Summary of “The HARPS search for southern extra-solar planets

XI: Super-Earths (5 and 8$M_\oplus$) in a 3-planet system” (2007)

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Detecting exo-planets has become an exciting and press worthy branch of astronomy in recent years. This paper is the summary of one particularly interesting discovery, that of small planets detected in the Gliese 581 system. The discovery was made using the High Accuracy Radial Velocity Planet Searcher or HARPS, a high precision spectrograph telescope located in Chile. Following the original findings published in the HARPS paper, Gliese 581 has received a great deal more scientific attention and is still a strong candidate for possible future space exploration.

To begin, it is important to first realize the significance of M dwarfs when planet hunting. They provide excellent circumstances if you are using the radial velocity technique, which requires very sensitive spectroscopy detection. Thanks to Newton, we know that if two planets of equal size revolve around their parent star, the star with greater mass will experience a smaller shift in radial velocity than that of the smaller star. With the limits of currently technology, this makes M dwarfs ideal for finding smaller terrestrial planets; more importantly, for finding Earth-like planets. The findings in the HARPS paper reveal two newly discovered planets located in the system's habitable zone, sometimes referred to as the 'Goldilocks Zone', which is the zone around a star where a planet with an efficient atmosphere can retain liquid water. With our limited understanding of what circumstances make life possible, this discovery becomes all the more significant because the only evidence of life in the universe we currently have exists on a tiny rock covered mostly in water.

The stellar characteristics of the Gliese 581 system were first described in great detail upon the discovery of a revolving Neptune-sized planet in 2005 (Bonfils et al. 2005). The highlighted attributes, first published in 2005, that are relevant for this newer discovery include the fact that the host star, Gliese 581, is one of the least active stars currently in the HARPS M dwarf catalogue. This has been shown by monitoring the chromospheric activity and by checking the stability of the line shapes through bisector measurements on the cross-correlation functions. In 2007, this was the reliable way to check for the star's stability because no established quantitative relation had been established. The measured rotational velocity of Gliese 581 is quite low, $v \sin(i) < 1$ km/s. Due to its relatively low activity and low rotational velocity, Gliese 581 is expected to have low inherent radial velocity noise, which means the data is solid and reliable. Photometric observational techniques have also been exhausted to support the findings of Gliese 581's stability, though they will need to be examined and re-examined at high precisions over longer timescales to ensure the reliability of applying this technique. Last but not least, the star itself has been found to have a "sub-solar" metallicity, which is somewhat of an anomaly compared to most star systems that house planets (Bean et al. 2006). Conservative planet formation models based on the core-accretion process predict that a low-mass primary star with a low metallicity makes the probability of forming a gas giant planet very unlikely; further evidence that the system itself is stable and the data is well-founded. It has been shown that the formation of lower-mass planets is favored for solar-mass stars that are metal deficient (Ida & Lin 2004; Benz et al. 2006). What makes Gliese 581 so special is that it is a metal poor star of $0.3 M_{\odot}$, so detecting lower mass planets is exactly what one should expect to find when looking for bodies revolving around it.

Determining the features of the Gliese 581 planetary system was done with a typical S / N (signal to noise ratio) of about 40. The average radial-velocity uncertainty was around 1.3 m/s per measurement; this includes the uncertainties due to calibration. Looking at Figure 1, we see the periodogram of the 1-planet Keplerian solution, which was published upon the initial discovery of the Neptune-sized planet.

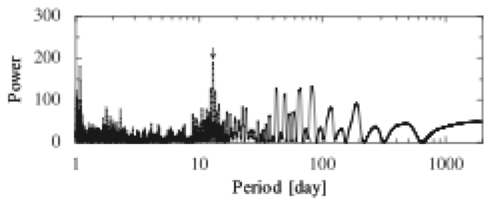

Fig. 1. Lomb-Scargle periodogram of the radial-velocity residuals around the 1-planet solution, clearly showing a peak close to 13 days and some extra-power between 70 and 90 days.

You will notice the peak at the 13-day velocity variation, which is not absurdly significant but it led to the desire for additional high-precision observations brought on by the fact that the false-alarm probability (an adaptive algorithm that detects background noise in the telescope) is only 0.25%.

