Lecture 4: Giant planets and brown dwarfs

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Zonal winds on the giant planets

Eastward wind (m/sec) vs. Latitude (deg)

Sukoriansky et al. (2002) - Jupiter
Kaspi et al. (2013) - Saturn, Uranus, Neptune
<table>
<thead>
<tr>
<th></th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation (hours)</td>
<td>9.92</td>
<td>10.57</td>
<td>17.24</td>
<td>16.11</td>
</tr>
<tr>
<td>Mean radius (km)</td>
<td>69,911</td>
<td>58,232</td>
<td>25,362</td>
<td>24,622</td>
</tr>
<tr>
<td>Max. wind velocity (m/s)</td>
<td>140</td>
<td>480</td>
<td>240</td>
<td>380</td>
</tr>
<tr>
<td>Obliquity</td>
<td>3°</td>
<td>27°</td>
<td>98°</td>
<td>28°</td>
</tr>
<tr>
<td>Rossby number, u/ΩL</td>
<td>0.02</td>
<td>0.04</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Small Rossby number $u/\Omega L \ll 1$ implies geostrophic balance – a balance between Coriolis accelerations and pressure-gradient forces at large scale.
Temperatures are relatively homogeneous:
Energy budgets

Internal heat fluxes are substantial compared to solar flux on Jupiter, Saturn and Neptune

Internal structure:
Jupiter and Saturn’s temperatures and clouds
Jupiter’s Zonal Winds

Saturn’s zonal winds at the dawn of Cassini

Sanchez-Lavega et al. (2004, 2007); Porco et al. (2005)
Cassini confirmed strong vertical shear at the equator with a slowdown in the upper troposphere (relative to Voyager).

Choi et al. (2009), Garcia-Melendo et al. (2010, 2011)
Thermal and jet structure above the clouds

Read et al. (2009); Flasar et al. (2005); Li et al. (2008)
Stratospheric equatorial jet oscillations

Guerlet et al. (2011), Orton et al. (2008); Fouchet et al. (2008); Schinder et al. (2011); Li et al. (2011)
**Basic Jet Scenarios**

- **Models for jet structure:**
  - *Shallow:* Jets confined to outermost scale heights below the clouds
  - *Deep:* Jets extend through molecular envelope (Taylor-Proudman theorem)

- **Models for jet pumping:**
  - *Shallow:* Turbulence at cloud level (thunderstorms or baroclinic instabilities)
  - *Deep:* Convective plumes penetrating the molecular envelope

These are among the most important unsolved problems in planetary atmospheres.

Note that the issues of structure and forcing are distinct!
Rotation also causes alignment of convection at large scales
Evidence for eddy-momentum convergences into the jets at cloud level

These measurements demonstrate that the jets *are* being driven at cloud level.

Salyk et al. (2006), Del Genio et al. (2007), Del Genio & Barbara (2012)
Puzzles

• What causes the banded structure, with ~20 jets on Jupiter and Saturn yet only ~3 on Uranus and Neptune? What is the jet-pumping mechanism?

• How deep do the jets extend?

• Why do Jupiter and Saturn have superrotating equatorial jets whereas Uranus and Neptune do not?

• What causes the vortices? What controls their behavior? How do they interact with the jets?

• What is the temperature structure and mean circulation of the stratosphere and upper troposphere?
Gravitational sounding of giant planet interiors: answering the question of how deep the jets extend
Gravitational signature of internal dynamics

On the giant planets, the dynamics may involve a considerable fraction of the mass, and therefore density fluctuations due to dynamics may be detectable in the gravity field.

Gravitational potential represented as

\[ V(\vec{r}) = \frac{GM}{r} - a^n \sum_{n=2}^{\infty} \frac{J_n P_n(\mu)}{r^n} \]

where \( J_n \) are the gravitational harmonics, defined as

\[ J_n = - \frac{1}{Ma^n} \int r^n P_n(\mu)(r, \phi, \theta) d^3r \]

\( \rho \) is density, \( P_n \) are Legendre polynomials, \( a \) is planetary radius, \( r \) is radial distance, \( \phi \) is longitude, \( \mu \) is cosine of angle from rotation axis, and \( M \) is total mass.

