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The HARPS search for southern extra-solar planets*

XI. Super-Earths (5 & 8 $M_\oplus$) in a 3-planet system

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Abstract. This Letter reports on the detection of two super-Earth planets in the Gl 581 system, already known to harbour a hot Neptune. One of the planets has a mass of 5 $M_\oplus$ and resides at the "warm" edge of the habitable zone of the star. It is thus the known exoplanet which most resembles our own Earth. The other planet has a 7.7 $M_\oplus$ mass and orbits at 0.25 AU from the star, close to the "cold" edge of the habitable zone. These two new light planets around an M3 dwarf further confirm the formerly tentative statistical trend for i) many more very low-mass planets being found around M dwarfs than around solar-type stars and ii) low-mass planets outnumbering Jovian planets around M dwarfs.

Key words. stars: individual: Gl 581, stars: planetary systems – techniques: radial velocities – techniques: spectroscopy

1. Introduction

M dwarfs are of primary interest for planet-search programmes. First of all, they extend the stellar parameters domain probed for planets. For high precision radial-velocity planet searches, M dwarfs are excellent targets as well, because the lower primary mass makes the detection of very light planets easier than around solar-type stars. In particular, Earth-mass planets around M dwarfs are within reach of current high-precision radial-velocity planet-search programmes. Furthermore, the habitable zones of M dwarfs reside much closer to these stars (around 0.1 AU) than for Sun-like stars. Habitable terrestrial planets are thus detectable today. Such detections will provide targets for future space missions looking for life tracers on other planets, like the ESA Darwin and NASA TPF-C/I projects. To find such very light planets in the habitable zone of M dwarfs, our consortium (Mayor et al. 2003) dedicates ∼10% of the Guaranteed Time Observations on HARPS to the precise radial-velocity monitoring of some 100 nearby M dwarfs.

In this Letter we present the detection of two additional planets orbiting Gl 581, where we previously found a 1^{st} close-in Neptune-mass planet. The minimum mass of the 2^{nd} new planet is 5.03 terrestrial mass, the lowest for any exoplanet to date, close to the 5.5 $M_\oplus$ of the microlensing candidate OGLE-2005-BLG-390Lb (Beaulieu et al. 2006) found at a large separation from another M dwarf. It resides at the inner edge of the habitable zone of Gl 581. The 3^{rd} planet, at 0.25 AU from the star, is also in the super-Earth category (7.7 $M_\oplus$), and is situated close to the outer edge of the habitable zone of the system. Section 2 briefly recalls some relevant properties of the parent star. Section 3 describes the precise HARPS velocities and characterizes the new planets. We also examine the possibility that the long-period low-mass planet is actually an artefact of dark spots modulated by rotation of the star, and conclude that this is unlikely. The Letter ends with conclusions.

2. Stellar characteristics of Gl 581

The paper reporting the first Neptune-mass planet on a 5.36-d orbit around Gl 581 (Bonfils et al. 2005b) describes the properties of the star. We will here just highlight those characteristics which are most relevant for this paper:

i) Gl 581 is one of the least active stars of our HARPS M-dwarf sample. Bonfils et al. (2005b) checked that line shapes are stable down to measurement precision through bisector measurements on the cross-correlation functions, and the level

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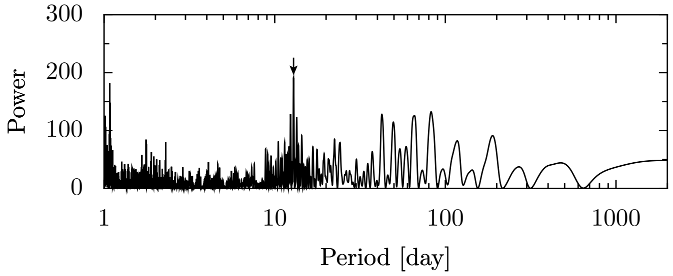

Fig. 1. Lomb-Scargle periodogram of the radial-velocity residuals around the 1-planet solution, clearly showing a peak close to 13 days and some extra-power between 70 and 90 days.

