Has CoRoT discovered the first transiting Super-Earth around a main sequence star?

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Short period planets: the small component

- 2006: first Super Earth detected with gravitational lensing
  - Beaulieu et al. Nature 06
- Recent results from radial velocity point to a very significant population of Super-Earth: most recent
  - 7.5 M$_{\oplus}$ Bouchy et al. A&A accepted
- Today 20 planet w M < 0.1 M$_{\text{Jup}}$
- Not yet a size measured
  - needed for deriving the structure
- One of important goal of CoRoT
  - detect transits of Super-Earth
  - performances allow it
  - A first case?
The star and the data taking

- Field: LRa01 anti-center direction - 135 days long
- The star: LRa01_E2_165
  \[ mV = 11.7 \]
- The mask on CoRoT CCD:
- 3 colors
- Sampling: 32s
The star and its fundamental parameters

- Spectra taken with UVES, HARPS
- Analyzed by several groups
  - See Magali Deleuil presentation for the details
- Parameters:
  - K0V star
  - Teff = 5250 K
  - $R_\odot = 0.87 \pm 0.04$
  - $M_\odot = 0.93 \pm 0.03$
  - $M/H = 0.05 \pm 0.05$
  - Distance = 130 pc ± 30
  - $0.5 < \text{age} < 8 \text{ Gyr} (1.2 \text{ preferred ?})$
  - active: emission feature in core of H and K Ca lines
The overall light curve

- Very active star with 2% modulation
- Spots crossing the disk because of rotation are clearly seen
  \( \Rightarrow \) rotation period = 23 days
The folded light curve

- First detected by alarm mode
- 153 transits, all ~ seen when superimposed
- Short period: \( P = 0.8536 \) days
  \[ \Rightarrow \text{transit depth}: \Delta F/F = 0.035\% \]
Is this actually a small transiting planet?

FOLLOW-UP IS MANDATORY!
A big effort of the whole team
The enemy: the false positive!
which produces a signal analogous to a transiting planet

- Eclipsing Grazing Binary
- Eclipsing Binary in a dwarf/giant system
- Eclipsing Binary in a triple system
Follow-up 1: spectroscopy

- UVES and HARPS spectra
  - no blend
  - K0V star
- Corot-Exo7 cannot be a giant star
- Exclude a binary system dwarf/giant
Follow-up

- ON/OFF photometry with CFHT and 80cm IAC
- PSF + mask
  - light in corot-aperture:
    - 99.63% from E2_0165
    - 0.24% V=15.5 17" NE
    - <0.1% V=13.6 30" SE
- Only those 2 stars could produce false alarm
- ON/OFF photometry:
  - NO $\Delta$mag > alarm
- BEB (not within PSF) are excluded
Follow-up 3: Good seeing Imaging

- Good angular resolution images using CFHT-MEGACAM in g-band
  - sub-pixel recentering
  - median of the cube
- Two faint stars detected @ 4.5 & 5.5"
- Magnitude estimate (fake stars added): \( \Delta m = 10 \)
  - too faint to cause a \( 3.5 \times 10^{-4} \) \( \Delta F/F \)
- Close BEB excluded
Follow-up 4: Adaptive Optics Imaging

- High angular resolution image in J-band with NACO-VLT
  - rotation on the sky: 5 positions
  - median substraction (E2_165 vanishes)
  - derotation
  - median stacking

- Three new stars (2 on CFH)
  - all at angular distance > 4"
  - J = 18.4 - 18.7
  - redenning $\Delta m(g) \approx 10 = CFHT$
  - too faint to be BEB false positive

- BEB between 0.5” to 4” excluded
Follow-up 5: IR spectra w CRIRES

- Triple system with BEB?
- IR spectra with CRIRES-VLT:
  - AO + 0.3" slit  R=6 $10^4$
  - K-band: CO overtone lines
- Very sensitive method since
  - $\Delta m_K$ is small between M and K
  - CO lines are strong in M stars
- Result:
  - No late K or M earlier than M6 and brighter than K=12.3 at the distance of Corot-Exo7 within 0.3"
- Eclipsing binary of M stars earlier than M6 orbiting Corot-Exo7b excluded
Follow-up 6: X-ray activity

