Probing the interior and composition of exoplanets

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Thanks to: Nicolas Crouzet, Mathieu Havel, Masahiro Ikoma, Diana Valencia
• **Motivations**

• **Inflated planets & the “missing physics” problem**
  - HD209458b
  - Analyzing 40+ transiting planets
  - The special case of CoRoT-2b

• **The star-planet metallicity correlation**

• (CoRoT-7b: an evaporating super-Earth)

• (ASTEP)
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Exoplanets with radial velocimetry: 2009
Exoplanets in transit: 2009
M-R relations
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HD209458b: the planet that was too large

1999: Discovery of HD209458 b (Charbonneau et al.; Henry et al.)

2001: Bodenheimer et al. show that HD209458 b is in fact too large. They propose that this is due to ongoing orbit circularisation.

2002: Guillot & Showman also argue for an anomalously large radius. They propose that kinetic energy generated in the atmosphere may be transported deep and slow the contraction.

2003: Confirmation of the radius problem by Baraffe et al., Laughlin et al.; Burrows et al. show that the transit radius is different from the 1 bar radius.

2005: HD209458b has a negligible eccentricity (Deming et al., Laughlin et al.)

2005: Winn & Holman propose a dissipation mechanism involving orbital locking into a Cassini state and a spin-orbit resonance.

2006: Levrard et al. show that the probability to be trapped into a Cassini state is small $\sim 10^{-3}$ at 0.05 AU. Then, Fabrycky, Johnson & Goodman also find obliquity tides not to be a plausible scenario.

2007: Burrows et al. propose increased opacities as a possible solution. Chabrier & Baraffe propose that heat could be stored by semi-convection, implying a slower contraction.

2008: Laine, Lin & Dong propose that ohmic dissipation in the planet may inflate it.
Explaining the radius of HD209458b

Explaining the radius of HD209458b

“Weather noise”

Knutson et al. 2007

**Orbit**

**Atmosphere**

**Interior**

- **gravitational torques**
- **dynamical torques**

---

- Stellar photons heat the atmosphere
- Kinetic energy is generated
- Penetrates to deep levels
- Is dissipated there

---

Knutson et al. 2007
"Weather noise"

Guillot & Showman (2002)

- Orbit
- Atmosphere
- Interior

- gravitational torques
- dynamical torques

Guillot & Showman (2002)

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but: Burkert et al. (2005) ?
Orbital & thermal evolution with tides
Orbital & thermal evolution with tides

Ibgui & Burrows (2009)
(see also Jackson et al. 2008)
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$T_{eq}$ vs planetary radius

std deviations from no correlation = $-3.9$

significance level = 0.0001
$T_{eq}$ vs radius anomaly

std deviations from no correlation = -3.0
significance level = 0.0028
$T_{eq}$ vs radius anomaly

missing physics

heavy elements

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significance level = 0.0028
$T_{eq}$ vs radius anomaly

missing physics

heavy elements

std deviations from no correlation = -3.0
significance level = 0.0028
\( T_{eq} \) vs radius anomaly\(^*\)

opacity \( \times 30 \)

missing physics

heavy elements

std deviations from no correlation = \(-2.4\)

significance level = 0.0151
$T_{eq}$ vs radius anomaly*
weather noise (0.5% of incoming stellar flux)

missing physics

heavy elements

std deviations from no correlation = −0.8
significance level = 0.4080
Orbital & thermal evolution with tides

Plots showing the relationship between observed radius and tidal evolution for planets ordered by increasing stellar irradiation.
Orbital & thermal evolution with tides

Miller, Fortney & Jackson (2009)
What is the missing physics?
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- Anomalously large planets are frequent
  - Rules out a “chance” mechanism (e.g. spin-orbit coupling)
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  - Weather noise model
  - Tidal model?
    - seems unlikely to work, but global statistics is to be assessed
  - Increased opacity model?
    - only marginally
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• Not due to problems with EOS
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CoRoT-2a&b: observations