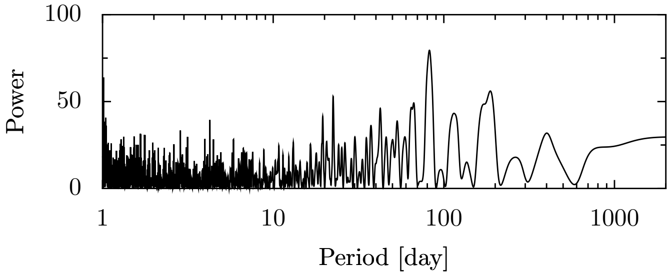

Fig. 2. Periodogram of the radial-velocity residuals around the 2-planet Keplerian model for Gl 581 showing power at $P = 84$ d.

of all chromospheric activity indices similarly points toward a low activity. Such indices represent useful diagnostics of the stellar radial-velocity jitter from rotational modulation of star spots or other active regions on the stellar surface, though no quantitative relation has been established for M dwarfs yet. Bonfils et al. (2007) used variations of these indices to unveil a 35 days rotation period for Gl 674, later confirmed by a photometric campaign, but those of Gl 581 do not measurably vary. The low rotational velocity which we measure for Gl 581 ($v \sin i < 1$ kms^{-1}) would require large spots to produce noticeable radial-velocity variations through line asymmetries. Figure 1 of Bonfils et al. (2007), displaying the Ca[II] line for Gl 674 and Gl 581, clearly demonstrates that Gl 581 is significantly less active than Gl 674. It very probably has proportionately smaller spots, and a longer rotational period than the 35 days of Gl 674. We finally note that Gl 876, hosting the close-in 7 $M_{\oplus}$ planet (Rivera et al. 2005), is more active than Gl 581. Gl 581 is thus expected to have a very low intrinsic radial-velocity noise.

ii) Along the same lines, photometric observations of Gl 581 depict a stable star. Weis (1994) showed that on short time scales the star varies by less than 6 mmag, and the López-Morales et al. (2006) photometric search for a potential transit of the 5.36-d period planet similarly show a low 1.17 mmag dispersion on scales of a few hours. The Geneva photometry founds the star constant within the 5 mmag catalogue precision for 10.5 magnitude stars. Photometric observations have thus so far found no large spots. The photometric stability will however need to be checked at high precision on longer timescales.

iii) Very interestingly, Gl 581 has a sub-solar metallicity ($[Fe/H] = -0.25$ in (Bonfils et al. 2005a); $[Fe/H] = -0.33$ in (Bean et al. 2006)), contrarily to most planet-host stars. Mainstream theoretical and numerical studies of planet formation, based on core-accretion models, predict that the joint effects of a low-mass primary and low metallicity make giant planet formation very unprobable. This finding is supported by the radial-velocity observations (e.g. Santos et al. 2004; Bonfils et al. 2006). Formation of low-mass planets on the other hand is not hampered for deficient (Ida & Lin 2004; Benz et al. 2006) or low-mass stars (Laughlin et al. 2004; Ida & Lin 2005).

3. Description of the Gl 581 planetary system

3.1. HARPS radial-velocity measurements of Gl 581

The 20 high resolution HARPS spectra available when we detected Gl 581 b (Bonfils et al. 2005b) have typical S/N per pixel of ∼40, and at that time the typical radial-velocity uncertainty was 1.3 ms^{-1} per measurement, taking into account calibration uncertainties.