- If binary with $P=0.85$ days, Strong X-ray emitter
  - e.g.: YY Gem = M1V, $P = 0.81$ days

- ROSAT all sky survey
  - $0.1 - 2$ keV
  - region of Corot-Exo7b

- Results:
  - NO binary similar to YY Gem out to $250 \pm 100$ pc

- Late M binary system orbiting Corot-Exo7b excluded
Follow-up 7: CoRoT colors

- Triple system with a Jupiter transiting a second star?
- CoRoT Colors: 3 Light Curves
  - Blue, Green, Red
  - transit is achromatic!
- Eliminate a triple system because star_2, and thus the transit signal, would be red
Follow-up 8: Adaptive Optics Imaging

- Jupiter transiting a background star of same color as Corot-Exo7?
  - Would not be detected in Corot colors
  - The star must be $3.5 \times 10^{-2}$ fainter

- High angular resolution image with NACO-VLT
  - Add a fake mV=16.7 star at 0.2” and 0.3”
  - Do the same processing as before
  - A star with $\Delta m = 5$ would be detected at 300 mas and likely at 200 mas

- Probability to have a star of mag 16.5 and same color, w a transiting Jupiter within 0.25” < $2 \times 10^{-4}$
  - Independant evaluation by F. Fressin
Follow-up 9: Radial Velocity with HARPS

Veloctimetry with HARPS:
- see talk by F. Bouchy
- Many nights of observation
- Preliminary results
- NO stellar, substellar or Jupiter mass
- compatible with a transiting planet $M < 11 M_\oplus$
- Data reduction still continuing

Most recent:
- Scargle diagram peak at .851 days!
All known cases of false positives practically eliminated with a high level of confidence.

The transit should be due to a Super Earth planet with a fairly high probability.
Planet characteristics

Period: $P = 0.8536$ d (one year = 20.5 h)

$a = 0.017$ AU $= 2.8 R_\oplus$

Other parameters: depend on LC analysis.

- Two groups used independent methods
- Variability is also a player: it makes the game difficult

Group 1:
- Transit with rather sharp edges
- Medium impact parameter
- Straightforward analysis (Kepler + Eddington limb-darkening)
- Impact param = $0.67 \pm 0.03$
- $R_{pl} = 1.74 R_\oplus \pm 0.13$
Group 2:

- transit with rather long ingress/egress
  high impact parameter
- More sophisticated analysis (Gimenez 03)
- Correction for suspected Time Transit Delays
  Stellar parameters do not conflict w spectroscopy
  Uses then spectroscopy parameters
- impact param = 0.86 ± .09
- $R_{pl} / R = 0.020$
- $R_{pl} = 1.76 \, R_\oplus$
- Good agreement
Nature of CorotExo7b?

A lot of exciting physics! For example:

- Longation under tidal forces: 1%
- Temperature
  - Between 1100 et 2000 K depending on albedo: pretty hot!
- Structure?
  - Rocky: if $M > 6 M_{⊕}$
    - Solid or liquid lava?
  - Ocean-planet: if $M < 5 M_{⊕}$
    - Then super-critical water
- Atmosphere?
  - Escape of volatiles requires 0.1 to 1 Gyr
so...

COROT-exo-7b

the

first transiting Super-Earth

around a main sequence star?

we gave good reasons to believe it!

Still a lot of work to characterize it fully and
determine its structure

And a great thank to the technical team
The End of this talk

... the continuation of an intensive work for the team!
Eddington limb-darkening effect in K0V star

- Claret 2003 in V, R and I band (≈ CoRoT spectrum): solid
- Eddington (dash line): $I/I_0 = .4 \ (1 + 3/2 \mu)$
Could be due to satellite perturbations
▷ excluded for the time being
gravitational perturbations by another closein planet ?
▷ more likely
▷ debate on the amplitude of the effect : 10 minutes or hours ?
can be taken into account
Structure of Corot-Exo-7b