynamo or they would have decayed by now!
Conditions for a Planetary (or Stellar) Dynamo

Absolutely necessary

- **An electrically conducting fluid**
  - Stars: plasma
  - Terrestrial planets: molten metal (mostly iron)
  - Jovian planets: metallic hydrogen (maybe molecular H)
  - Ice Giants: water/methane/ammonia mixture
  - Icy moons: salty water

- **Fluid motions**
  - Usually generated by buoyancy (convection)

- **Rm >> 1**
  - Too much ohmic diffusion will kill a dynamo
Conditions for a Planetary (or Stellar) Dynamo

Not strictly necessary but it (usually) helps

- **Rotation**
  - **Good**: helps to build strong, large-scale fields (promotes magnetic self-organization)
  - **Bad**: can suppress convection (though this is usually not a problem for planets)

- **Turbulence** (low viscosity / $Re \gg 1$)
  - **Good**: Chaotic fluid trajectories good at amplifying magnetic fields (chaotic stretching)
  - **Bad**: can increase ohmic dissipation
The MHD Induction Equation: Alternate View

\[ \frac{\partial B}{\partial t} = -B \nabla \cdot v + B \cdot \nabla v - v \cdot \nabla B - \nabla \times (\eta \nabla \times B) \]

- Compression
- Advection
- Diffusion
- Shear production
- Rotation
- Large-Scale Shear (differential rotation)
- Small-Scale Shear (helical rolls)

**Convection Simulations**

- Non-rotating
- Rapidly-rotating
- Red upflow
- Blue downflow

*Rotating convection naturally generates both small-scale and large-scale shear!*
Rotation Yields Helical Convection

Non-rotating or Fast Convection

Rapidly-rotating or Slow Convection

"alpha-effect"

Olson et al., 1999, JGR
Helical rolls (or their turbulent counterparts) probably form the central engine of most planetary and stellar dynamos.

So where do they come from?
The (hydro) momentum equation

- Consider incompressible flow with constant diffusivities

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

- Consider perturbations about background state:

\[ \rho = \rho' + \bar{\rho} \quad \rho' \ll \bar{\rho} \quad \bar{\rho} = \text{constant} \]

\[ P = P' + \bar{P}(r) \quad P' \ll \bar{P} \]
The (hydro) momentum equation

- Subtract out hydrostatic balance
- Divide by $\overline{\rho}$

$$\frac{\partial \mathbf{u}}{\partial t} = -\mathbf{u} \cdot \nabla \mathbf{u} - 2(\mathbf{\Omega} \times \mathbf{u}) + \frac{\rho'}{\rho} \mathbf{g} - \frac{1}{\rho} \nabla P' + \nu \nabla^2 \mathbf{u}$$

- Recast density perturbation in terms of temperature

$$\frac{\rho'}{\overline{\rho}} = -\alpha T'$$

Hotter than surroundings = low density
Cooler than surroundings = high density

$\alpha > 0$
The (hydro) momentum equation

\[ \frac{\partial u}{\partial t} = -u \cdot \nabla u - 2(\Omega \times u) + \alpha T' g \hat{r} - \frac{1}{\rho} \nabla P + \nu \nabla^2 u \]

\[ \frac{\rho'}{\rho} = -\alpha T' \quad \alpha > 0 \]

- Hot fluid rises
- Cool fluid sinks
- This leads to convection (under the proper circumstances)
Convection 101

- **Background Temperature**
  - Warm
  - Cool

- **Height**
  - Input $E$
  - Output $E$

- **“Conductive” state** (no convection)

- Gravity
Convection 101

Background Temperature vs. Height

- Warm fluid parcel
- Cool fluid parcel

Input E and Output E

Gravity direction
Convection 101

- Background Temperature
- Height

- Warm fluid parcel
- Cool fluid parcel

- Gravity
- Small displacement

input E → output E
Convection 101

- Background Temperature
- Height

Gravity

T’ > 0 rises

T’ < 0 sinks

Warm fluid parcel

Cool fluid parcel
Convection 101

• Possible temperature profiles depend on strength of convection

• So what determines that?