The periodogram of their residuals from the 1-planet keplerian solution showed a tentative 2^{nd} signal at a frequency of 1/13 d^{-1}. With this limited number of observations the low amplitude of the 13-day velocity variation only had modest significance, but it prompted us to gather 30 additional high-precision observations with HARPS (uncertainty < 1.5 ms^{-1}). We also took advantage of a concerted effort to improve the reduction pipeline with a special emphasis on wavelength calibration (Lovis & Pepe 2007). These improvements are directly visible on the new set of barycentric radial velocities (available in electronic form at CDS): their average uncertainty is 0.9 ms^{-1} (including photon noise, calibration uncertainty and spectrograph drift uncertainty). The 50 high-precision HARPS radial velocities confirm the 5.36-d period planet, and we now clearly see the 13 days signal in the periodogram of the residuals around the 1-planet solution (Fig. 1). Some power around 80 days is also visible. The false-alarm probability of the 13 days peak is only 0.0025.

3.2. A 5 $M_{\oplus}$ planet at 0.07 AU from the star

Although the new radial-velocity measurements strongly confirm the 5.36-day planet, their modeling by a single keplerian orbit is poor: the residuals around the 1-planet solution are very high (3.2 ms^{-1} standard deviation) compared with the 0.9 ms^{-1} typical measurement errors, and the reduced χ^2 per degree of freedom is $\chi^2_{red} = 17.3$. This, and the 13-days periodogram peak, motivates investigating a 2-planet model. For the first planet, that solution gives orbital parameters consistent with the Bonfils et al. (2005b) orbit. The 2nd planet moves on a slightly eccentric orbit ($e \simeq 0.28 \pm 0.06$), with a period of 12.895 days.

The measured radial-velocity semi-amplitude is only 3.5 ms^{-1}, or 4 times our typical noise on individual measurements. At this small-amplitude radial-velocity variation, this solution represents a highly significant improvement in

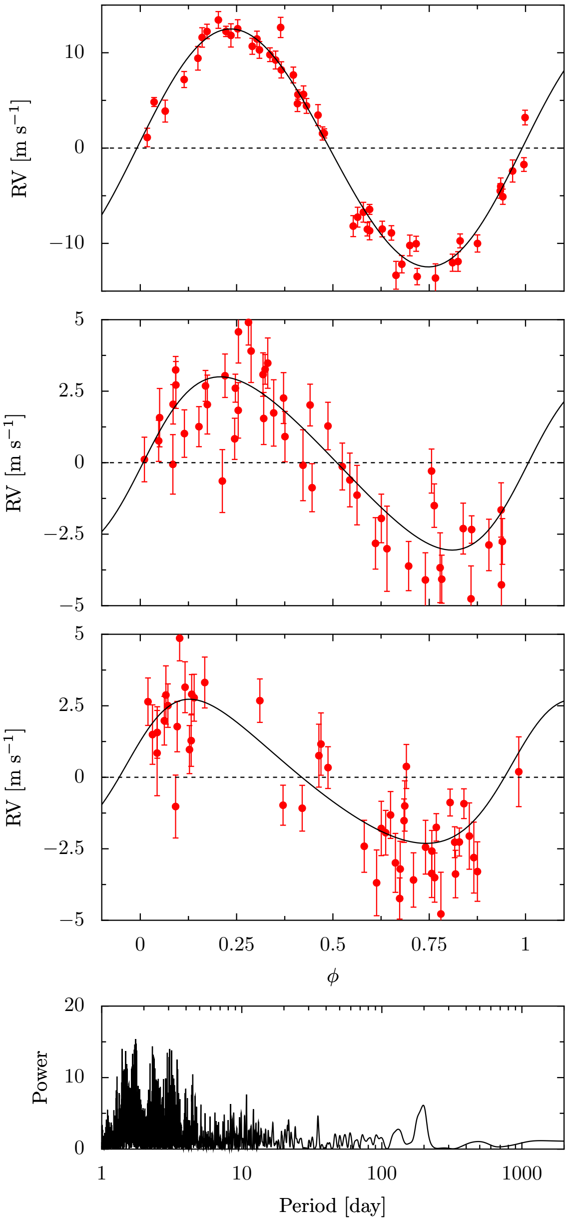

Fig. 3. 3-planet Keplerian model of the Gl 581 radial-velocity variations. The upper panels display the phase-folded curve of each of the planets, with points representing the observed radial velocities, after removing the effect of the other planets. The bottom panel presents the periodogram of the residuals.