(See Hubbard 1984 for a review.)
• Use the observed winds and assume an idealized interior vertical structure with a decay length $H$.

$$u = u_{cyl}e^{-\left(\frac{a-r}{H}\right)}$$

• Calculate corresponding density structure from thermal wind equation.

Kaspi, Hubbard, Showman, & Flierl (2010)
Predicted Jupiter gravity spectrum for various depths of zonal flow

Key point: gravitational signature of jets will be detectable by Juno if jets extend at least ~500 km into the interior. Juno will measure to $J_{12}$ or $J_{14}$. Jets dominate over solid-body rotation beyond $J_{10}$ if they extend deeply enough.
Odd gravity harmonics are a very sensitive probe of deep dynamics

Hemispheric (N minus S) difference in Saturn zonal winds

Gravity spectrum under various assumptions for how deep the jets penetrate

Kaspi (2013)
What about Uranus and Neptune?

Observed jets are broad, and winds are fast. Thus, winds cause a large perturbation to low gravity harmonics like $J_4$. This suggests that we can constrain depth of jets on Uranus and Neptune now with current data—namely, $J_2$ and $J_4$—unlike the case of Jupiter where we need a close flying orbiter like Juno.

Kaspi et al. (2013)
Procedure to infer depth of jets from $J_4$

- Calculate the full suite of static, wind-free interior models that match all data—mass, radius, $J_2$, and atmospheric density—but without using $J_4$ as a constraint.

- Determine the $J_4$ values that these wind-free interior models imply.

- If the $J_4$ calculated for these wind-free models is consistent with observations, then winds are not needed to explain the data (i.e., winds are not strong enough to influence the gravity, implying jets are shallow).

- But if the $J_4$ calculated for these wind-free models differs significantly from the observed $J_4$, then the discrepancy must be explained by dynamics (which would require that the jets extend deep into the interior).
If winds extend too deeply, the meteorological perturbation to $J_4$ would exceed the maximum possible difference between the observed $J_4$ and the allowable $J_4$ from static, wind-free models. This implies that:

- On Neptune, winds confined to outermost ~1000 km (~3000 bars, 0.2% of planetary mass)
- On Uranus, winds confined to outermost ~1500 km (~4000 bars, 0.35% of planetary mass)

Kaspi, Showman, et al. (2013)
Storms and lightning

Vasavada & Showman (2005)
Local features on Saturn

Spots cluster at a certain size (~500-1000 km), putting constraints on the deformation radius.
The White Ovals formed in 1938-40 during an instability on a jet:

There were 3, but 2 merged in 1998 and the remaining 2 merged in 2000, leaving only one left:
Models support the idea that large Jovian ovals formed by jet instability:

Williams (2002); Dowling & Ingersoll (1989), Read & Hide (1983, 1984), Sommeria et al. (1988)
A new frontier: directly imaged planets and brown dwarfs
Brown dwarf basics

• Brown dwarfs are fluid hydrogen objects intermediate in mass between giant planets and stars. They are often free floating, though many also orbit stars.

• Presumed to form like stars (i.e., directly collapsing from a hydrogen cloud) but have masses too low to fuse hydrogen. Generally defined as objects with masses of 13 to ~80 Jupiter masses.

• Since they cannot fuse hydrogen, they cool off over time (like Jupiter). But massive brown dwarfs cool slowly and can still have surface temperatures >1000 K even after many billions of years.

• Over a wide mass range (~0.3 to ~80 Jupiter masses), brown dwarfs and giant planets have radii very close to Jupiter’s.

• >1000 brown dwarfs have been discovered, mostly with high temperature (>700 K) but now including objects as cool as ~300 K.

Evolution tracks: luminosity versus time
Brown dwarfs are classified according to their IR spectra into M, L, T, and Y (from hot to cold). Unlike most stars, their spectra are dominated by molecular features. Dust (i.e., silicate clouds) affects the spectrum of M and L dwarfs, but not T dwarfs.
Brown dwarfs show evidence for condensate (dust) clouds

L dwarfs are cloudy, leading to flat spectral features:

T dwarfs are generally cloud free:

This behavior is explained by the fact that condensate levels lie in the atmosphere for hot objects (M, L dwarfs) but sink into the interior for cool objects (T dwarfs):
Color-magnitude diagrams are useful for understanding overall trends among brown dwarfs. The change in color across the L/T transition is due to the loss of clouds, which opens the spectral windows. This occurs better in J than K, causing a shift to the blue as the clouds disappear.
Color-magnitude diagrams are useful for understanding overall trends among brown dwarfs

