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Surfing the photon noise: New techniques to find low-mass planets around M dwarfs

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The current precision radial velocities techniques to detect low mass planets in M dwarf are quickly reviewed. This includes high resolution spectroscopic observations made both in the optical and in the near infrared. We discuss that, given the current instrumental performance, optical RVs are still far ahead over other approaches. However, this situation might change soon with the advent of new spectrographs with red/nIR capabilities. We review a newly developed method to obtain precision RV measurements on stabilized spectrographs and how it is implemented to archival HARPS observations. In addition to get much closer to the photon noise, this approach allows us to identify and filter out wavelength dependent noise sources achieving unprecedented accuracy on G, K and specially M dwarfs. We show how including red/infrared observations is of paramount importance to efficiently and unambiguously detect very low mass planets around cool spectral types. As examples, we show new measurements on Barnard's star indicating that the star is stable down to 0.9 cm s^{-1} over a time-span of 4 years and how RV signals correlated with activity indices disappear when using the reddest half of the HARPS wavelength range. To conclude, we present new results, detections and describe the implications in terms of planet/multi-planet abundances around cool stars.

1 Introduction

In the last 15 years, major improvements in technology and detection techniques enabled the systematic exploration of the sky for planets orbiting other stars. In particular, the most successful and efficient method to detecting and/or confirm exoplanets around nearby stars is Doppler spectroscopy – e.g., Mayor & Queloz (1995) and Butler et al. (2006). The method consists on detecting the periodic changes in the radial velocity of a star due to an unseen low mass companion orbiting it. When a planet is closer to the star, the radial velocity signal increases substantially. While Jupiter inflicts a periodic signal of 13 years to the Sun with an amplitude of ~ 10 m s^{-1}, the wobble caused by the Earth is about 10 cm s^{-1} only. State-of-the-art spectrographs (e.g. HARPS/La Silla, HIRES/Keck) can currently deliver Doppler precision at the 1 m s^{-1} level, so the detection of Earth-like objects around Sun-like stars is still beyond our reach.

Low mass stars (the most abundant stellar population in the galaxy) are significantly less luminous than sun-like stars and the orbits at which an Earth-like planet could sustain liquid water on its surface have much shorter periods (Kasting et al. 1993). This combined with their lower masses, makes the Doppler signal of a few Earth-mass planets in the habitable zones of M dwarfs already detectable with current techniques. However, M dwarfs are intrinsically faint at optical wavelengths having most of the flux in the optical red (0.7 to 0.9 μm) and the near infrared (from 0.9 to 2.5 μm). With the idea of optimally exploring the presence of planets around low mass stars, a number of projects are investigating wavelength calibration techniques suitable for the available high resolution near infrared spectrographs (e.g. CRIRES/VLT, NIRSPEC/Keck, C-SHELL/IRTF).

The most successful attempt to date used the CRIRES/VLT spectrograph with an absorption cell filled with ammonia gas and used the same principle than the Iodine cell method in the optical (Butler et al. 1996). That program (Bean et al. 2010) reported Doppler precisions at

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the level of ~ 5 m s^{-1}on a small sample of very nearby M dwarfs including GJ 699 (Barnard's star), Proxima Cen (GJ 551) and a few others. These stars have also been observed using the High Accuracy Radial velocity Planet Searcher (HARPS) installed at the 3.6 m telescope of La Silla/ESO. HARPS is a stabilized high-resolution spectrograph ($R \sim$ 110 000) and covers a wavelength range from 380 nm to 680 nm in a single shot. The public ESO archive contains about 20 spectra on each object over a time-span of a year. Since HARPS was primarily designed as a precision Doppler machine, the HARPS-ESO Data Reduction Software (DRS) also provides final data products as the radial velocity measurement (obtained by the cross-correlation function method, or CCF) and several other spectroscopic indices (e.g., CCF bisector span, FWHM of the CCF, etc. Lovis et al. 2011).

Although the collecting area of the 3.6 m telescope is only ~ 20 % of an 8.2 m VLT, the rms of the residuals of 20 HARPS epochs on both aforementioned stars (GJ 699 and GJ 551) is of the order of 2 m s^{-1}. It is worth mentioning that these are the two nearest M dwarfs to the Sun and that the integration times are already at the limit of what would be reasonable for precision Doppler measurements (900 sec for GJ 699). In order to identify the key elements in the significant better performance of HARPS and, with the aim of identifying the critical design parameters for a potential red/nIR spectrograph, we considered that a more detailed analysis of the HARPS data was mostly needed.