  - pure conduction
  - weak convection
  - strong convection
The Internal Energy Equation

- Consider incompressible flow with constant diffusivities

\[
\frac{\partial T}{\partial t} = -\mathbf{u} \cdot \nabla T + \kappa \nabla^2 T
\]

- Competition between advection and diffusion
The competition: buoyancy vs. diffusion

- As a fluid parcel rises or falls, it also diffuses.
- If diffusion is too large, it dissipates heat/momentum before making it very far.
- We can quantify this.

(time & height)
Exercise: The diffusive timescale

• Consider the 1-D diffusion equation:

\[ \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} \]

• Seek a solution of the form:

\[ T = A e^{\frac{t}{\tau}} \sin \left( \frac{\pi}{L} x \right) \]

• What is \( \tau \)? Is it positive or negative?
Exercise: The diffusive timescale

• **Solution:**

\[ \tau = \frac{L^2}{\kappa \pi^2} \]

• **Neglect factor of** \( \pi^2 \):

\[ \tau \sim \frac{L^2}{\kappa} \]

• **Diffusion time for length scale** \( L \)
Important Timescales

thermal diffusion time

\[ \tau_K \sim \frac{L^2}{\kappa} \]

viscous diffusion time

\[ \tau_\nu \sim \frac{L^2}{\nu} \]

buoyancy timescale?

\[ \tau_B \sim ? \]
Exercise: buoyancy timescale

- Consider simplified momentum equation:
  \[ \frac{\partial u}{\partial t} = \alpha \tilde{T} g \]

- What is freefall time (\( \tau_B \)) over a distance \( L \)? (assume \( \tilde{T} \) is constant)
  \[ \tau_B = \sqrt{\frac{2L}{\alpha \tilde{T} g}} \]
Important Timescales

- **thermal**
  \[ \tau_k \sim \frac{L^2}{\kappa} \]

- **viscous**
  \[ \tau_v \sim \frac{L^2}{\nu} \]

- **buoyancy**
  \[ \tau_B \sim \sqrt{\frac{L}{\alpha \tilde{T} g}} \]

Can quantify competition between buoyantly driven advection and diffusion via the Rayleigh number Ra:

\[ Ra = \left( \frac{\tau_k}{\tau_B} \right) \left( \frac{\tau_v}{\tau_B} \right) = \frac{\alpha \tilde{T} g L^3}{\nu \kappa} \]
Why Helical Rolls?

Coriolis Force:
\[ \frac{\partial u}{\partial t} = 2u \times \Omega \]

Lorentz Force:
\[ \frac{\partial u}{\partial t} = qu \times B \]
Some Important Numbers

\[ Ra = \frac{\alpha \tilde{T} g L^3}{\nu \kappa} \]

- Dissipation Timescale
- Buoyancy Timescale

\[ Ro = \frac{U}{2 \Omega D} \]

- Rotational Timescale
- Convective Timescale

\[ Ek = \frac{\nu}{2 \Omega D^2} \]

- Rotational Timescale
- Viscous Timescale
Understanding the Dynamics

Conservation of momentum in MHD

\[
\rho \frac{\partial \mathbf{v}}{\partial t} = - (\rho \mathbf{v} \cdot \nabla) \mathbf{v} - 2\rho (\Omega \times \mathbf{v}) - \nabla P + \rho \mathbf{g} + \frac{c^{-1}}{\mathbf{J} \times \mathbf{B}} - \nabla \cdot \mathbf{D}
\]

Convection established by buoyancy

But rotation exerts an overwhelming influence

Coriolis accelerations happen quickly (days) compared to convection and dynamo time scales (hundreds to thousands of years)

\[
Ro = \frac{U}{2\Omega D} \ll 1 \quad \text{Ek} = \frac{\nu}{2\Omega D^2} \ll 1
\]
Dynamical Balances

\[ c^{-1} J \times B \approx 2\rho (\Omega \times v) + \nabla P - \rho g \]

Now set \( B = 0 \) and assume that \( \nabla \rho \) is mainly radial

Then the \( \phi \) component of the curl gives (anelastic approximation):

\[ \Omega \cdot \nabla (\rho v) = \frac{\partial}{\partial z} (\rho v) = 0 \]

Taylor-Proudman Theorem

Incompressible version:

\[ \frac{\partial v}{\partial z} = 0 \]

Rapidly rotating flows tend to align with the rotation axis
What might convection look like in a rapidly-rotating spherical shell?

