An Earth mass planet orbiting Alpha Centauri B

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Exoplanets down to the size of Earth have been found, but not in the habitable zone, i.e. the distance to the parent star where water, if present, would be liquid. There are planets in the habitable zone of stars cooler than our Sun, but for obvious reasons, such as tidal locking, strong stellar activity, are unlikely to harbour water-carbon life as we know it. The detection of a habitable Earth-mass planet orbiting a star similar to our Sun is extremely difficult because such a signal is completely overwhelmed by stellar perturbations. Here we report the detection of the smallest minimum mass planet detected so far around a solar-type star. This planet, orbiting our neighbour star Alpha Centauri B, is also the closest one to the solar system found to date. This result represents a major step towards the detection of Earth twins in the immediate vicinity of the Sun.

Since the discovery of the first exoplanet orbiting a solar-type star in 1995[1], the number of known planets has not stopped growing, reaching by now more than 750 confirmed planets[2] with minimum mass estimates and over 2300 transiting planet candidates detected with the *Kepler* satellite awaiting confirmation. Two major detection techniques have led to this impressive number of discoveries: the radial-velocity technique which measures the change in the velocity of the central star due to the gravitational pull of orbiting planets, and the transit method which measures the small drop in flux when a planet passes in front of its host star. These two techniques are complementary, the first one giving the minimum mass of planets (minimum because the orbital inclination of the planet is unknown), while the second one, their radius.

One of the major challenges in the search for exoplanets is the detection of an Earth twin, i.e. an Earth-mass planet orbiting in the star's habitable zone. Towards this goal, Alpha Centauri B is one of the most interesting targets. At a distance of 1.3 parsecs, it is a member of the closest stellar system to the Sun, composed of itself, Alpha Centauri A and Proxima Centauri. It also exhibits low stellar activity, similar to the solar activity level, usually associated with a small perturbing contribution of stellar intrinsic activity to measured radial velocities. Alpha Centauri B is cooler than the Sun (effective temperature[3,4, 5, 6] of T_{eff} = 5214 ± 33 K, spectral type K1V), and have a smaller mass that our parent star[7] (M_{*} = 0.934 ± 0.006 M_{sun}). These two conditions ease the detection of a potentially habitable planet with radial velocities, the first one implying a habitable zone closer to the star, and the second one, a stronger radial-velocity variation for a similar mass planet. In addition, theoretical studies show that the formation of an Earth twin is possible around Alpha Centauri B[8, 9]. Finally, the brightness of the star (visual magnitude V=1.33) would allow for an efficient characterization of the atmosphere of potential orbiting planets.

An Earth twin induces a typical radial-velocity variation of a few tenths of a meter-per-second on a star like Alpha Centauri B. Such detections, technically possible with the most stable high-resolution spectrographs, are however challenging due to the presence of stellar intrinsic signals inducing a radial-velocity "jitter" at the level of a few meters-per-second, even for quiet stars.

We report here the discovery of a planetary companion around Alpha Centauri B, unveiled by a radial-velocity signal with a semi-amplitude K of 0.51 meters-per-second, a period P of 3.236 days, and a semi-major axis a of 0.04 AU. This planet, with a minimum mass similar to Earth, is the lightest orbiting a solar-type star and the closest to the solar system found to date. Being much closer to its parent star than the Earth is to the Sun, it is not yet an Earth twin. However, the small amplitude of the signal shows that the radial-velocity technique is capable of reaching the precision needed to detect habitable super-Earth planets around stars similar to our Sun, or even habitable Earths around cooler stars (i.e. M-dwarfs). In addition, statistical studies of exoplanets suggest that small-mass planets are preferentially formed in multi-planetary systems[10, 11, 12]. There is therefore a high probability that other planets orbit Alpha Centauri B, maybe in its habitable zone.

