Small planets in tight orbits around a hot B subdwarf star

Influence of sub-stellar bodies on late stages of stellar evolution

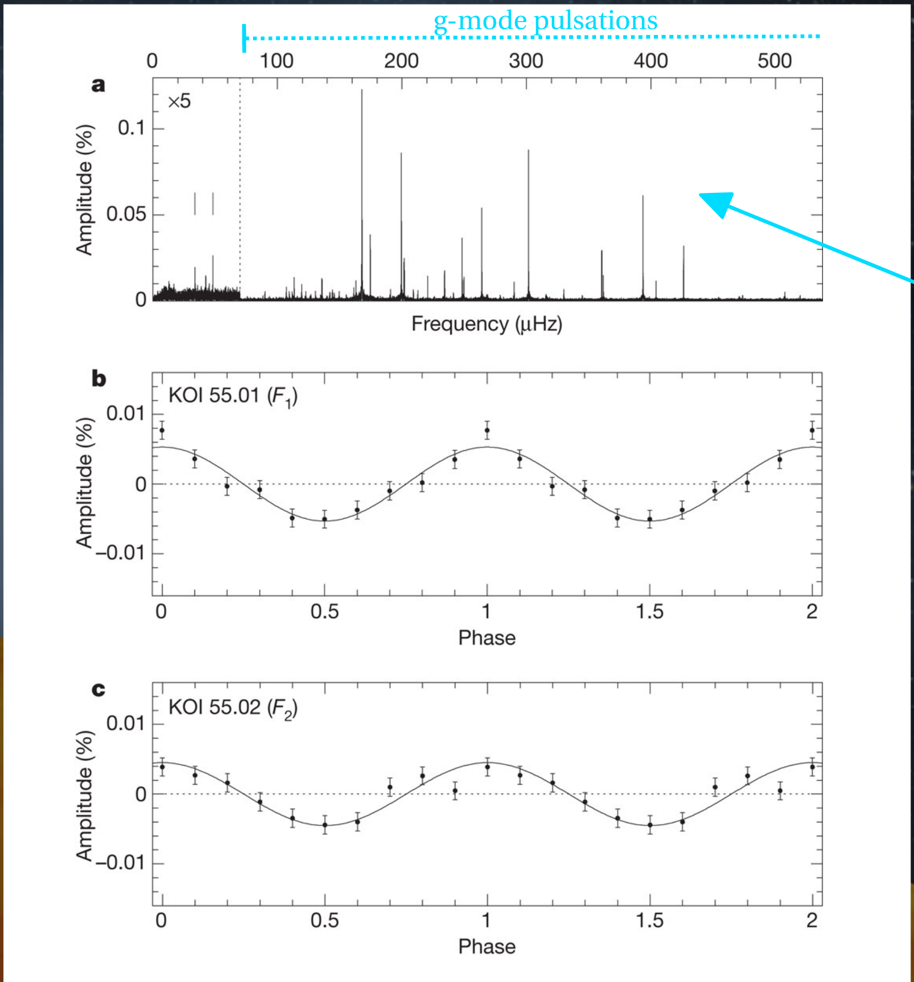
Stéphane Charpinet
(IRAP – Université de Toulouse / CNRS)

In collaboration with

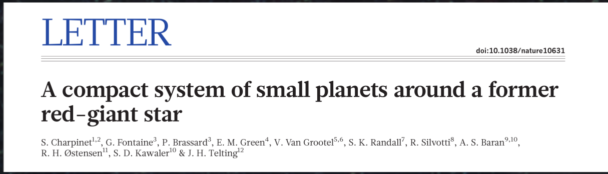
G. Fontaine & P. Brassard (U. de Montréal), V. Van Grootel (U. de Liège),
E.M. “Betsy” Green (U. of Arizona), S.K. Randall (ESO),
R. Silvotti (INAF), A.S. Baran (Iowa State U.), R.H. Østensen (KU Leuven),
S.D. Kawaler (Iowa State U.), J.H. Telting (NOT)

KOI 55 and its planetary companions

Q2+Q5-Q8: 14 months of *Kepler* data spanning 21 months



(Charpinet et *al.* 2011, *Nature*, **480**, 496)



LETTER

doi:10.1038/nature10631

A compact system of small planets around a former red-giant star

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KOI 55
(aka KPD 1943+4058, KIC 05807616)

Hot B subdwarf star observed with *Kepler*
Hybrid pulsator (g-modes + p-modes)

From asteroseismology (Van Grootel et al. 2010):

V = 14.87 , Distance = 1,180 pc
M = 0.496 $M_\odot$, R = 0.203 $R_\odot$
T_{eff} = 27,730 K , log g = 5.52
Age since ZAEHB ~ 18 Myr