1.73 day period planet

4.5 day period star

Planet: ~3 Mjup, ~1.5 Rjup

Rossiter: $l = 7.2^\circ \pm 4.5^\circ$

Secondary transit: $e = 0.03 \pm 0.03$

Alonso et al. 2008

Bouchy et al. 2008

Alonso et al. 2009
CoRoT-2b among its peers

updated from Guillot 2008
Evolution models (standard)

Havel et al.,
Guillot & Havel, in preparation
Evolution models (modified atmosphere)

Havel et al., Guillot & Havel, in preparation
Evolution models (energy dissipation)

$2 \times 10^{29}$ erg s$^{-1}$

$3 \times 10^{28}$ erg s$^{-1}$

$1\%$ K.E. ($8 \times 10^{26}$ erg s$^{-1}$)

standard model

Havel et al., Guillot & Havel, in preparation
Evolution models (including tides)

Tidal evolution model includes synchronisation & circularisation based on Barker & Ogilvie (2009)
Evolution models (including tides)

CoRoT-2b’s size can be explained but as a transient phenomenon: tides, or recent impact.

Tidal evolution model includes synchronisation & circularisation based on Barker & Ogilvie (2009).
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[Fe/H] vs radius anomaly

Guillot et al. 2006

missing physics

heavy elements
[Fe/H] vs radius anomaly

Guillot 2008
[Fe/H] vs radius anomaly

missing physics

heavy elements

std deviations from no correlation = 2.0
significance level = 0.0447

updated from Guillot 2008
[Fe/H] vs radius anomaly

missing physics

heavy elements

std deviations from no correlation = 2.8
significance level = 0.0050

updated from Guillot 2008
(stellar) [Fe/H] vs. (planetary) Mz

(Weather noise model)

Guillot et al. 2006
(stellar) [Fe/H] vs. (planetary) $M_z$

(Weather noise model)

Guillot 2008
(stellar) $[\text{Fe/H}]$ vs. (planetary) $M_z$

(increased opacity model)

Burrows et al. 2007; Guillot 2008
(stellar) [Fe/H] vs. (planetary) Mz

(increased opacity model)

Burrows et al. 2007; Guillot 2008
(stellar) [Fe/H] vs. (planetary) Mz

(Weather noise model)

std deviations from no correlation = -3.8
significance level = 0.0002

1 HD209458
2 OGLE-TR-56
4 OGLE-TR-132
5 OGLE-TR-111
7 TrES-1
8 HD149026
9 HD189733
10 XO-1
11 HAT-P-1
13 WASP-1
15 HD147506
16 XO-2
17 TrES-3
19 HAT-P-3
20 HAT-P-4
23 HAT-P-6
28 CoRoT-Exo-3
29 XO-3
31 CoRoT-Exo-4
32 XO-4
33 XO-5
35 HAT-P-8
37 HAT10-WASP11
(stellar) [Fe/H] vs. (planetary) Mz/Mtot

(Weather noise model)
Planetary composition

- Very clear dependence between Mz or Mz/Mtot vs [Fe/H]
  - 3-4 sigma
  - Weakly dependent on assumed model (weather noise, increased opacities)
- High planetary masses in heavy elements
  - up to 100 Mearth
- Some planets remain problematic
  - CoRoT-Exo-2b, XO-4b, HAT-P-8b...
    - will require a case by case study
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A transiting “super-Earth”

CoRoT-Exo-7b:
1.68 +/- 0.09 \( R_{\text{Earth}} \)
4.8 +/- 0.8 \( M_{\text{Earth}} \)

Léger et al. 2009

CoRoT-Exo-7b (artistic view)

Venus (real photo)
CoRoT-7b: Earth like?

Valencia, Ikoma, Guillot & Nettelmann, submitted to A&A
CoRoT-7b: vapor planet?

