The CoRoT Exoplanet programme: an overview of results

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The CoRoT satellite
COROT : a European project

CoRoT : Convection Rotation Transit

France (80%) :
- CNES main contractor
- Alcatel Alenia Space
- Institutes : LESIA (Observatoire de Paris), LAM (Marseille), IAS (Orsay)

Other partners : Austria, Spain, Germany, Belgium, ESA, Brazil

Operation started in 2007

Mission extended until end 2013
(more in discussion)
CoRoT: a photometric satellite

- Continuously monitors thousands of stars during periods of 5 months each (+ some 2-4 weeks periods)
- Two programmes conducted in parallel:
  - **Asterosismology:**
    - ~ 15 stars
    - One exposure / sec
  - **Exoplanets (transits):**
    - ~ 12,000 stars
    - One exposure / 32 sec
    - 3 colors
The CoRoT Instrument

**Télescope**
- Pupil diameter: 27 cm
- Afocal telescope: 2 parabolic mirrors
- Long baffle

**Wide field camera**
- Dioptric objective with 6 lenses
- Focal plane: 4 CCD of $2048^2$ pixels
  - 2 (⇒1) CCD astero-sismology
  - 2 (⇒1) CCD exoplanets
- Exoplanet field: $3.45(°)^2$
Observing strategy

- Polar orbit
- Sun *in the back* ➔ Flip each semester
- Up to 150 days of continuous observation on each field
- 16 fields already observed
  - 5 short
  - 6 medium
  - 5 long

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Launch

With a good old faithful Soyuz
Exoplanet field: 2 (now 1) × 6000 stars
The focal plane

Photometry in 3 « colors »

PSF : 60 - 80 pixels
Depending on magnitude

Exoplanets field
Seismology field
CCD chip

Bi-prism
CoRoT “eyes”: different stellar densities

11 ≤ V ≤ 16

10° radius circle

“anti-center” centered at 6h50

“center” centered at 18h50
Processing of a light curve

- Detection of a planet candidate: at least three transit-like periodic events
  - orbital periods $T < 50$ days

Original

Low frequencies: stellar fluctuations

High frequencies: transits
Beware of false positives

The enemy: the false positive!
produces a signal that mimics a transiting planet

- The star is a Grazing Eclipsing Binary (GEB)
- Eclipsing Binary in the Background (BEB)
- Eclipsing Binary in a dwarf/giant system

FOLLOW-UP FROM THE GROUND IS MANDATORY!
How identifying a liar? Follow-up!

- Transit: V-shape and secondary eclipse
  ➔ grazing binary
  Corot LC
- CoRoT Coulours of the transit
  ➔ binary system
- Radial Velocity
  ➔ mass of secondary:
  HARPS, HIRES, SOPHIE
- Spectroscopy
  ➔ giant star or blend:
  HARPS, Tautenburg, SOPHIE
- ON/OFF Photometry of field stars
  ➔ background eclipsing binaries
  CFHT-Megacam, IAC-80, WISE, OHP, BEST,..
- Adaptive Optics (NACO):
  ➔ Identification of blends
The CoRoT planets sample
CoRoT Light Curves

- 17 runs: 1400 days, 150,000 stars
- ~ 90,000 Light Curves (LC) > 60 days
- ~ 60,000 LC in Short Runs
From CoRoT LC to planets ...

~ 300 candidates per run / ~ 1800 in total
CoRoT team has analyzed \( \approx 10^5 \) stars and confirmed (so far) 20 substellar objects: 18 transiting planets and 2 brown dwarves.

- All in long runs
- 200-300 detections of periodic events / run: 2-3%
- 1-4 detections of planets / run: 0.5 - 2% of periodic cases

The dispersion in yields is likely due to extinction variations.

CoRoT planets on the R vs M diagram

- Corot covers well the whole range
  - Densities from 0.21 to 55 g cm\(^{-3}\)
- Corot extended towards both extremes:
  - Corot-15b: 65 M\(_{\text{Jup}}\) and Corot-7b: .015 M\(_{\text{Jup}}\)
- 2 brown dwarves
  - Corot-15b and Corot-3b
Periods of transiting systems

- CoRoT appears to be unbiased with respect to orbital period values
  - three medium periods: 9 - 13 days
  - one long period: 95 days

![Graph showing periods of transiting systems with CoRoT and non-CoRoT data points.](image-url)
CoRoT sample supports an already mentioned (and expected) trend
“Long period” systems

CoRoT-4b: 7 transits
Period = 9.2 days
\( M_p = 0.72 \ M_{\text{Jup}} \)
\( R_p = 1.19 \ R_{\text{Jup}} \)
\( \rho = 0.525 \ \text{g/cm}^3 \)

CoRoT-6b: 15 transits
Period = 8.88 days
\( M_p = 2.96 \ M_{\text{Jup}} \)
\( R_p = 1.16 \ R_{\text{Jup}} \)
\( \rho = 2.32 \ \text{g/cm}^3 \)
[Fe/H] = -0.20