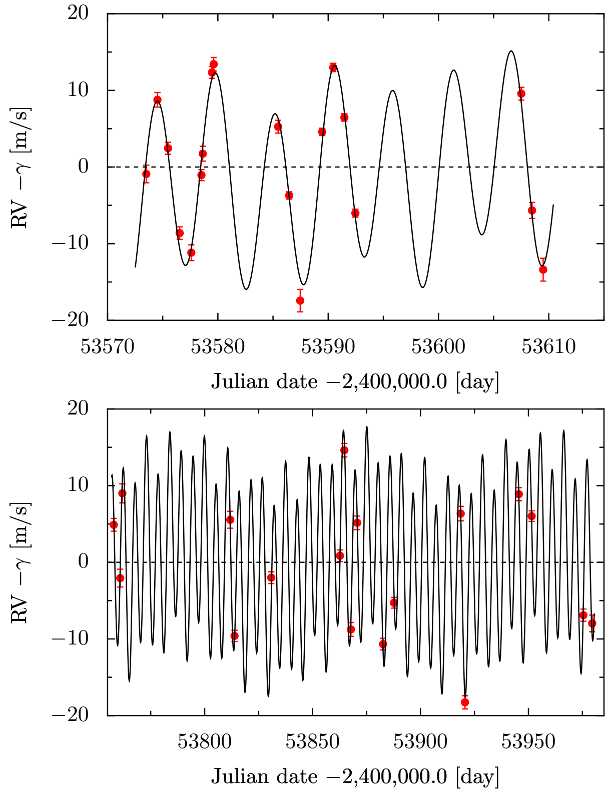

Fig. 4. Temporal display of the 3-planet Keplerian model of Gl 581, on time intervals with dense observational sampling.

the system modeling: χ^2_{red} decreases from 17.3 to 9.2, and the weighted rms of the residuals around the solution is now 2.2 ms^{-1}. We can note here that a circular orbit for the 2nd planet provides a solution of equal quality with a $\chi^2_{red} = 9.0$. The observed dispersion of the residuals is, however, still larger than the internal errors, and the periodogram of the residuals from this 2-planet fit (Fig. 2) shows clear power at 84 days (the false alarm probability of this signal is only 0.0028). In the next section we examine this 3rd signal in terms of an additional planet, and discuss whether it could instead be caused by magnetic activity.

For the 0.31 $M_\odot$ mass of Gl 581 (Bonfils et al. 2005b), the derived orbital parameters for the 2nd planet lead to a $m_2 \sin i \simeq 5.6\,M_\oplus$ minimum mass and a separation $a = 0.073$ AU. From the 0.013 $L_\odot$ stellar luminosity (Bonfils et al. 2005b), we compute an equilibrium temperature for the planet of −3° C (for a Venus-like albedo of 0.64) to +40° C (for an Earth-like albedo of 0.35). With a planetary radius of ~1.5 $R_\oplus$ (Valencia et al. 2006) and a temperature that would be +20° C for a 0.5 albedo, Gl 581c is probably the most Earth-like of all known exoplanets. It is however obvious that the actual surface temperature of the planet very much depends on the highly uncertain composition and thickness of its atmosphere, which govern both the planetary albedo and the strength of the greenhouse effect. It is probable that the planet is located towards the “warm” edge of the habitable zone around the star. A detailed study will also need to consider the possible tidal locking of the planetary rotation to the orbital period.

3.3. A 3rd low-mass planet in the system

Since the periodogram has significant power around 84 days, we examined a 3-planet model. That solution changes the orbital parameters of the inner two planets only slightly from the 2-planet solution (lower eccentricities). The mass of the 2nd planet is now 5.03 $M_\oplus$. Adjusting their eccentricities finds that they are not constrained according to a Lucy & Sweeney (1971) test. We thus provide in Table 1 the orbital parameters for both cases (free and fixed-to-zero eccentricities). The 3rd planet has an 83.6 days period and a slightly eccentric orbit ($e = 0.2$). The

Table 1. Orbital and physical parameters derived from 3-planet Keplerian models of Gl 581 for the free-eccentricity and circular cases. Uncertainties are directly derived from the covariance matrix.