High-precision radial velocities

High-precision measurements have been obtained for Alpha Centauri B between February 2008 and July 2011 using the HARPS spectrograph (Supplementary Information, Sec. 1, and supplement text file). HARPS is a high-resolution (R = 110,000) cross-dispersed echelle spectrograph installed on the 3.6-m telescope at La Silla Observatory (ESO, Chile). This instrument has demonstrated a long-term precision of 0.8 meters-per-second, thereby becoming the most powerful machine to hunt for exoplanets using the radial-velocity technique[13,14, 12]. Alpha Centauri B was observed with HARPS following an intensive observational strategy, optimized to sample and mitigate as much as possible high- and medium-frequency stellar intrinsic signals[15]. The star is visited every possible night three times, with exposure times of ten minutes, and with measurements optimally separated by two hours[14].

The raw radial velocities of Alpha Centauri B (see Fig. 1(a)) exhibit several contributing signals that we could identify. Their origin is associated with instrumental noise, stellar oscillation modes, granulation at the surface of the star, rotational activity, long-term activity induced by a magnetic cycle, the orbital motion of Alpha Centauri AB, and the light contamination from Alpha Centauri A.

In the following, we will consider each of these contributions separately, modelling and removing them one by one, from the largest to the smallest amplitude. The model parameters estimated for each contribution will then be used as initial conditions for a global fit that will remove all the identified radial-velocity signals. In the residuals, we will be able to search for small-amplitude planetary signals.

Perturbing signals for planet searches

Alpha Centauri B is a quiet star among the targets monitored in low-mass planet searches. However, the exquisite precision of HARPS allows us to discern in the measurements different perturbing signals at the meter-per-second level. Compared to the radial-velocity signal induced by terrestrial planets, at the level of a few to a few tens of centimetres-per-second, these perturbing signals are non-negligible and must be modelled and mitigated before searching for small-mass planets.

Instrumental noise: Guiding noise and other possible instrumental noise are not considered in the data error bars. Their global effect is estimated to be 0.7 meters-per-second, given the typical dispersion obtained for the most stable stars of the HARPS high-precision program.

Stellar oscillation modes: Alpha Centauri B exhibits high-frequency oscillation modes[16, 17], with typical periods of less than five minutes. An exposure time of ten minutes thus averages out efficiently, to a level of a few centimetre-per-seconds, the signal due to oscillation modes.

Granulation: Alpha Centauri B is a solar-type star and has therefore an outer convection zone responsible for a granulation pattern on its surface. Depending on temperature, granulation cells have positive or negative radial velocities, resulting in a non-zero global radial-velocity signal when their individual contributions are integrated over the disc of the star, weighted by the luminosity of the cells. The granulation effect introduces radial-velocity variations on timescales ranging from fifteen minutes to several hours[18, 19]. For Alpha Centauri B, models of granulation[20] suggest a radial-velocity r.m.s of 0.6 meters-per-second.

Rotational activity signal: Due to stellar rotation and the Doppler effect, one side of the star has a positive radial velocity compared to average, while the other side, a negative one. However, if a spot (darker or brighter than the mean stellar surface) is present on one side of the star, the velocity balance will be broken and a residual radial velocity will be measured. With stellar rotation, a spot will move from one side of the stellar disk to the other, introducing periodic signals at the stellar rotational period and the corresponding harmonics[21]. The lifetime of spots on the stellar surface is typically of a few rotational periods[22], therefore after several rotations, the configuration of spots will be different, thus changing the phase and amplitude of the signal.

The radial velocities of Alpha Centauri B show a clear signal at 38.7 days (Figs. 1(d) and 2(b)), which corresponds to the rotational period of the star[23]. An efficient way to model rotational activity effects is to select radial-velocity measurements over time intervals of a few rotational periods, and fit sine waves at the rotational period and the corresponding harmonics[21] (Supplementary Information, Sec. 2). The best fit for the rotational activity signal for each observational season can be seen in Fig. 3.

Long-term activity signal: During a solar-like magnetic cycle, the number of spots on the stellar surface (dark spots, plage faculae) varies from zero to several hundreds. Inside these spots, a strong magnetic field is present, which freezes the convectionm[24, 25, 26, 27, 28]. For the Sun, as for other stars similar to Alpha Centauri B in spectral type[29], convection induces a blueshift of the stellar spectra[30, 31, 32] Therefore, no convection means no convective blueshift inside these regions, and so the spectrum of the integrated stellar surface will appear redshifted. Since a redshift means a measured positive radial velocity, a positive correlation between the magnetic cycle variation and the long-term radial-velocity variation is then expected.