How can you get the heat out while still satisfying the Taylor-Proudman theorem?

\[ \frac{\partial \mathbf{v}}{\partial z} = 0 \]

Can you satisfy it everywhere?
Linear Theory

The most unstable convective modes in a rapidly-rotating, weakly-stratified shell are Busse columns aka Banana Cells

The preferred longitudinal wavenumber (m) scales as $E_k^{-1/3}$

Coriolis vs viscous diffusion
Linear Theory

The Tangent Cylinder
Delineates two distinct dynamical regimes

Implication of the Taylor-Proudman theorem
Earth

Dynamo!

Field strength
~ 0.4 G

Dipolarity
~ 0.61

Tilt
~ 10°

Archetype of a terrestrial planet!
Direct measurements of Earth’s magnetic field date back to the early 1500’s, with a boost in the early 1800’s with the Magnetic Crusade led by Sabine in England and Gauss and Weber in Germany.

Today we also have satellite measurements.

Jones (2011)

Longer time history can be inferred from measurements of magnetic signatures in crustal rocks.
Magnetic poles flip every ~ 200,000 years on average, but randomly

Irregular reversals!
Earth

Mantle convection responsible for plate tectonics but not the geodynamo
Earth

Mantle
non-conducting, slow

Overturning time
~100 million years

Outer Core
conducting, fast

Overturning time
~500 years
Earth

Rotational influence quantified by

Rossby number

\[ \text{Ro} = \frac{U}{2\Omega D} = \frac{1}{4\pi} \frac{P_{rot}}{\tau_c} \]

\[ \text{Ro} \sim 4 \times 10^{-7} \]

Outer Core conducting, fast

Overturning time

\sim 500 \text{ years}
Spherical Harmonic expansion of the surface field allows for a backward extrapolation to the core-mantle boundary (CMB)

Assuming no currents in the non-conducting mantle & crust

\[ B_r \propto r^{-(\ell+2)} \]
Earth

\[ B_r \propto r^{-(\ell+2)} \]

Dipole dominates at large distances from the dynamo region \( \sim r^3 \)

Time evolution of surface field can be used to infer flows at the CMB

Jones (2011)
Energy sources for convective motions

- **Outward heat transport by conduction**
  - Cooling of the core over time
  - Proportional to the heat capacity

- **Latent heat**
  - Associated with the freezing (phase change) of iron onto the solid core

- **Gravitational Differentiation**
  - Redistribution of light and heavy elements, releasing gravitational potential energy

- **Radioactive Heating**
  - Energy released by the decay of heavy elements
Venus

No Dynamo

No field detected

Why?

Core may be liquid and conducting, but it may not be convecting (rigid top may inhibit cooling)

Also - slow rotation
Mars

No Dynamo

*Fields patchy, reaching ~ 0.01 G in spots but no dipole*

Why?

*It had a dynamo in the past (remnant crustal magnetism) but it cooled off fast, freezing out its molten core*
**Mercury**

**Dynamo!**

- **Field strength**: $\sim 0.003$ G
- **Dipolarity**: $\sim 0.71$ G
- **Tilt**: $\sim 3^\circ$

*Huge iron core relative to size of planet that is still partially molten*

Schubert & Soderlund (2011)
Ganymede!

Dynamo!

*Field strength*
\[ \sim 0.01 \, \text{G} \]

*Dipolarity*
\[ \sim 0.95 \, \text{G} \]

*Tilt*
\[ \sim 4^\circ \]

*Other icy satellites have induced magnetic fields from passing through the magnetospheres of their planets*

Schubert & Soderlund (2011)
Juno!
Jupiter

Big Whopping Dynamo!