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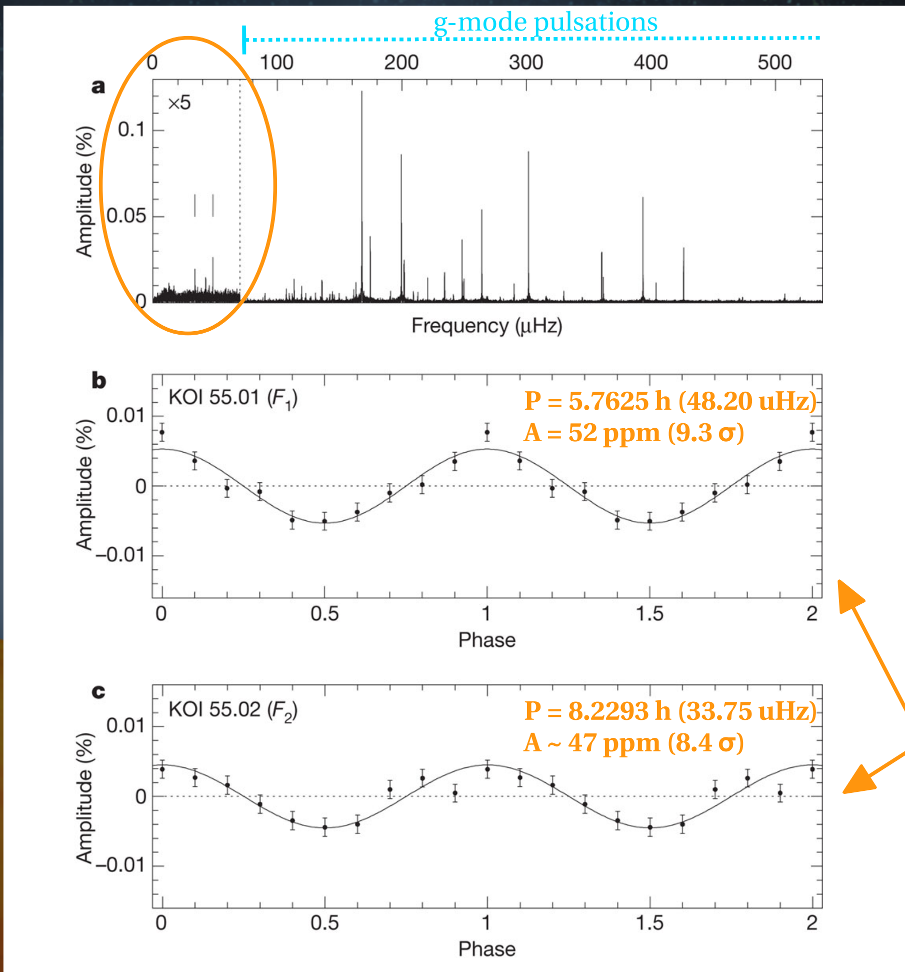

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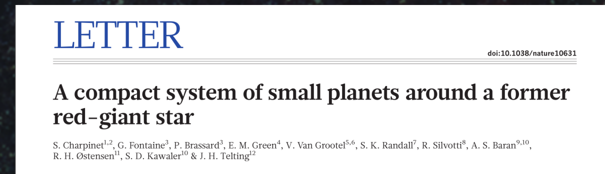

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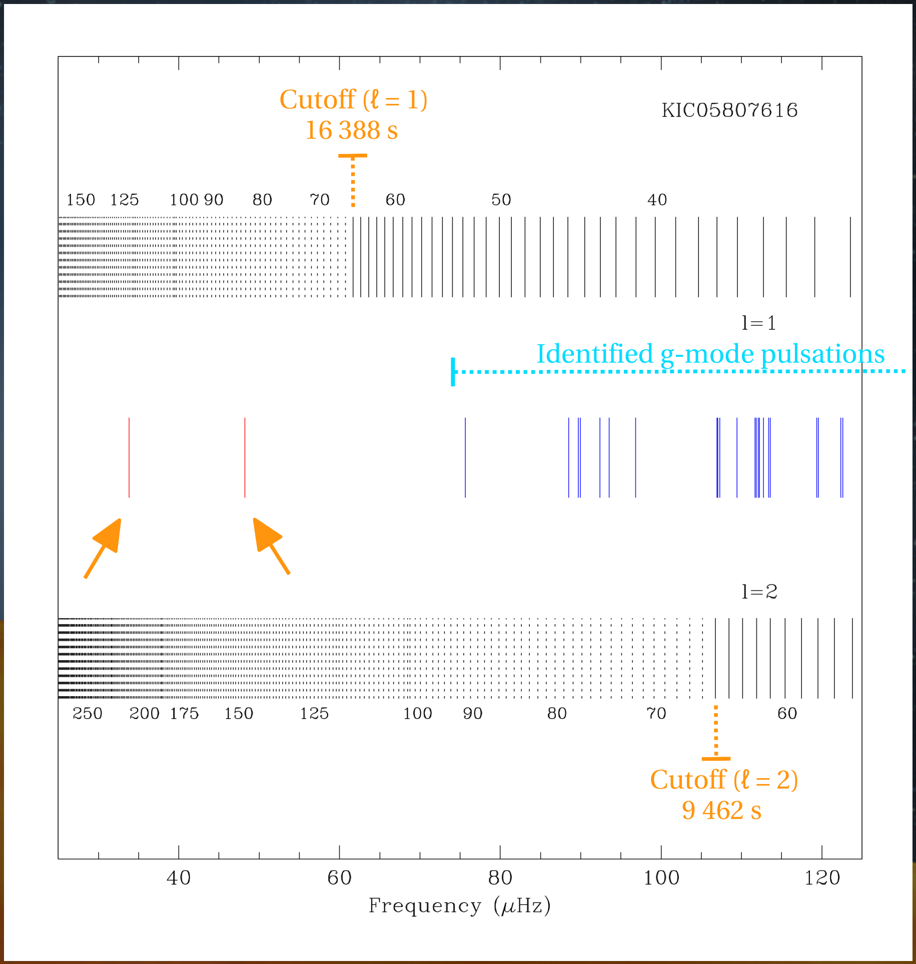
Two intriguing periodic and coherent brightness variations are found at low frequencies, with tiny amplitudes.