Alpha Centauri B shows signs of weak but detectable chromospheric activity probed by the re-emission in the centre of the Ca II H and K lines (the $\log(R'_{HK})$ activity index). Alpha Centauri B exhibits a magnetic cycle with a minimum amplitude of $A_{R'HK} \sim 0.11$ dex (Fig. 2(a)). To correct the radial-velocity effect due to the magnetic cycle (see Figs 1(b) and 1(c)), we assume a linear correlation between the $\log(R'_{HK})$ activity index and the activity-related radial-velocity variation[33] (i.e. both variations have the same shape, Supplementary Information, Sec. 3).

Binary signal: The orbital period of the Alpha Centauri AB system is P_{AB} = 79.91 years[7]. The HARPS observations of Alpha Centauri B cover an interval of only four years. The orbit of the system over such an interval can then adequately be approximated by a second order polynomial (see Fig. 1(a)).

Contamination: Due to the close separation on the sky between Alpha Centauri A and B, the spectra of B can be contaminated by light coming from A when the observing conditions are poor. The resulting effect on the radial-velocity measurements was estimated and problematic observations discarded (Supplementary Information, Sec. 4).

Imprecise stellar coordinates: When estimating stellar radial velocities with regard to the barycenter of the solar system, we need to remove the component of the velocity of the Earth in the direction of the star. Imprecise coordinates will then result in an imprecise correction and therefore in a residual signal in the radial velocities. This effect was first pointed out for search of planets around pulsars, where the time of arrivals were varying periodically in time due to imprecise pulsar coordinates[34]. Due to the circular orbit of the Earth around the Sun, this signal will be a sinusoid with a one-year period. Alpha Centauri A and B are gravitationally bound, resulting in a binary orbital motion, which has to be corrected to obtain precise coordinates for Alpha Centauri B (Supplementary Information, Sec. 5).

Removing the various signals

To remove or mitigate the effect of the various signals potentially masking the existence of a small-amplitude planet, the different approaches used have been described in the preceding paragraphs. For contamination coming from Alpha Centauri A, we removed observations with a too high level of contamination. For instrumental noise and granulation that cannot be easily modelled, the estimated radial-velocity contribution from each source is quadratically added as white noise to the raw error bars. For the other effects, parametric models have been proposed. A global fit to the data, including the binary signal, the long-term activity signal and the rotational activity effect, involves 23 free parameters (Supplementary Information, Sec. 6).

A one Earth minimum mass planet

The Generalized Lomb-Scargle periodogram[35] of the radial-velocity residuals shows two peaks at 3.236 and 0.762 days, with a FAP lower than a conservative 1% limit (Fig. 4(a)). These two periods are aliases of one another. A careful analysis of the structure in frequency of the periodogram suggests that the 3.326 days peak is the true signal (Supplementary Information, Sec. 7).

The global model makes use of parameters associated with different timescales. One could thus worry whether the signal at 3.236 days could be introduced during the process of eliminating the stellar signals. We carried out Monte-Carlo simulations to determine if this could be the case, and concluded that the signal is real and not an artifact of the fitting process (Supplementary Information, Sec. 8).

The peak at 3.236 days in the radial-velocity residuals is significant with a FAP of 0.02%. Using a Markov Chain Monte Carlo algorithm coupled to a genetic algorithm to characterize the Keplerian solution, we obtained a signal with a well-constrained period and amplitude. The eccentricity is poorly constrained but compatible with zero within a 1.4-sigma uncertainty (Supplementary Information, Sec. 9). To fit this planetary signal simultaneously with the other contributions to the radial velocities, we added a sinusoidal signal representing the circular planet orbit to the global fit (Supplementary Information, Sec. 6). The observed dispersion of the residuals around the final solution is 1.20 meters-per-second and the reduced chi2 value is 1.51 (with 26 parameters for 459 radial-velocity points). The semi-amplitude of the planetary signal is $K = 0.51 \pm 0.04$ meters-per-second, which corresponds to a planet with a minimum mass of 1.13 ± 0.09 Earth mass, considering a stellar mass of 0.934 solar mass and with $P = 3.2357 \pm 0.0008$ days. The orbital and planet parameters are given in Table 1. In the residuals of the global fit, a signal with a false-alarm probability of 0.3% is present, however its origin could be multiple (Supplementary Information, Sec. 6).