Upon obtaining 30 additional high-precision observations, it became obvious that the 1-planet solution was not a good enough model to describe the reality of events. The proposal of a second planet with a minimum of 5.03$M_{\oplus}$ becomes necessary to explain the data. Looking at Figure 2, we see that the new data remains consistent with the initial data used in Figure 1, but notice the peak in power at P = 84 days. The false-alarm probability of the signal is 0.28%. Proposing a two-planet model and deriving its orbital parameters reveal that the mass of this second planet is m2 sin(i)$\simeq$ 5.6$M_{\oplus}$and has a semi-major axis a = 0.073 AU, which gives a period of 12.895 days.

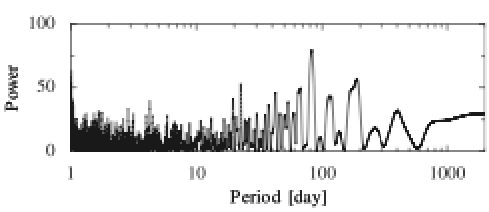

Fig. 2. Periodogram of the radial-velocity residuals around the 2-planet Keplerian model for Gl 581 showing power at $P = 84$ d.

It is worth pointing out here that the HARPS paper initially suggests the potential surface temperatures at equilibrium between -3°C and $+40^{\circ}$C, depending on the albedo of the planet and the reliability of terrestrial planet models. Their paper goes on to state that “Gl 581 c is probably the most Earth-like of all known exoplanets”. Upon further analysis, using updated terrestrial planet climate models, Gliese 581 c has been shown to most likely have a runaway greenhouse gas effect similar to that of Venus and therefore is uninhabitable for life (Vogt et. al. 2010).

The peak power around 84 days in Figure 2 was significant enough to warrant proposing a 3-planet model which only slightly changes the orbital parameters of this new system. Under these conditions, the mass of the 2nd planet becomes 5.03$M_{\oplus}$, while the 3rd planet has a period of 83.6 days, a semi-major axis of 0.25 AU, giving it an inferred planet mass of 7.7$M_{\oplus}$. The introduction of this third planet, Gliese 581 d, vastly improves the interpretation of the data and significantly improves the statistics of the data. In this model, the χ^2_{red} plunges from 9.2 to 3.45 and now the internal error of the rms residual resembles a typical 0.9 m/s. Below is Table 1, which lists both possible 3-planet models and their corresponding measurements with error.

Table 1. Orbital and physical parameters derived from 3-planet Keplerian models of Gl 581 for the free-eccentricity and circular cases, with uncertainties 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-2 400 000]	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)	[m s^{-1}]		1.28			1.23	
$\chi^2_{\rm red}$			3.17			3.45	

Looking at other possible explanations for the peak at P = 84 days, the stability of Gliese 581 makes the 3-planet scenario all the more likely. The 84 day signal could reflect a spot somewhere on the surface of the star, though the data from Figure 1 and comparisons to other M dwarfs such as Gl 674 confidently show that the rotation rate is most likely more than ~ 40 days; so the spot would have to be huge, covering 2.6% of the surface. This is something one would expect in a very active star, which Gliese 581 is not. Further analysis is required to confirm the existence of this 3rd planet but there is plenty of evidence pointing toward this as the solution.

In conclusion, this 3 planet model places Gliese 581 d near the outer edge of the habitable zone while 581 c is near the inside. If 581 c had an Earth-like composition (which it has since been shown most likely not to), then its radius would be close to 1.5$R_{\oplus}$, making it the smallest exoplanet planet currently known (Vogt et al. 2010). It must be stated that determining the edges of the habitable zone is currently a difficult task due to the lack of realistic cloud models available and the problems that arise when defining the spectral characterizations of the atmospheres these planets possess. The discovery of these two low mass planets are supported by plenty of evidence. They continue the current statistical trends in the planet hunter game, that small planets occur more frequently than giant ones around M dwarfs, and the fraction of lower mass planets around M dwarfs is much greater than the corresponding ratio for solar-like stars.

References

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