KOI 55 and its planetary companions

Theoretical g-mode spectrum of KOI 55 (Van Grootel et al. 2010, ApJ, **718**, L97)



(Charpinet et *al.* 2011, *Nature*, **480**, 496, Suppl. Inf.)

These cannot be pulsations

→ The two frequencies are isolated and well separated from the pulsation modes

→ They are well above the cutoff period for g-modes (see Hansen et al. 1985, ApJ, **297**, 544)

KOI 55 and its planetary companions

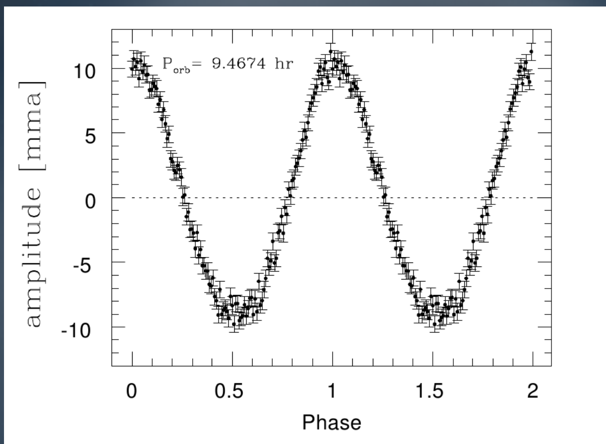
Various possible interpretations for these modulations – which one holds?

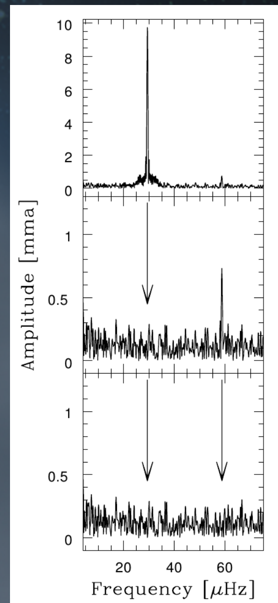
- Stellar pulsations ? → rejected (beyond period cutoff)
- Modulations of stellar origin : spots ? → rejected (pulsations: star rotation ~ 39.23 d)
- Contamination from a fainter nearby star ? → rejected based on pixel data analysis
- **Modulations of orbital origin ?**

KOI 55 and its planetary companions

Example of a non-eclipsing sdB+dM close binary
(KIC 11179657: Reflection + irradiation effect)

Amplitude ~ 1% (10 000 ppm)





(Kawaler et *al.* 2010, *MNRAS*, **409**, 1509)

Orbital signatures at these frequencies are indeed common for sdB stars

- sdB+dM binaries with reflection effect
- sdB+WD binaries with ellipsoidal effect

→ But they typically have much higher amplitudes (unless system seen pole-on)

KOI 55 and its planetary companions

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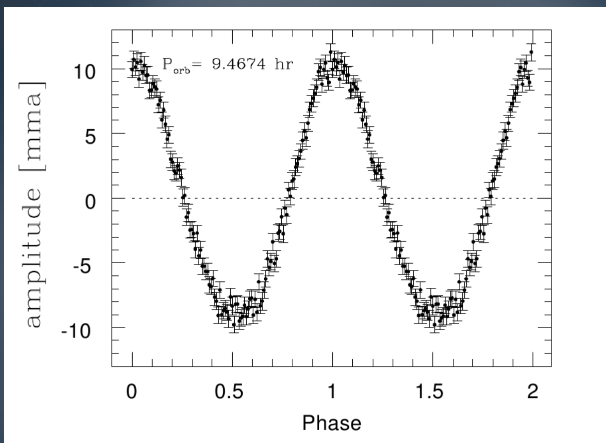

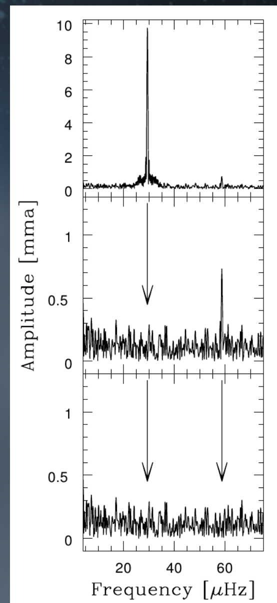

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For KOI 55

- Ampl. ~ 50 ppm (2 ord. of mag. smaller)
- Two signatures are seen (2 objects)
- Pulsations → star inclination > 20°
  and likely ~ 65°
- Measured RV limit ~ 2.4 km/s (2σ)
  → incl. < 3° for a typical dM companion