		Circular case			Free eccentricity case		
Parameter		**Gl 581 b**	**Gl 581 c**	**Gl 581 d**	**Gl 581 b**	**Gl 581 c**	**Gl 581 d**
P	[days]	5.3687±0.0003	12.931±0.007	83.4±0.4	5.3683±0.0003	12.932±0.007	83.6±0.7
T	[JD-2400000]	52999.99±0.05	52996.74±0.45	52954.1±3.7	52998.76±0.62	52993.38±0.96	52936.9±9.2
e		0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	0.02±0.01	0.16±0.07	0.20±0.10
V	[km s^{-1}]		-9.2115 ± 0.0001			-9.2116 ± 0.0002	
ω	[deg]	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	273±42	267±24	295±28
K	[m s^{-1}]	12.42 ± 0.19	3.01±0.16	2.67±0.16	12.48 ± 0.21	3.03±0.17	2.52±0.17
$a_1 \sin i$	[10^{-6} AU]	6.129	3.575	20.47	6.156	3.557	18.98
$f(m)$	[$10^{-13} M_\odot$]	10.66	0.365	1.644	10.80	0.359	1.305
$m_2 \sin i$	[$M_{\rm Jup}$]	0.0490	0.0159	0.0263	0.0492	0.0158	0.0243
$m_2 \sin i$	[$M_\oplus$]	15.6	5.06	8.3	15.7	5.03	7.7
a	[AU]	0.041	0.073	0.25	0.041	0.073	0.25
$N_{\rm meas}$			50			50	
Span	[days]		1050			1050	
σ (O-C)	[ms^{-1}]		1.28			1.23	
$\chi^2_{\rm red}$			3.17			3.45	

inferred planet mass is 7.7 $M_\oplus$ (8.3 $M_\oplus$ in the circular case) and the mean star-planet separation is 0.25 AU, putting the planet close to the outer edge of the habitable zone. Aside from being most prominent in the frequency analysis, the 84-d period naturally comes out in global solution searches based on the genetic-algorithm approach. This makes a misidentified alias unlikely. An on-going stability study of the system (Beust et al. in prep) shows that the system is stable over millions of years, even in the more eccentric case ($e+\sigma_e$). Figure 3 displays the 3-planet Keplerian solution together with the phase-folded radial velocities, and Fig. 4 plots time sequences for densely sampled measurement intervals.

Introducing a 3^{rd} planet adds 5 free parameters and will thus always lower residuals, but here the quality of the solution improves impressively, and statistically very significantly: its χ^2_{red} drops from 9.2 to 3.45, and the 1.2 ms^{-1} rms residual is now closer to the 0.9 ms^{-1} typical internal error. A modeling of the system including planet-planet gravitational interactions gives the same results and shows that for those small masses the mentioned interactions are negligible.

Can the 84-d radial-velocity variation have another source? Among the very low-mass planets around M dwarfs, the recent Gl 674 b detection provides a particularly illustrative comparison: the radial-velocity measurements of Gl 674 show two superimposed small-amplitude variations with 4.7 and 35 days, but monitoring of chromospheric indices and photometric observations demonstrate that the 35 days variation reflects rotational modulation of stellar activity, leaving only one 11 $M_\oplus$ planet with a 4.7-d period (Bonfils et al. 2007). This recent example emphasizes that the interpretation of small-amplitude radial-velocity variations of M dwarfs needs care, since most are expected to be at least moderately active, and illustrates the value of chromospheric diagnostics and photometric followups for these stars.

