In some worlds there is no Sun and Moon, in others they are larger than in our world, and in others more numerous. In some parts there are more worlds, in others fewer (...); in some parts they are arising, in others failing. There are some worlds devoid of living creatures or plants or any moisture. **Democritus** (~460-370 B.C.)

There are infinite worlds both like and unlike this world of ours. For the atoms being infinite in number, as was already proven, (...) there nowhere exists an obstacle to the infinite number of worlds. **Epicurus** (341-270 B.C.)

There cannot be more worlds than one. **Aristotle** (384-322 B.C.)
GIANT PLANETS AT SMALL ORBITAL DISTANCES

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Received 1995 November 8; accepted 1995 December 19

4. THERMAL AND NONTHERMAL EVAPORATION
OF A GAS GIANT

If 51 Peg B is a gas giant, is it stable to evaporation and, if so, what is its current evaporation rate? We consider two potential loss mechanisms: (1) classical Jeans evaporation, and (2) the nonthermal production of hot hydrogen atoms and ions by absorption of ultraviolet radiation from 51 Peg A.

The classical Jeans escape flux is proportional to $e^{-\lambda}(\lambda + 1)$, where $\lambda = GM_pm_H/kTR_p$ (Chamberlain & Hunten 1987). Here $m_H$ is the mass of the hydrogen atom or molecule, $k$ is Boltzmann’s constant, and $T$ is the temperature of the planet at the escape level. For atomic hydrogen, if $T = 1300$ K, $R_p = 3 R_J$, and $M_p = 0.5 M_J$, $\lambda$ is close to 30 and Jeans escape might be important. The dash-dotted line on Figure 2 is the
An extended upper atmosphere around the extrasolar planet HD209458b

Outline

• Aeronomy of Jupiter, Briefly
• Aeronomy of HD209458b
  – Thermal Structure
  – Composition and Chemistry
  – Escape
• Comparison with more Recent Calculations and Observations
• Tides and their Consequences
• Comments on Escape
  – Boundary Conditions
  – Drag Forces and Heavy Molecules
• Assumptions, Considerations, and Complications
Jupiter Thermal Structure

- The effective temperature of Jupiter is \(~110\) K
- The exobase temperature is 900 K
- There are large waves in the upper atmosphere
- The thermal profile is not well understood

Measured T by ASI on Galileo Probe (from Seiff et al. 1998)
Ionosphere of Jupiter

- Ionosphere is highly variable
- Variability is poorly understood
- Altitude and Density at Ne peak is poorly understood
- $\text{H}_3^+$ is a significant component and radiates strongly in infrared
- Temperature in auroral zones is controlled by $\text{H}_3^+$

Yelle and Miller (2004)
Jovian Aurora

The energy input associated with aurora is highly variable but ~10x that from solar EUV.
Lyman-alpha absorption by HD209458b

15% absorption implies an extended H cloud of several planetary radii.

Aeronomical Models for HD209458b


Models obtained from solution of 1D coupled continuity, momentum, diffusion, and energy equations.

Chemical changes and heating are driven by deposition of stellar EUV flux.
Hydrodynamics applies

Collisionless

Hydrodynamics fails

Boundary Conditions

LOG(N/N0)

exobase

RP/R

0.65

0.45

0.25

BOTH
Non-equilibrium Composition of Upper Atmosphere of HD209458b

- $\text{H}_2$ at low altitudes
- H at intermediate altitudes
- $\text{H}^+$ at high altitudes
- $\text{H}_2 \rightarrow \text{H}$ transition driven by thermal decomposition of $\text{H}_2$
- $\text{H}_3^+$ density is significant

Ballester et al. (2007) detected a 0.03% absorption. This could be produced by a layer of ~5000 K, atomic hydrogen, consistent with Yelle (2004) model.
Energy Balance in the Upper Atmosphere of HD209458b

At low altitudes, H$_3^+$ radiation balances stellar heating.

At high altitudes, adiabatic cooling balances stellar heating.

Heating efficiency high for H$_2$, low for H.

H$^+$ absorbs no photons.

Escape Rate Follows Stellar Input - Energy Limited

## Comparison of Escape Calculations

<table>
<thead>
<tr>
<th></th>
<th>Rate (gm/s)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lecavelier de Estangs (2004)</td>
<td>$5 \times 10^{11}$</td>
<td>Estimated T, used Jeans escape &amp; Tidal Forces</td>
</tr>
<tr>
<td>Yelle (2004)</td>
<td>$4.5 \times 10^{10}$</td>
<td>Navier-Stokes with variable composition, somewhat detailed heating.</td>
</tr>
<tr>
<td>Tian (2005)</td>
<td>$3.5 \times 10^{10}$</td>
<td>Navier-Stokes with constant composition, fixed heating efficiency.</td>
</tr>
<tr>
<td>Garcia-Munoz (2006)</td>
<td>$4.8 \times 10^{10}$</td>
<td>Navier-Stokes with variable composition, various B.C.</td>
</tr>
<tr>
<td>Penz et al. (2007)</td>
<td>$7 \times 10^{10}$</td>
<td>N.-S., constant composition, heating efficiency, tides</td>
</tr>
</tbody>
</table>
Fairly Good Agreement?

Penz et al. (2007)
Is the Watson et al. Formulation Useful?

Fig. 7.—Escape rate calculation using our method and that of Watson et al. (1981) in a hydrogen-dominated atmosphere of an Earth-like planet.

Tian et al. (2005)
The Effect of Tidal Forces

From Garcia-Munoz (2007)
Tidal Effects More Accurately

Erkaev et al. (2007)
Evolution of Hot Jupiters

Lecavelier des Etangs (2007)
More Species ?!

HI, OI, and CII lines have been detected with absorptions of 5%, 13%, and 7.5% (Vidal-Madjar et al. 2004).
Heavy Molecules and Drag Forces

• Where does the O and C around HD209458b come from?
• Escaping light species can carry off heavier species (Hunten et al. 1987)
• Cross-over mass $m_c = m_1(1 + H_1 F_1 / b_{12})$
• For Yelle (2004) reference model, $m_c \sim 13$
• A combination of eddy mixing and drag may bring heavy species to the exobase
Auroral Energy Deposition on Extrasolar Planets?

**Fig. 3.** Magnetosphere of the tidally locked planet HD 209458b, with field lines. The scale is given in planetary radii. *Left*: age of parent star is 4.6 Gyr. *Right*: age of parent star is 0.5 Gyr.

Greißmeier et al. (2004)
Final Thoughts

• All models are highly simplified - we didn’t correctly predict characteristics of Jupiter’s upper atmosphere.
• Are waves important?
• Tides have yet to be taken into account in an accurate way.
• Stellar wind energy input (aurora) may be significant (Grießmeier et al. 2004).
• Planetary B field could inhibit escape.
• Transition from “atmosphere” to “extended cloud” has yet to be modeled accurately.
• Observational Verification is Crucial!
The worlds come into being as follows: many bodies of all sorts and shapes move from the infinite into a great void; they come together there and produce a single whirl, in which, colliding with one another and revolving in all manner of ways, they begin to separate like to like. Leucippus (~480-420 B.C.)
Aeronomy of extra-solar giant planets at small orbital distances

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Received 20 August 2003; revised 12 February 2004
Available online 24 April 2004