KOI 55 and its planetary companions

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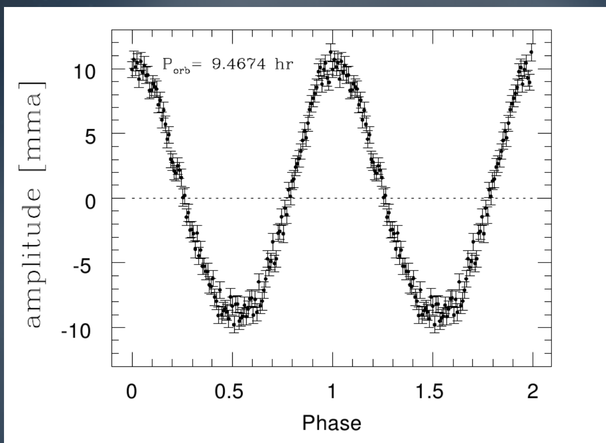

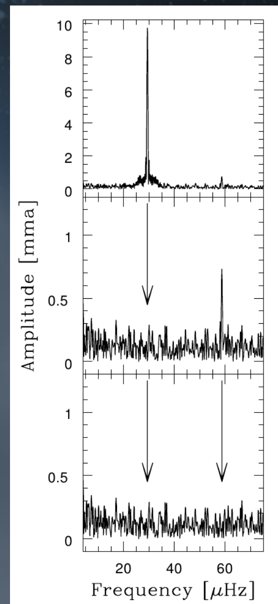

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Are we seeing sub-stellar companions ?

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KOI 55 and its planetary companions

What sizes should these objects have to produce the observed variations ?

Two effects : light reflection + thermal re-emission, both modulated along the orbit

Signal amplitude

Object radius

$$R_j = \left(\frac{A_j}{\sin i}\right)^{\frac{1}{2}} \left(\frac{\alpha_j}{8a_j^2} + \frac{1}{2R_*^2}\,\frac{F_R(T_j) - F_R(\beta T_j)}{F_R(T_*)}\right)^{-\frac{1}{2}}$$

System inclination

$$a_j = \left(\frac{GM_*}{4\pi^2}\right)^{\frac{1}{3}} P_j^{\frac{2}{3}}$$

Star light reflection

α : Albedo

$$T_j = \left(\frac{1-\alpha_j}{8\pi\sigma}\,\frac{\mathscr{L}_*}{a_j^2}\,\frac{1}{1+\beta^4}\right)^{\frac{1}{4}} \quad \text{and} \quad T_j(\text{dark}) = \beta T_j$$