Field strength ~ 7 G

Dipolarity ~ 0.61

Tilt ~ 10°

Archetypical Jovian planet!
Jupiter

Layer composed of Hydrogen and Helium in liquid state

Layer composed of metallic Hydrogen

The core made of rock, metallic Hydrogen and Helium

Hydrogen and Helium in gas state
Jupiter: Internal Structure

\( \eta \) (\( m^2 \text{ s}^{-1} \))

\[ Rm = \frac{UD}{\eta} \]

Transition from metallic to molecular (liquid) H

French et al. (2012)
Jupiter: Internal Structure

\[ \eta (m^2 s^{-1}) \]

Convection Zone?

Dynamo Region?
Jupiter: Magnetic Field (Pre-Juno)

Ridley & Holme (2016)
Initial results from Juno

Stronger and more patchy than expected (higher-order multipoles)

\[ B_r \propto r^{-(\ell+2)} \]

Moore et al (2017)
**Saturn**

**Dynamo!**

*Field strength*
\[ \sim 0.6 \text{ G} \]

*Dipolarity*
\[ \sim 0.85 \text{ G} \]

*Tilt*
\[ < 0.5^{\circ} \]

**Remarkably axisymmetric!**

A surprise!

**Cowling’s Theorem:** It is not possible for a dynamo to produce a steady axisymmetric field!!

Connerney (1993)

Jones (2011)
Uranus & Neptune

Dynamos!

Field strength $\sim 0.3$ G

Dipolarity $\sim 0.42, 0.31$

Tilt $\sim 59^\circ, 45^\circ$

Jones (2011)

Connerney (1993)
Nonlinear Regimes require Numerical Models

Solve the MHD equations in a rotating spherical shell
Anelastic or Boussinesq approximation
\(\rho, T, P, S\) are linear perturbations about a
**hydrostatic, adiabatic** background state

**Convection simulations:** heating from below, cooling from above
## Numerical Models: The Challenge

\[ P_m = \frac{\nu}{\eta} \]

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Jupiter</th>
<th>Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ra</td>
<td>$10^{31}$</td>
<td>$10^{37}$</td>
<td>$10^6$-$10^7$</td>
</tr>
<tr>
<td>Ek</td>
<td>$3 \times 10^{-15}$</td>
<td>$10^{-9}$</td>
<td>$10^{-6}$ - $10^{-7}$</td>
</tr>
<tr>
<td>Rm</td>
<td>300-1000</td>
<td>400-$3 \times 10^4$</td>
<td>50-3000</td>
</tr>
<tr>
<td>Pm</td>
<td>$5-6 \times 10^{-7}$</td>
<td>$6 \times 10^{-7}$</td>
<td>0.1-0.01</td>
</tr>
</tbody>
</table>
The Sun is Even Worse...

**Convection Zone Bulk**

- Temperature: 14,400K
- Density: $2 \times 10^{-6}$ g cm$^{-3}$

- Temperature: 2.3 million K
- Density: 0.2 g cm$^{-3}$

- 11 density scaleheights
- 17 pressure scaleheights
- Reynolds Number $\approx 10^{12} - 10^{14}$
- Rayleigh Number $\approx 10^{22} - 10^{24}$
- Magnetic Prandtl Number $\approx 0.01$
- Prandtl Number $\approx 10^{-7}$
- Ekman Number $\approx 10^{-15}$

Nevertheless...
Axial alignment persists even in turbulent parameter regimes


Axial vorticity $\omega \cdot \Omega$

$Ek = 2.3 \times 10^{-7}$

$Ek = 2.6 \times 10^{-6}$

Busse columns give way to vortex sheets but the flow is still approximately 2D

$Ek = \frac{\nu}{2\Omega R^2}$
...and in MHD

\[ \text{Ra} = \frac{G M D \Delta S}{\nu \kappa C_P} = \frac{\text{buoyancy driving}}{\text{dissipation}} \]

Ra = \(8 \times 10^5\)

Ra = \(2.5 \times 10^7\)

Jones et al (2011)
General trends

Complexity of magnetic field depends mainly on the rotational influence

Rapid rotators tend to be more dipolar

Christensen & Aubert (2006)
Dynamical Balances

\[ \rho \frac{\partial v}{\partial t} = - (\rho v \cdot \nabla) v - 2\rho (\Omega \times v) - \nabla P + \rho g + c^{-1} \mathbf{J} \times \mathbf{B} - \nabla \cdot \mathbf{D} \]