In Fig. 5, we show the radial-velocity measurements corrected from stellar and binary effects, folded in phase with the 3.236 days period, superimposed on the derived solution for the planetary signal. In Fig. 4(b), we show that the 3.236 days signal conserves its phase for each observational year, which is expected for a planetary signal.

An important piece of information about the inner composition of exoplanets is obtained when the planet is transiting its parent star, allowing one to measure its radius. Combined with the real mass estimate, the radius leads to the average density of the planet. In the present case, given a stellar radius[36] of $R_* = 0.863$ R_{sun} and a one Earth radius, the planet transit probability is estimated at 10%, with a transit depth of 10^{-4}. The detection of a potential planet transit, only possible from space, would ascertain the rocky nature of the detected planet around Alpha Centauri B.

The radial-velocity r.m.s induced by rotational activity amounts to 1.5 meters-per-second on average. The detection of the tiny planetary signal, with a semi-amplitude $K = 0.51$ meters-per-second, demonstrates thus that stellar activity is not necessarily a definitive limitation to the detection of small-mass planets. Using an optimized observational strategy and the present knowledge about activity-induced radial-velocity effects, it is possible to model precisely and mitigate activity signals, and therefore improve considerably the planet detection limits.

With a separation to its parent star of only 0.04 AU, the planet is orbiting very close to Alpha Centauri B compared to the location of the habitable zone. However, the observed radial-velocity semi-amplitude is equivalent to the one induced by a four Earth minimum mass planet in the habitable zone of the star ($P = 200$ days[37]). The HARPS spectrograph has therefore the precision to detect a new category of planets: Habitable super-Earths. This sensitivity was expected from simulations of stellar intrinsic signals[15], and actual observations of planetary systems[14].

The optimized observational strategy used to monitor Alpha Centauri B is capable of reaching the precision needed to search for habitable super-Earths around solar-type stars using the radial-velocity technique. However, it requires an important investment in observation time, and thus only few targets can be observed over several years. Recent statistical analyses and theoretical models of planetary formation suggest that low-mass rocky planets and especially Earth twins should be common[12, 38, 39, 40]. We are therefore confident that we are on the right path to the discovery of Earths analogues.

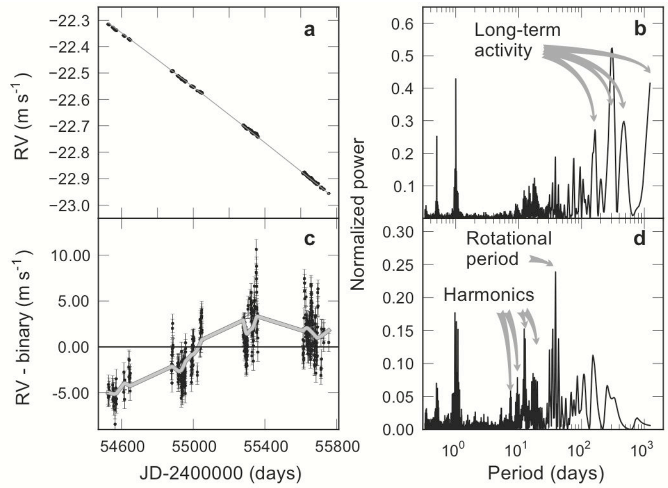

Fig. 1: Radial velocities (RV) and fit of the long timescale stellar signals. After subtracting the binary's signature from the raw radial velocities (**a**), signals at long period are visible in the periodogram of the residuals (**b**). These signals correspond to the effect of the magnetic cycle. The grey curve show the variation of the low frequency part of the activity index scaled to the radial-velocity variation (**c**). When removing these low frequency perturbations, signals induced by rotational activity can be seen at the rotation period of the star and its harmonics (**d**). In panel **c**, one-sigma error bars are shown.