Thermal re-emission

α : Bond albedo

β : night vs day side mean temperature ratio

<u>For KOI 55, this is the dominant term as long as $\beta < 0.9$</u>

$$F_R(T_j) = \int_0^\infty B_\lambda(T_j)\,\mathscr{T}_\lambda^K\,d\lambda$$

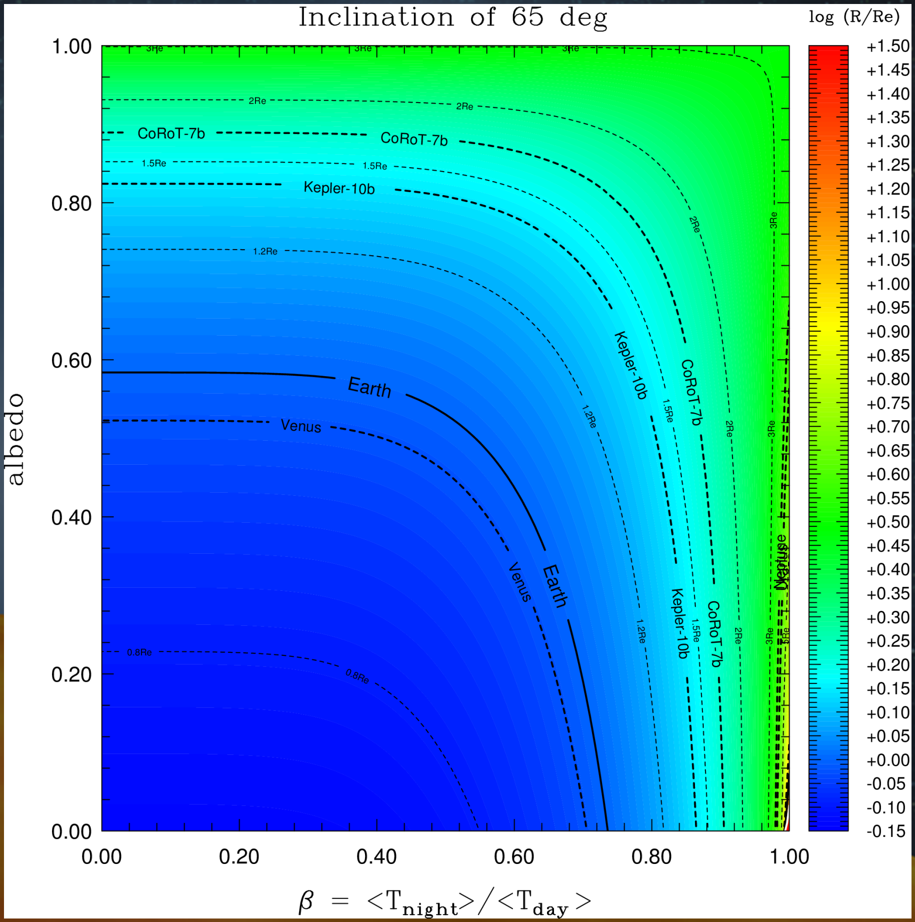
Kepler transmission curve

<u>Underlying hypothesis:</u>

- Planet rotation synchronised
- Circular orbits
- Radiative equilibrium
- Black body re-emission

KOI 55 and its planetary companions

Estimated radius for KOI 55b as a function of albedo and β



Parametric exploration
and the inferred radii

No transits → i < 80°

From pulsations → i ~ 65°
(assuming orbits aligned with equatorial plane)

Most relevant parameter range :
low values for the albedo and β

→ The estimated radii are comparable to Earth radius, and likely smaller

Only unplausible cases would suggest larger objects (giant planets):

i.e, near equal mean temperatures on day/night sides (β > 0.9) and very high albedo

KOI 55 and its planetary companions

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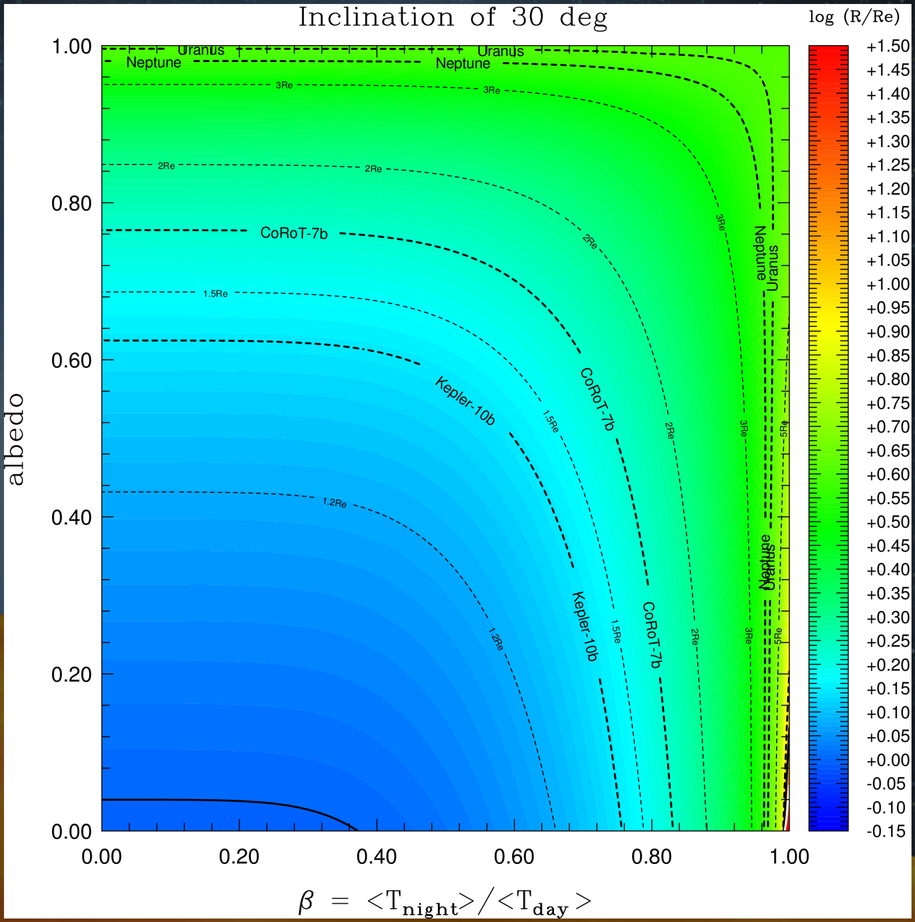

Parametric exploration and the inferred radii

Relaxing the constraint on the inclination

→ The same conclusion holds unless we consider very low inclinations

(but, again, from pulsations i > 20°, ~ 65°)