Result: Flows evolve quasi-statically in so-called Magnetostrophic (MAC) Balance

\[ c^{-1} \mathbf{J} \times \mathbf{B} \approx 2\rho (\Omega \times v) + \nabla P - \rho g \]
Question

Assuming MAC balance, compute the ratio of \( \text{ME/KE} \). How does it scale with \( \text{Ro} \)?

\[
c^{-1} \mathbf{J} \times \mathbf{B} \approx 2\rho (\Omega \times \mathbf{v}) + \nabla P - \rho g
\]

\[
\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J}
\]

\[
\text{ME} = \frac{B^2}{8\pi}
\]

\[
\text{KE} = \frac{1}{2} \rho \mathbf{v}^2
\]

\[
\text{Ro} = \frac{U}{2\Omega D}
\]
**Question**

\[ c^{-1} \mathbf{J} \times \mathbf{B} \approx 2\rho (\Omega \times \mathbf{v}) + \nabla P - \rho g \]

Assuming MAC balance, compute the ratio of ME/KE

How does it scale with Ro?

\[ \frac{ME}{KE} \sim Ro^{-1} \]

>>1 if \( Ro \ll 1 \)!

*But how do KE and Ro (and thus, ME) depend on observable* *global parameters like \( \Omega \) and \( F_c \)?

*in principle*
Field strength scales with the heat flux through the shell (independent of $\Omega$!)

Rapid rotators seem to operate at maximum efficiency, tapping all the energy they can

Christensen et al (2009)
Numerical Models: The Hope

Realistic simulations might be possible if you can achieve the right dynamical balances (e.g. MAC balance)

The most important parameters to get right
(or as right as possible)

- **Ro**
  - Appropriate rotational influence on the convection

- **Rm**
  - Reasonable estimate of the ohmic dissipation

- **Ek**
  - At least get it small enough that viscosity isn’t part of the force balance
Example: The Geodynamo

Points of comparison: Field strength, morphology (spectrum, symmetry, etc), Reversal timescale

Christensen et al (2010)
Best matches are those with $Ek < 10^{-4}$ and $Rm$ “large enough”
Example: The Geodynamo

Inferred from observations

But be careful! They could be right for the wrong reasons! For example, both c and d have a higher Ra and lower Ek than b. They should be more realistic, right?
Observations


$B_r$ CMB

$L_{\text{max}} \sim 13$

Models

Soderlund et al. *EPSL* 2012

$B_r$ CMB

On the surface, things look pretty good...
**Observations**


\[ B_r \text{ CMB} \]

\[ L_{\text{max}} \sim 13 \]

**Models**

Soderlund et al. *EPSL* 2012

\[ z\text{-vorticity} \]

Beneath the surface ...

... probably unphysical
Rotating Convection Columns: column size set by Ekman number $E$

$$E = \frac{\tau_{rotation}}{\tau_{viscous}} = \frac{\nu}{\Omega L^2}$$

Models:

$$E \sim 1e^{-4}; l_c \sim 0.1$$

Earth’s Core:

$$E \sim 1e^{-15}; l_c \sim 1e^{-5}$$

(i.e., $10^4$ x smaller than scale of flux patches)
Rapidly Rotating MHD:

We observe large scales ...

... but we know the small scale matter (a lot)

Rubio, Julien, Weiss, Knobloch PRL 2014
Numerical Models: Summary

Lessons Learned

- Rapid Rotation has a profound influence on the dynamics
- Success attributed to correct dynamical balances and (when possible) realistic Rm

Future challenges

- What happens at really low Ek (tiny $\nu$)?
- Peculiarities of particular planets (Saturn, Mercury, Uranus, Neptune...)
  - Boundary conditions (adjacent layers)
  - Rapid variations of $\eta$
  - Energy sources
  - Compositional convection
- Moving to more realistic parameters doesn’t always improve the fidelity of the model
- Exoplanets!
Juno!
Juno!
Heimpel et al. 2018 (in-prep)