![Graph showing the relationship between mass and radius for different compositions of CoRoT-7b, comparing it to Uranus and Neptune.](image-url)
The CoRoT-7b precursor

\[ \frac{dM}{dt} = \frac{3 \varepsilon F_{\text{EUV}}}{G \rho K_{\text{tide}}} \sim 10^{11} \text{ g/s} \]

Terrestrial origin

Volatile origin

Valencia, Ikoma, Guillot & Nettelmann, submitted to A&A
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Results from the first campaign of ASTEP South and perspective for planet-findings from Dome C, Antarctica


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Abstract: Dome C offers favorable conditions for planet searches thanks to a long continuous night and very good weather conditions. ASTEP South is the first phase of the ASTEP project that aims to determine the quality of Dome C for future photometric searches for transiting exoplanets and to discover extraterrestrial planets. The instrument consists of a front-illuminated 40k pixel camera, a 10 cm refractor, and a simple mount in a thermally isolated enclosure. A double-glass window is used to reduce temperature variations and its accompanying turbulence on the optical path. The telescope is fixed and observes a 4° x 4° field of view centered on the continental South pole. With this design, ASTEP South is very stable and observes with low and constant airmass, both being important issues for photometric precision. During the 2008 Antarctic winter, between June and October, ASTEP South collected 1500 hours of data. A global analysis of the data allows us to infer the weather conditions, seeing and photometric quality of Dome C for a great fraction of the winter. Using these results in a probabilistic analysis of detection of transiting planets, we show the potential of Dome C for future planet discoveries.

1) ASTEP South : the 2008 campaign

Astrom - The instrument observes a 4° x 4° field of view, centered on the continental South pole, which contains around 800 stars up to 6m. The observations are performed on an image taken on July 12, 2008. The exposure is 30 seconds and the nominal full well maximum is 2.5×10^5 electrons.

2) Weather conditions at Dome C

A measurement of the clear sky fraction at Dome C is made with ASTEP South based on the number of stars detected in the field. Since this number varies with the sky background level and the Point Spread Function (PSF) size, we build a model to evaluate the number of stars that should be detected on any given image if the weather was excellent, taking into account these parameters. We then compare the theoretical to the measured number of stars. This gives the weather statistics for the 2008 winter at Dome C: between 52.3% and 66.4% of excellent weather, 17.4% of veiled weather and 13.7% of white-out.

3) Planet detection probability

We investigate the potential of ASTEP South for transit detection using CoRoT/Tess and compare Dome C and La Silla observing sites. CoRoT/Tess performs statistical simulations of transit events for a survey given the star distribution in the field of view, instrumental parameters and observation windows (Fressin 2007). We consider the ASTEP South instrument and the South Pole field site population with different observation windows: the ASTEP South 2008 campaign, a winter at Dome C: only limited by the Sun and weather conditions, and a complete year at La Silla for the field of view used. In spite of technical problems at the beginning of the winter the planet detection efficiency for the ASTEP South 2008 campaign is comparable to the ones obtained for one year at La Silla. Moreover the detection efficiency is improved at Dome C compared to La Silla both in terms of period and transit depth. For example we have 0.05 at Dome C vs. 0.47 at La Silla for a 2 day planet period, and 0.17 at Dome C vs. 0.44 at La Silla for a 2% transit depth. The detection efficiency is still higher at Dome C for longer periods. We also evaluate the number of detections considering a signal to noise ratio higher than 10:1.63 planet at Dome C (101 planets over 1000 runs), 1.08 planet for the ASTEP South 2008 campaign and 1 planet at La Silla. This shows the high potential of Dome C for future planet discoveries.

Conclusion: ASTEP South is the first transit survey from Dome C. The instrument inside its thermalized box has observed towards the continental South pole for more than 1500 hours during the 2008 winter and during all the 2009 winter. A preliminary data analysis of the 2008 campaign allows to evaluate the weather statistics at Dome C during the winter: between 52.3% and 66.4% of excellent weather, 17.4% of veiled weather and 13.7% of white-out. These statistics are used to compare Dome C and La Silla for the detection of transiting planets. From a statistical analysis we find that the detection probability is higher at Dome C both in terms of planet period and transit depth. This shows the high potential of Dome C for future planet discoveries.