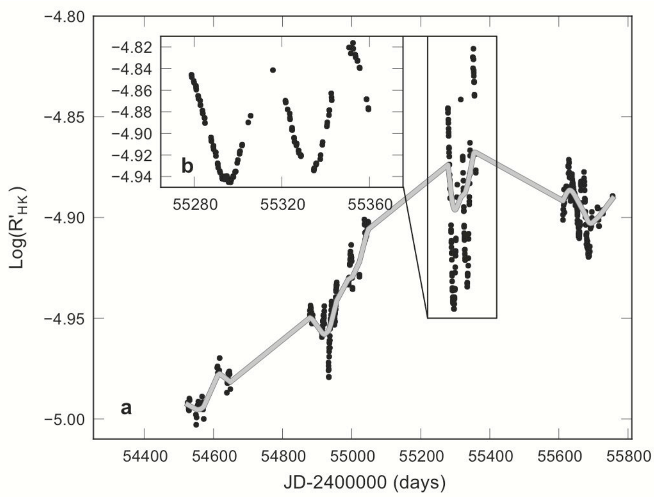

Fig. 2: Magnetic cycle of Alpha Centauri B. a, The grey curve represent a low pass filter applied to the activity index measurements. **b**, The observations done in 2010 are zoomed in to show the variation induced by rotational activity, which highlights the HARPS precision in determining activity indexes. The one-sigma errorbars are plotted on the graph but cannot be seen due to their small values (smaller than 0.015 dex).

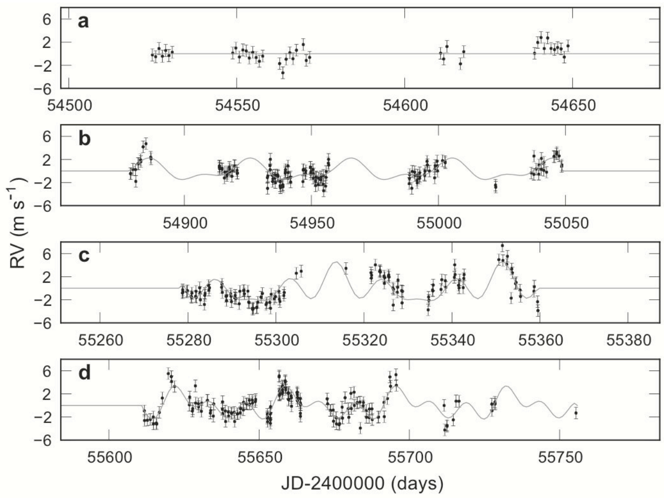

Fig. 3: Fit of the rotational activity. From **a** to **d**, the radial velocities (RV) after correction of the binary, magnetic cycle and coordinates effects, for the years 2008, 2009, 2010 and 2011, are shown as black dots with one-sigma errorbars. The grey curve represents for each plot the fit of the rotational activity signal, ajusting sinusoids at the stellar rotational period and the corresponding harmonics. The rotational period estimated from the stellar activity model decreases from the second season of observation to the last one, with estimated periods of 39.76, 37.80 and 36.71 days, respectively (Supplementary Information, Sec. 6). This can be explained if the star exhibits differential rotation. Indeed, it is shown for the Sun, that spots appears at latitude of +30 or -30 degrees at the start of a magnetic cycle (like in 2008) and then migrate towards the equator during the cycle. Due to differential rotation, observed for the Sun, the rotational period estimated by activity modelling should decrease from the start to the end of a magnetic cycle. A similar effect is seen here for Alpha Centauri B. We therefore believe that differential rotational has been detected here for this slow rotator[41] (Dumusque et al. in prep.).