Magnitude (brightness) in J band, which is a spectral window. The change in color across the L/T transition is due to the loss of clouds, which opens the spectral windows. This occurs better in J than K, causing a shift to the blue as the clouds disappear.
The L/T transition

- Although the loss of clouds across the L/T transition makes sense, the details are a puzzle: the transition occurs too fast.
  - 1D models of uniform cloud decks sinking into the interior predict that the J-band flux continually dims across the transition:
  - But in reality the J-band flux actually increases temporarily across the transition (the “J-band bump”), despite the fact that T dwarfs are cooler than L dwarfs
  - This suggests that the cloud decks are not simply disappearing from view, but becoming patchy or getting thin as they do so
- 1D models that assume the cloud deck gets patchy across the transition do a much better job of reproducing the “J-band bump”

This suggests a strong role for meteorology in controlling the transition
Chemical disequilibrium

- In cool giant planets and brown dwarfs, the equilibrium form of carbon and nitrogen at the top are \( \text{CH}_4 \) and \( \text{NH}_3 \). The equilibrium form at depth are \( \text{CO} \) and \( \text{N}_2 \).

- In the absence of dynamics, equilibrium would prevail. But vertical mixing can dredge \( \text{CO} \)-rich, \( \text{CH}_4 \)-poor, and \( \text{NH}_3 \)-poor air from depth and mix it into the atmosphere.

- This will result in an excess of \( \text{CO} \), and a deficit of \( \text{CH}_4 \) and \( \text{NH}_3 \), in the atmosphere.

- Just such excesses and deficits are observed, and are interpreted as the result of vertical mixing. The observed abundances can be used to constrain the mixing rates.

Thus, dynamics is required to explain the chemical disequilibrium.

Saumon et al. (2006)
T2.5 brown dwarf SIMP 0136 shows weather variability

Artigau et al. (2009); see also Radigan et al. (2012), Buenzli et al. (2012), and many upcoming papers by Apai, Metchev, Radigan, Flateau, ....
Light Curves

Apai et al. (2013)

Artigau et al. (2009)
Doppler imaging technique: a method to map the surface patchiness of brown dwarfs

Showman (2014); see also Rice (2002)
Maps of Luhman 16B, the closest known brown dwarf to Earth

Crossfield et al. (2014, Nature), see also Showman (2014, Nature)
Summary of evidence for dynamics/weather on brown dwarfs

1) Existence of clouds is required to explain spectra of many brown dwarfs.

2) Explaining the L/T transition requires change in cloud dynamics/physics, e.g., opening of holes in the clouds, as objects cool off over time.

3) Disequilibrium chemistry (quenching of CO, CH\textsubscript{4}, NH\textsubscript{3}) implies mixing from below, and allows mixing rate to be inferred if chemical kinetics are understood.

4) IR variability implies cloudy and cloud-free patches rotating in and out of view. Shape of lightcurves vary over time, implying that the \textit{spatial pattern} of cloud patchiness evolves rapidly.

5) Doppler imaging allows global maps of surface patchiness to be inferred for the brightest brown dwarfs.
Dynamical Regime of brown dwarfs

- Rapid rotation (Period ~ 1.5-12 hours) implies rotational domination (Rossby numbers << 1)

- Stably stratified atmosphere overlies vigorously convecting interior

- No external irradiation no imposed horizontal gradients in heating or temperature (unlike solar system planets or transiting exoplanets)

- Wave generation will play a key role. Atmospheres may be mechanically driven, like stratospheres of Earth and Jupiter
Some questions

• What is the atmospheric circulation like on brown dwarfs? Are there zonal jets? Large vortices? Fluctuating turbulence? What are the wind speeds, temperature fluctuations, and key length scales?

• How does the circulation work? What types of waves are generated by the convection, and by what mechanisms might they drive a circulation? How coupled is the atmosphere to the interior?

• What are the vertical mixing rates? To what extent is the mixing dominated by breaking gravity waves rather than large-scale overturning?

• How do clouds couple to the circulation? How patchy are the cloud layers?
Jupiter at many wavelengths
References


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