CoRoT-10b: 15 transits
Period = 13.24 days
\( M_p = 2.75 \ M_{\text{Jup}} \)
\( R_p = 0.97 \ R_{\text{Jup}} \)
\( e = 0.53 \)
\( \rho = 3.7 \ \text{g/cm}^3 \)
K1V [Fe/H] = 0.26
Corot-9b: a Mercury-like orbit

Period = 95.27 days
$M_p = 0.84 \pm 0.07 \, M_{\text{jup}}$
$R_p = 1.05 \pm 0.04 \, R_{\text{jup}}$
$\rho = 0.525 \pm 0.15 \, \text{g/cm}^3$
Will soon be re-observed

Deeg et al., Nature 2010
CoRoT-3b:
34 transits

F3V - v$_{\text{sin}i}$ = 17 km/s
Period = 4.26 days
M$_p$ = 21.6 ± 1.00 M$_{\text{jup}}$
R$_p$ = 1.01 ± 0.07 R$_{\text{jup}}$
ρ = 26.4 ± 5.6 g/cm$^3$

- Super-planet or brown dwarf?
- Definition of a planet?
- An exceptional object or just one member of a new class?
CoRoT-15b: a bona fide Brown Dwarf

Bouchy et al., 2010

CoRoT-15b:
34 transits
F7V vsini = 19.0 km/s
Period = 3.06 days

\[ M_p = 63.3 \pm 4.10 \, M_{\text{Jup}} \]
\[ R_p = 1.12 \pm 0.3 \, R_{\text{Jup}} \]
\[ \rho = 59.0 \, \text{g/cm}^3 \]
CoRoT-8b: a Neptune-like planet

- CoRoT-8b
- 49 transits
- Period = 6.21 days
- $M_p = 0.22 \pm 0.03 \, M_{\text{jup}}$
- $R_p = 0.57 \pm 0.02 \, R_{\text{jup}}$
- $\rho = 1.6 \pm 0.10 \, \text{g/cm}^3$
- $[\text{Fe/H}] = 0.30 \pm 0.10$
- Bordé et al., 2011 A&A
CoRoT-11b: a bloated planet around a fast rotator

- CoRoT-11b
  - F7V - vsini = 40 km/s
  - 49 transits
  - Period = 2.99 days
  - $M_p = 2.33 \pm 0.34 \, M_{\text{jup}}$
  - $R_p = 1.43 \pm 0.03 \, R_{\text{Jup}}$
  - $\rho = 0.99 \pm 0.15 \, \text{g/cm}^3$
  - $[\text{Fe/H}] = -0.03 \pm 0.08$

Gandolfi et al., 2011 A&A
CoRoT-16b : hot, despite excentric Jupiter!

- CoRoT-16b
  - G5V
  - 16 transits
  - Period = 5.35 days
  - $M_p = 0.535 \pm 0.084 \, M_{\text{jup}}$
  - $R_p = 1.17 \pm 0.15 \, R_{\text{jup}}$
  - $\rho = 0.44 \pm 0.17 \, \text{g/cm}^3$
  - $[\text{Fe/H}] = -0.03 \pm 0.08$
  - $e = 0.33 \pm 0.1$ => interaction w another planet?

Ollivier et al., A&A submitted
CoRoT-17b: an old Jupiter

- CoRoT-17b
  - G2V – age: 11±1 Gyr →
  - one of the oldest
  - Soon to be engulfed by its mother star becoming a giant?
  - 49 transits
  - Period = 3.77 days
  - \( M_p = 2.43 \pm 0.3 \, M_{\text{jup}} \)
  - \( R_p = 1.02 \pm 0.07 \, R_{\text{Jup}} \)
  - \( \rho = 2.82 \pm 0.38 \, \text{g/cm}^3 \)
  - \([\text{Fe/H}] = -0. \pm 0.

Csizmadia et al., A&A accepted
Corot-7b: the first hot super-earth

The folded light curve

- Transits first detected by quick-look analysis (« alarm » mode)
- 153 transits, all ~ seen when superimposed
- Extremely short period: $P = 0.8536$ days
  - very small transit depth: $\Delta F/F = 0.033\%$
A vigorous follow-up programme

Such a small transit signal
- IF A PLANETARY ONE -
means a very small planet:
\[ R_{pl} = 1.7 \, R_{\text{earth}} \]

A vigorous Follow-up programme from the ground, using top-level instruments in the world was conducted:

- ON/OFF photometry (BEB) : CFHT, Canarias
- IR spectra (CO bands of a M binary) : VLT / CRIRES
- Adaptive Optics (closest BEB) : VLT / NACO
- CoRoT color (triple system) : Corot LC
- X-ray survey (close M binary) : ROSAT
- Radial velocity : SOPHIE, HARPS
Radial Velocity with HARPS

- 106 measurements (70h) during 4 months

Difficulty: **strong variability** of the star affects the analysis
- obvious correlation w rotation (23 days)

Scargle analysis (≈ Fourier Transform)
- after filtering of rotation (3 harmonics)
- first peak: 3.7 days
- Subtracted ➔ 2nd peak at 0.85 days
- Phase of 0.85 d peak agrees w transit

Clear confirmation of Corot-7b
And discovery of **a second planet!**
2 (3?) small planets!