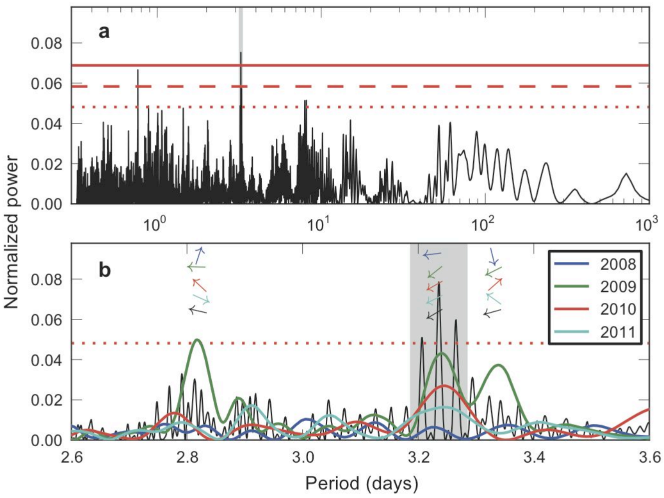

Fig. 4: Periodograms of the radial-velocity residuals after removing the non-planetary signals. In **a** the periodogram of the velocities after correction for stellar, imprecise coordinates and binary effects is displayed, with continuous, dashed and dotted lines indicating the 0.1%, 1% and 10% FAP, respectively. The highest peak, at 3.236 days inside the shaded region, has a FAP of 0.02%. In **b** we show a small part of the periodogram around the planet signal. The periodogram for all seasons is shown in black and the yearly periodograms for each observational period (2008, 2009, 2010 and 2011) in different colors. The amplitudes of the yearly periodograms are normalized so that the 10% FAP of each matches the 10% FAP of the periodogram for all seasons. The phase of the most important peaks are shown as arrows. The direction of the arrow gives the phase between 0 and 360 degrees. For each year of observation, the peak at 3.236 days conserves the same phase, which is expected for a planetary signal. On the contrary, the peak at 2.8 days and its alias at 3.35 days do not keep the same phase and are therefore associated to noise (these peaks appear only in 2009 and their FAPs are higher than 10%).

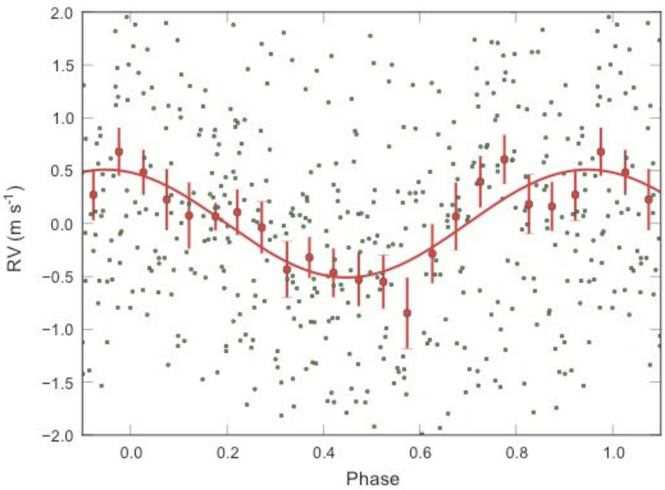

Fig. 5: Phase-folded radial-velocity (RV) curve with a period of 3.2357 days. In green, we see the radial velocities after correction of the stellar, binary, and coordinates effects. The red dots represent the same radial velocities binned in phase, with a bin size of 0.05. The errorbar of a given bin is estimated using the weighted r.m.s of the global fit residuals (including the planetary fit) that make this bin, divided by the square root ot the number of measurements included inside this bin. This estimation of the bin errorbars assumes Gaussian noise. This is justified by the binning in phase, which regroups points that are uncorrelated in time. The r.m.s around the planetary solution is 1.20 meters-per-second for the raw points (grey dots) and 0.21 meters-per-second for the binned points (red dots). The red curve represents the global fit solution of the planet, with a semi-amplitude of 0.51 meters-per-second.

Table 1: Orbital parameters of the planet orbiting Alpha Centauri B ($m.s^{-1}$ stands for meters-per-second).