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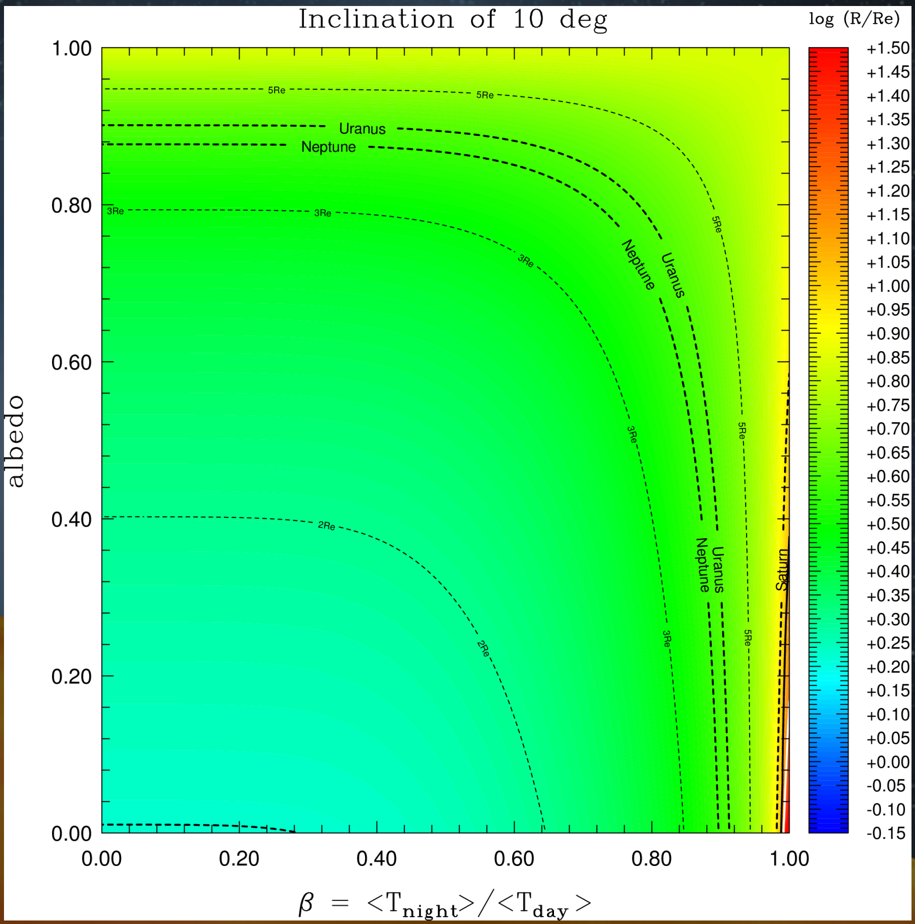

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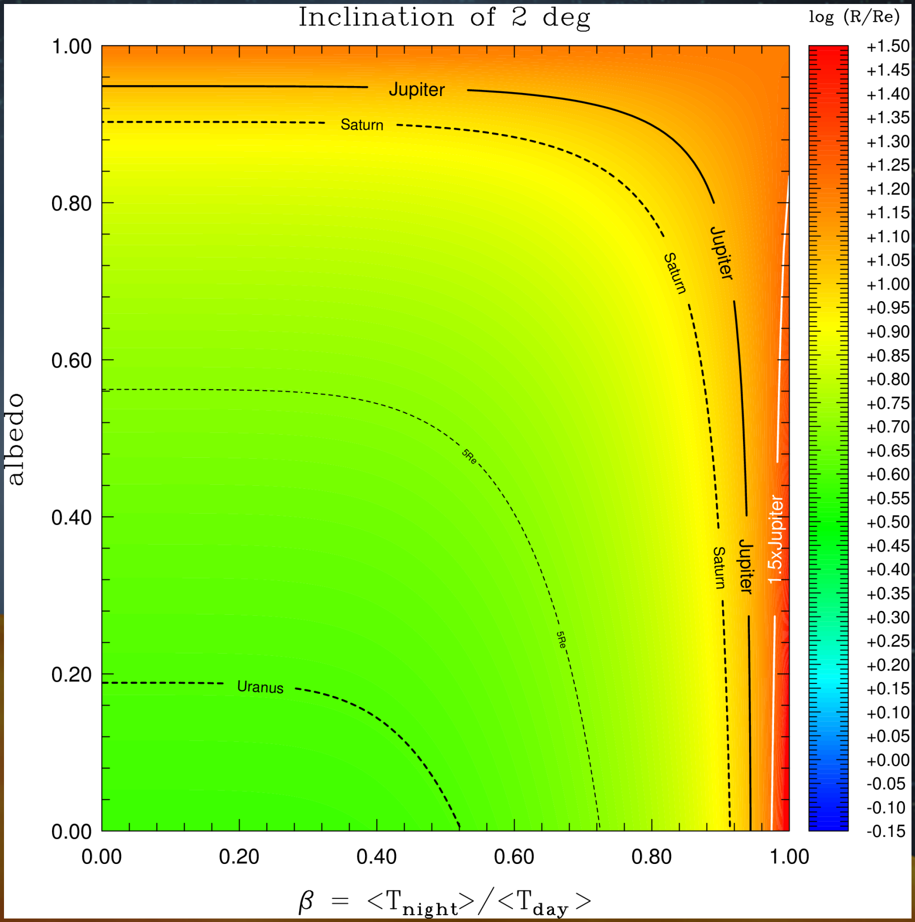

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KOI 55 and its planetary companions