Since a comparison with Gl 674 (Fig. 1 of Bonfils et al. 2007) shows that Gl 581 is significantly less active, its rotational period is most likely longer than ~40 days, and it could potentially coincide with the 84-d signal. One therefore needs a serious look at the possibility that the 84-d signal reflects a spot on the stellar surface. At such a low rotation rate, one would however need a huge spot to affect the radial velocities at the several ms^{-1} level. Scaling from Saar & Donahue (1997), a spot responsible for the observed variation needs to cover 2.6 % of the stellar surface[1]. Such a large spot would only be expected in a fairly active star, which Gl 581 is not. Planned spectroscopic (radial velocities and activity index) and photometric monitoring of the star will settle that issue for good, but we are already confident that the 3^{rd} planet is real.

4. Summary and discussion

We report the detection of two new very light planets orbiting the low metallicity M dwarf Gl 581, already known to harbour a 15.7 $M_\oplus$ closer-in planet (Bonfils et al. 2005b). The high radial-velocity precision reached with the HARPS spectrograph on the ESO 3.6-m telescope enabled these discoveries.

The first planet, Gl 581 c, is a 5.03 $M_\oplus$ super-Earth at a distance of 0.073 AU from the star. Its mass is the smallest found so far for an exoplanet. At its separation from an M3 dwarf, the planet resides at the inner edge of the habitable zone of this low luminosity star. With a radius close to 1.5 $R_\oplus$, the planet is the closest Earth twin to date. The HARPS radial velocities also reveal a longer-period planetary companion of mass 7.7 $M_\oplus$, on a 83.6-d period orbit, close to the outer edge of the star habitable zone. Considering uncertainties on the determination of the edges of the habitable zone, mainly due to the lack of realistic cloud models, these two planets are promising targets for future observatories. The spectral characterization of their atmosphere would provide a crucial constraint on the actual limits of the habitable zone.

The two new very low-mass planets further support statistical trends already outlined in the literature:

[1] The same estimate for Gl 674 with $P_{\rm rot} = 35$ days, $R_\star = 0.29\,R_\odot$, and $K = 5$ ms^{-1} gives a 1.7 % spot, close to the observed 2.6 %.

i) Small planets (Neptune mass and below) are more frequent than giant planets around M dwarfs (6 very low-mass detections against 3 Jovian planets). This result was significant at the 97 % level before the detection of the two new Gl 581 planets (Bonfils et al. 2007), even without accounting for the poorer detection efficiency for lower-mass planets.

ii) The fraction of detected Neptune (and lower-mass) planets around M dwarfs is much larger than the corresponding ratio for solar-type stars (Bonfils et al. 2006). The absolute numbers of detections are similar, but the number of surveyed solar-type stars is an order of magnitude larger. This may be an observational bias due to the lower mass of M-dwarf primaries, or truly reflects more frequent formation of Neptune-mass planets around M dwarfs. The factual conclusion remains that Neptune-mass planets are easier to find around M dwarfs.

Recent planet-formation simulations (Laughlin et al. 2004; Ida & Lin 2005) suggest that planet formation around low-mass primaries tends to produce lower mass planets, in the Uranus/Neptune domain. Formation of lower-mass planets is also favoured for solar-mass stars with metal-poor protostellar nebulae (Ida & Lin 2004; Benz et al. 2006)[2]. Gl 581 is a $0.3\,M_{\odot}$ metal-poor star, and its detected very light planets are thus just what was expected around this star. Additional detections of very-low mass planets will help understanding these 2 converging effects.

From both our observational programmes and planet formation simulations, very low-mass planets seem more frequent than the previously found giant worlds. They will thus provide preferential targets for space photometric transit-search missions like COROT and Kepler, and for projects like Darwin or TPF-I/C looking for biotracers in the atmospheres of habitable planets.

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[2] Note, however, that there is no general consensus. Kornet et al. (2006) suggest that smaller-mass primaries have denser disks, which would favour giant planet formation. Gravitational instability might also form super-Earth planets around M dwarfs as well (Boss 2006).