Parameter	Value
Orbital period (days)	3.2357 ± 0.0008
Time of maximum velocity (BJD)	2455280.17 ± 0.17
Eccentricity	0.0 (fixed)
Velocity semi-amplitude ($m.s^{-1}$)	0.51 ± 0.04
Minimum mass (M_{Earth})	1.13 ± 0.09
Number of data points	459
O-C residuals ($m.s^{-1}$)	1.20
Reduced chi2 value	1.51

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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1. Mayor, M. & Queloz, D., A Jupiter-mass companion to a solar-type star. *Nature* **378**, 355-359 (1995).
2. Schneider, J., Dedieu, C., Le Sidaner, P., Savalle, R. & Zolotukhin, I., Defining and cataloging exoplanets: the exoplanet.eu database. *Astron. Astrophys.* **532**, A79 (2011).
3. Fuhrmann, K. *et al.*, BESO échelle spectroscopy of solar-type stars at Cerro Armazones. *Mon. Not. R. Astron. Soc.* **411**, 2311-2318 (2011).
4. Valenti, J. A. & Fischer, D. A., Spectroscopic Properties of Cool Stars (SPOCS). I. 1040 F, G, and K Dwarfs from Keck, Lick, and AAT Planet Search Programs. *Astrophys. J. Supplement Series* **159**, 141-166 (2005).
5. Santos, N. C. *et al.*, Spectroscopic metallicities for planet-host stars: Extending the samples. *Astron. Astrophys.* **437**, 1127-1133 (2005).
6. Neuforge-Verheecke, C. & Magain, P., Spectroscopic analysis of the Alpha Centauri system. *Astron. Astrophys.* **328**, 261-268 (1997).
7. Pourbaix, D. *et al.*, Constraining the difference in convective blueshift between the components of α Centauri with precise radial velocities. *Astron. Astrophys.* **386**, 280-285 (2002).
8. Xie, J.-W., Zhou, J.-L. & Ge, J., Planetesimal Accretion in Binary Systems: Could Planets Form Around α Centauri B? *Astrophys. J.* **708**, 1566-1578 (2010).
9. Thébault, P., Marzari, F. & Scholl, H., Planet formation in the habitable zone of α Centauri B. *Mon. Not. R. Astron. Soc.* **393**, L21-L25 (2009).
10. Lissauer, J. J., Ragozzine, D., Fabrycky, D. C., Steffen, J. H. & Ford, E. B., Architecture and Dynamics of Kepler's Candidate Multiple Transiting Planet Systems. *Astrophys. J. Supplement* **197**, 8L (2011).
11. Latham, D. W., Rowe, J. F., Quinn, S. N., Batalha, N. M. & Borucki, W. J., A First Comparison of Kepler Planet Candidates in Single and Multiple Systems. *Astrophys. J. Letters* **732**, L42 (2011).
12. Mayor, M. *et al.*, The HARPS search for southern extra-solar planets. XXXIV. Occurrence, mass distribution and orbital properties of super-Earths and Neptune-mass planets. *Astron. Astrophys.* (2011); preprint at <http://arxiv.org/abs/1109.2497>.
13. Lovis, C. *et al.*, The HARPS search for southern extra-solar planets. XXVIII. Up to seven planets orbiting HD 10180: probing the architecture of low-mass planetary systems. *Astron. Astrophys.* **528**, A112 (2011).
14. Pepe, F. *et al.*, The HARPS search for Earth-like planets in the habitable zone. Very low mass planets around HD29794, HD85512 and HD192310. *Astron. Astrophys.* **534**, A58 (2011).
15. Dumusque, X., Santos, N. C., Udry, S., Lovis, C. & Bonfils, X., Planetary detection limits taking into account stellar noise. II. Effect of stellar spot groups on radial-velocities. *Astron. Astrophys.* **527**, A82 (2011).
16. Kjeldsen, H. *et al.*, Solar-like oscillations in Alpha Centauri B. *Astrophys. J.* **635**, 1281-1290 (2005).
17. Carrier, F. & Bourban, G., Solar-like oscillations in the K1 dwarf star alpha Cen B. *Astron. Astrophys.* **406**, 23-26 (2003).
18. Del Moro, D., Solar granulation properties derived from three different time series. *Astron. Astrophys.* **428**, 1007-1015 (2004).
19. Title, A. M. *et al.*, Statistical properties of solar granulation derived from the SOUP instrument on Spacelab 2. *Astrophys. J.* **336**, 475-494 (1989).