- A two Super-Earth solution was found

**Corot-7b**
- $M = 4.8 \pm 0.8 \, M_{\oplus}$
- $P = 0.853$ days
- $a = 0.017 \, AU$
- $R = 1.68 \pm 0.1 \, R_{\oplus}$

**Corot-7c**
- $M = 8.4 \pm 0.9 \, M_{\oplus}$
- $P = 3.70$ days
- $a = 0.046 \, AU$

- First case of a system with 2 Super-Earths, one in transit
- A third planet is suspected ➔ a very compact system!
Mass of Corot-7b? No more controversial

- Reanalyzing the RV data set
  - Several assessments: 2.3 – 8 M⊕: who can we trust?
  - Important consequence on density and thus structure
  - Léger et al. 2011 take the median value: 6.9 ± 1.2 M⊕
  - A smart idea from Artie Hatzes: only keep radial velocity data on nights where multiple measurements were made ➜ effectively removes the activity!
    (Hatzes et al, submitted)

  - \[ M = 7.3 \pm 1.4 \text{ M}_\oplus \]
  ➜ \[ \rho = 10.1 \pm 2.7 \text{ g cm}^{-3} \]
  as Kepler-10b: a twin on many aspects.
  - And now 55 Cnc e!
Corot-7b characteristics today

- A big sister of the Earth:
  - $M = 7.3 \, M_\oplus$ (Hatzes et al., 2011)
  - $R = 1.7 \, R_\oplus$ (Brunnt et al., 2010)
  - Deserves the Super-Earth denomination

- A very different *ecologic* environment
  - Period: $P = 0.85 \, d \rightarrow$ one year = 20.5 h!
  - Orbit radius: $a = 0.017 \, AU = 3.6$ stellar radius!
    - A sun of 30° in the sky!
  - A *Strange New World* without any doubt!
Nature of Corot-7b ?

- The first solid evidence for a rocky planet!
  - A lot of exciting physics (Léger et al. Icarus in press)

- Tidal forces:
  - Must be phase-locked \( t_{\text{synch}} < 1 \ \text{Myr} \): keeps one face towards the star
  - Moderately elongated under tidal forces < 150 km
  - Tidal heating could be extremely efficient if \( \text{excentricity is } \neq 0 \), but model predict \( e < 10^{-4} \)
Temperature

- dark side: 50K pretty cold! geothermal origin
- dayside: 1800-2600 K: pretty hot!
  - no heat redistribution by atmosphere nor ground

Thus, between the two… a temperate region of 90 km width only (270-370 K)
- life in this niche?
  - impossible: no water!
Nature of Corot-7b?

- **Structure / composition**
  - First time density of a SE measured
  - $10 \text{ g.cm}^{-3} \geq \text{Earth}$ → rocky
    - Most probably a « dry Earth »:
      - silicates mantle & iron core
  - Likely migrated from a wider orbit
    - core of a Neptune stripped by wind
    - or a true rocky telluric
    - In-situ formation from boulders not excluded

- **Surface**:
  - *Lava ocean* of liquid rock of 45 km depth,
    - up to a latitude of $= 45 - 50^\circ$
  - refractory oxydes: CaO (13%), Al$_2$O$_3$ (87%)
  - continent or frost H$_2$O, CO$_2$ elsewhere
Nature of Corot-7b?

Atmosphere

- Stellar wind + UV: escape of all volatiles within 0.1 to 1 Gyr (< age of the system)
- Composition: vaporised silicates
  - Should be extremely tenuous: $P = 5 - 0.05 \times 10^{-5}$ bar

![Atmospheric pressure graph](image)
A new class of Lava-Ocean planets

- The 2 other members:
  - Kepler-10b (Bathala et al. 2011): a quasi twin
  - 55 Cnc e (Winn et al. 2011)
- All three found in a narrow domain of period, radius and mass
- All three around a solar-like host star
- A density somewhat larger than Earth
- A good alignment on a unique silicate+iron theoretical $[M/R]$ curve (Valencia et al. 2006)
- All three must be spin-orbit synchronized
  - a star facing side extremely hot $\rightarrow$ lava ocean of melted rocks
  - a dark side extremely cold
  - secondary eclipse in the infrared should be detectable
- Atmosphere must have been expelled by stellar wind
4 new CoRoT planets will be announced!
Thank you for your attention

Rocky Corot-7b
Brown dwarves
Long period planet
Old Jupiter
Hot, yet excentric Jupiter
Massive very hot Jupiter