Table 1 | Derived parameters of KIC 05807616 and its two planet candidates

Stellar parameter[15]	KIC 05807616
Effective temperature, T_{eff} (K)	27,730 ± 270
Surface gravity, log[g (c.g.s.)]	5.52 ± 0.03
Mass, M_* ($M_\odot$)	0.496 ± 0.002
Radius, R_* ($R_\odot$)	0.203 ± 0.007
Mean density, ρ_* (g cm^{-3})	84.1 ± 2.9
Age after red-giant stage, A (Myr)	18.4 ± 1.0
Bolometric luminosity, L ($L_\odot$)	22.9 ± 3.1
Apparent Johnson V-band magnitude, V	14.87 ± 0.02
Distance from Earth, d (pc)	1,180 ± 95

Planetary parameter	Planet candidate 1 KOI 55.01	Planet candidate 2 KOI 55.02
Assumed Bond albedo*, α_j	0.10	0.10
Assumed temperature contrast†, β_j	0.2	0.2
Assumed inclination angle‡, i (degrees)	65	65
Assumed mean density§, ρ_j (g cm^{-3})	5.515	5.515
Orbital period, P_j (h)	5.7625 ± 0.0001	8.2293 ± 0.0003
Modulation amplitude, A_j (p.p.m.)	52 ± 6	~47
Orbit radius‖, a_j	8.9698×10^{10} cm 1.290$R_\odot$ 0.0060 AU	1.13749×10^{11} cm 1.636$R_\odot$ 0.0076 AU
Roche limit¶, d_R	0.0029 AU	
Mean temperature: day side#, T_j (K)	9,115	8,094
Mean temperature: night side#, T_j(dark) (K)	1,823	1,619
Planet radius☆, R_j ($R_\oplus$)	0.759	0.867
Planet mass**, m_j ($M_\oplus$)	0.440	0.655
Host star projected radial velocity††, v_j (m s^{-1})	0.65	0.86

(Charpinet et *al.* 2011, *Nature*, **480**, 496)

KOI 55b and KOI 55c
Most likely planets of small size

Assuming reasonable parameter values:

Bond albedo, α = 0.10
Day/night temp. contrast, β = 0.20
Inclination, i = 65°

Implies planets :

Smaller than Earth (76% and 87% of Re), presumably made of dense material

Orbiting very close to their parent star (0.0060 AU and 0.0076 AU)

Exposed to very high irradiation (extremely hot; and evaporating?)

Orbiting a hot/compact He-burning star

How can we explain this ?

The formation of Hot B subdwarf Stars

sdB stars are compact He-burning cores with only a tiny H-rich envelope left
How such stars form has been a long standing problem

For sdB stars in close binaries :
(~ 50 % of sdB stars)

In the red-giant phase : stable & unstable RLOF, Common Envelope Ejection (Han et al. 2003)

↓

The red-giant ultimately lose its envelope before/during Helium ignition (He-flash)

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Only the stripped core of the former red-giant remains, as a hot and compact sdB star, with a close stellar companion

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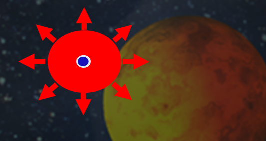
For single sdB stars (like KOI 55) :

(~ 50 % of sdB stars)



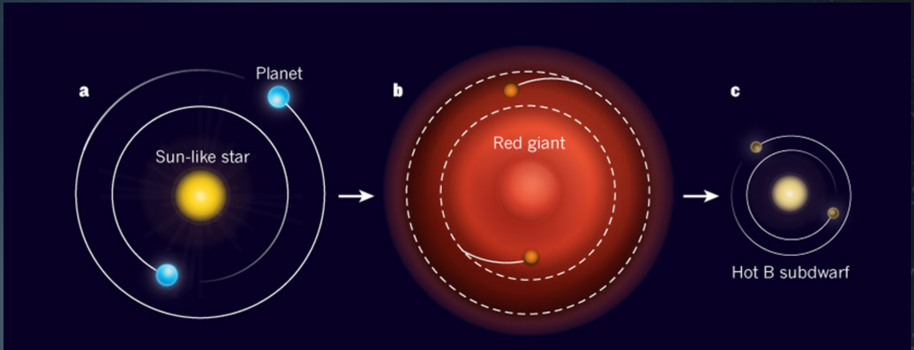
Single star evolution:
A red giant must lose its H-rich envelope but the mechanism is unclear in this case

Soker (1998) : substellar companions (planets) may play a role here

The merger scenario (Han et al. 2003):
Two low mass helium White Dwarfs merge to form a He core burning sdB star.