20. Dumusque, X., Udry, S., Lovis, C., Santos, N. C. & Monteiro, M. J., Planetary detection limits taking into account stellar noise. I. Observational strategies to reduce stellar oscillation and granulation effects. *Astron. Astrophys.* **552**, A140 (2011).
21. Boisse, I. *et al.*, Disentangling between stellar activity and planetary signals. *Astron. Astrophys.* **528**, A4 (2011).
22. Howard, R. & Murdin, P., in *Encyclopedia of Astronomy and Astrophysics*, edited by Murdin, P. (Bristol: Institute of Physics Publishing, 2000), pp. 3173-3177.
23. DeWarf, L. E., Datin, K. M. & Guinan, E. F., X-Ray, Fuv, and Uv Observations of A Centauri B: Determination of Long-Term Magnetic Activity Cycle and Rotation Period. *Astrophys. J.* **722**, 343-357 (2010).
24. Meunier, N., Desort, M. & Lagrange, A.-M., Using the Sun to estimate Earth-like planets detection capabilities. II. Impact of plages. *Astron. Astrophys.* **512**, A39 (2010).
25. Gray, D. F., *The observation and analysis of stellar photospheres.* (Cambridge: Cambridge University Press, 1992).
26. Brandt, P. N. & Solanki, S. K., Solar line asymmetries and the magnetic filling factor. *Astron. Astrophys.* **231**, 221-234 (1990).
27. Livingston, W. C., Magnetic fields, convection and solar luminosity variability. *Nature* **297**, 208-209 (1982).
28. Dravins, D., *Stellar lineshifts induced by photospheric convection.*, presented at Stellar Radial Velocities, Proceedings of IAU Colloquium No. 88, N.Y, 1985.
29. Gray, D. F., The Third Signature of Stellar Granulation. *Astrophys. J.* **697**, 1032-1043 (2009).
30. Dravins, D., Larsson, B. & Nordlund, A., Solar Fe II line asymmetries and wavelength shifts. *Astron. Astrophys.* **158**, 83-88 (1986).
31. Kaisig, M. & Durrant, C. J., The asymmetry of photospheric absorption lines. I - an analysis of mean solar line profiles. *Astron. Astrophys.* **116**, 332-340 (1982).
32. Beckers, J. M. & Nelson, G. D., Some comments on the limb shift of solar lines. II - The effect of granular motions. *Solar Physics* **58**, 243-261 (1978).
33. Lovis, C. *et al.*, The HARPS search for southern extra-solar planets. XXXI. Magnetic activity cycles in solar-type stars: statistics and impact on precise radial velocities. *Astron. Astrophys.* (2011); preprint at <http://arxiv.org/abs/1107.5325>.
34. Wolszczan, A. & Kuchner, M., in *Exoplanets*, edited by Seager, S. (Tucson, AZ: University of Arizona Press, 2010), pp. 175-190.
35. Zechmeister, M. & Kürster, M., The generalised Lomb-Scargle periodogram. A new formalism for the floating-mean and Keplerian periodograms. *Astron. Astrophys.* **496**, 577-584 (2009).
36. Kervella, P. *et al.*, The diameters of α Centauri A and B. A comparison of the asteroseismic and VINCI / VLTI views. *Astron. Astrophys.* **404**, 1087-1097 (2003).
37. Selsis, F. *et al.*, Habitable planets around the star Gliese 581? *Astron. Astrophys.* **476**, 1373-1387 (2007).
38. Bonfils, X. *et al.*, The HARPS search for southern extra-solar planets. XXXI. The M-dwarf sample. *Astron. Astrophys.* (2011); preprint at <http://arxiv.org/abs/1111.5019>.
39. Mordasini, C., Alibert, Y., Benz, W. & Naef, D., Extrasolar planet population synthesis. II. Statistical comparison with observations. *Astron. Astrophys.* **501**, 1161-1184 (2009).
40. Cassan, A. *et al.*, One or more bound planets per Milky Way star from microlensing observations. *Nature* **481**, 167-169 (2012).
41. Barnes, J. R. *et al.*, The dependence of differential rotation on temperature and rotation. *Mon. Not. R. Astron. Soc.* **357**, L1-L5 (2005).