→ KOI 55 is to be related to the planet channel suggested by Soker (1998)

The KOI 55 system : a consistent scenario



(Figure from Kempton 2011, *Nature*, **480**, 460)

KOI 55b,c interpretation:

1) Former close-in giant planets were deeply engulfed in a red-giant envelope

2) Their volatile layers were removed and only the dense cores survived and migrated where they are now seen

3) The planets were massive enough to trigger the enhanced mass loss for the red-giant to become a sdB star (as suggested by Soker 1998)

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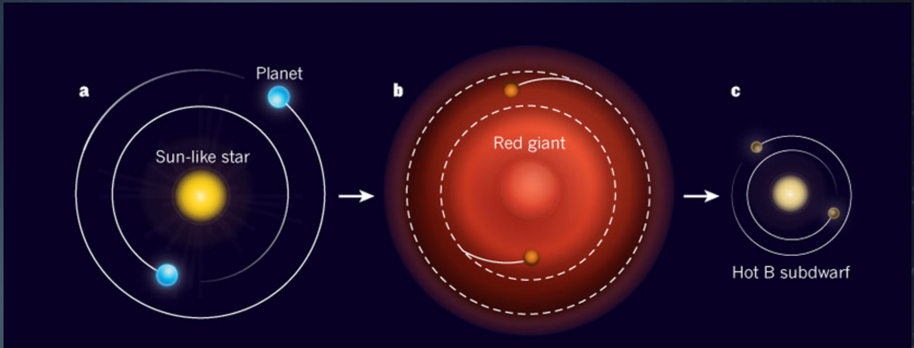

(Figure from Kempton 2011, *Nature*, **480**, 460)

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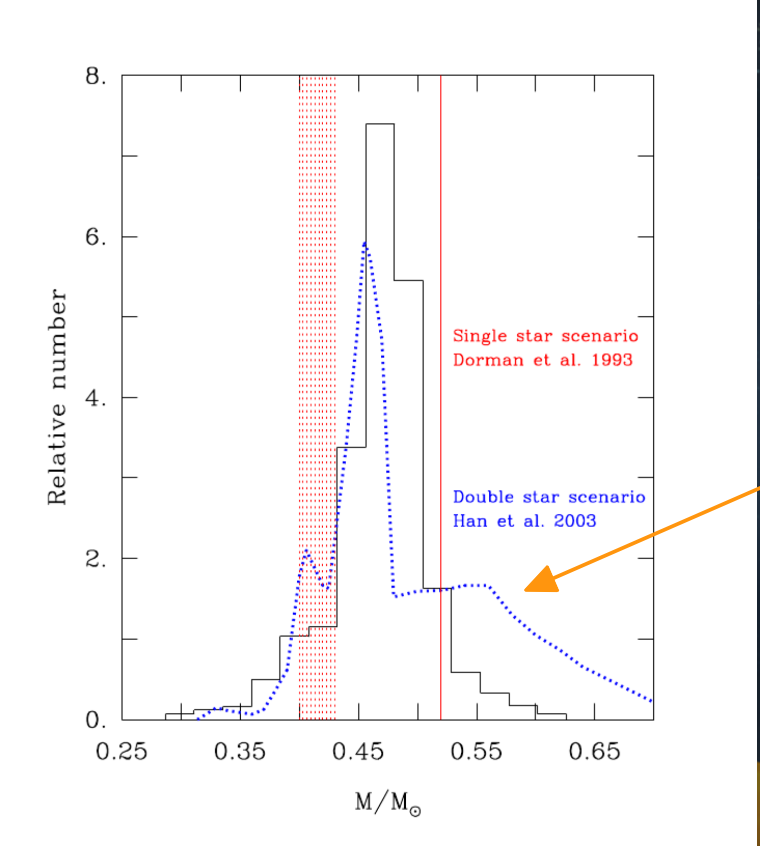
Alternative ideas :

- Small telluric planets engulfed in the red-giant envelope and that survived
  → but such planets are not massive enough to cause the red-giant envelope expulsion
  The formation of the hot B subdwarf star would remain unexplained in that case.

- Second generation planets formed after a merger of 2 He-WDs produced the sdB star
  → but difficult scenario in this harsh environment, close to a very hot star and in only a few Myr
  → KOI 55 is a very slow rotator (Prot ~ 39 days) unlikely to be the product of a merger

Where asteroseismology comes in ...



From Fontaine, Brassard, Charpinet, Green, Randall & Van Grootel (2012), A&A in press

Hot B subdwarfs empirical mass distribution from asteroseismology

Distribution strongly peaked near 0.47 $M_\odot$ (as expected)

No differences between sub-samples (eg, binaries vs single sdB stars)

Possible deficit of high mass sdB stars
(see V. Van Grootel, Conference at KITP, 2011)

→ The merger channel to form isolated sdB stars may not be prominent

→ sdBs from single star evolution exists
→ Substellar objects to form single sdB star reinforced as an alternative explanation

<u>A word of caution</u>:
These comparisons are still based on small number statistics and need to be improved for firmer conclusions

Conclusion

Several facts suggest that the sdB/Planet connection is important

- KOI 55 is possibly the first direct evidence of such a connection
- The mass distribution (from asteroseismology) may weaken the WD merger scenario, thus strenghtening the formation channel involving planets as a consistent alternative
- (not discussed here) Isolated sdB stars appear to rotate very slowly (see Geier et al.). KOI 55 is a very slow rotator (P~ 39.23 days). The He-WD merger channel could hardly explain this, unless very efficient angular momentum loss occurs after/during the merging
- ~ 7 % of MS stars have close-in giant planets that will presumably be engulfed during the red-giant phase → Configurations where "single" sdB stars could be potentially formed from star/planet(s) interaction(s) may be fairly common