2 Template matching on stabilized spectrographs

Despite the impressive results obtained with HARPS (Mayor et al. 2009, 2011), it is known that the cross-correlation function method implemented in the HARPS-DRS is suboptimal in the sense that it does not exploit the full Doppler information on the stellar spectrum (e.g., see Pepe et al. 2002; Queloz 1995). For this purpose, we developed from scratch a software tool called HARPS-TERRA (Template Enhanced Radial velocity Reanalysis Application) based on least-squares template matching. This is, the method consists in matching each observed spectrum to a very high signal-to-noise (S/N) template of the star build from the same observations. The details of the algorithms, performance and results on a representative sample of G, K, and M dwarfs was presented in Anglada-Escudé & Butler (2012). Here, we give a quick overview on the main and new results from that study, use them to show that some M dwarfs can be as stable as more massive stars (e.g., G and K dwarfs), and illustrate that the increase in precision leads to the detection of an emergent population of low mass exoplanets in high multiplicity systems. HARPS-TERRA also allows to measure Doppler shifts of individual echelle orders. This enables, for example, the possibility of exploring the wavelength dependence of the noise properties and/or suspicious signals.

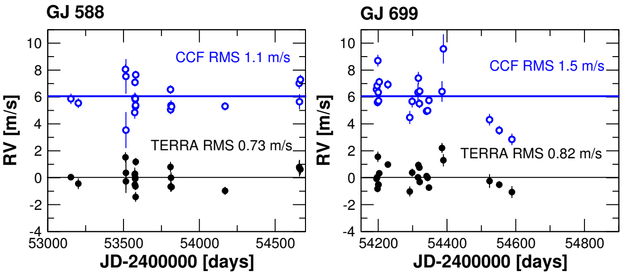

Fig. 1 (online colour at: www.an-journal.org) Comparison of the Doppler measurements as obtained by the HARPS-CCF method (blue hollow dots) to those obtained with HARPS-TERRA. GJ 699 is Barnard's star and the RV measurements were obtained using only the 8 red-most échelle orders.

3 Results on nominally stable stars

In Fig. 1, we present RV time series on the two most stable M dwarfs we have found so far (Barnard's star and GJ 588) compared to the corresponding CCF measurements using an M2 binary mask. In a detailed analysis of the Doppler measurements on more objects, we found that the radial velocities derived on several stars show excess variability at bluer wavelengths. To illustrate this in Fig. 2 we plot the RV root-mean-squared of the residuals (rms) as a function of the bluest HARPS aperture used for three representative (and nominally quiet) stars. The typically lower S/N of the blue orders is already accounted in computing the weighted mean of RV on each epoch, so the rms as a function of this blue cut-off should monotonically decrease if the noise were purely random noise and achromatic. Instead, nearly all stars did show a minimum in these diagrams (specially G and M dwarfs). Only a handful of very quiet stars produced truly achromatic random scatter (e.g., HD 85512/K6V central panel of Fig. 2 or GJ 588/M2V). For example, the rms on GJ 699 is strongly wavelength dependent achieving maximum accuracy (lowest rms) when only using the 10 red-most HARPS echelle orders. Similar behavior (extremely high Doppler content in the red) was also observed on most M dwarfs.

Moreover, we found this wavelength dependent *jitter* could be coherent in time inducing spurious periodicities in the Doppler measurements. In Fig. 3, we show how on HD 69830 (G8V dwarf), a very prominent Doppler signal correlated with the S-index (chromospheric activity index) vanishes as we move to redder wavelengths, while the rms of the residuals to a three planet fit (Lovis et al. 2006), stays roughly the same (or even improves). The correlation of wavelength dependent signals with chromospheric activity indicators (e.g., Ca II H + K S-index; Baliunas et al. 1995) has to be quantified and can provide a powerful method to identify, even remove, activity induced signals. Also in many cases, the residual rms (> 0.8 m s^{-1}) was found to be significantly larger than the photon noise and the internal errors computed using the standard deviation of the Doppler measurement over all the echelle orders. This is, while for some bright stars (e.g., τ Ceti, HD

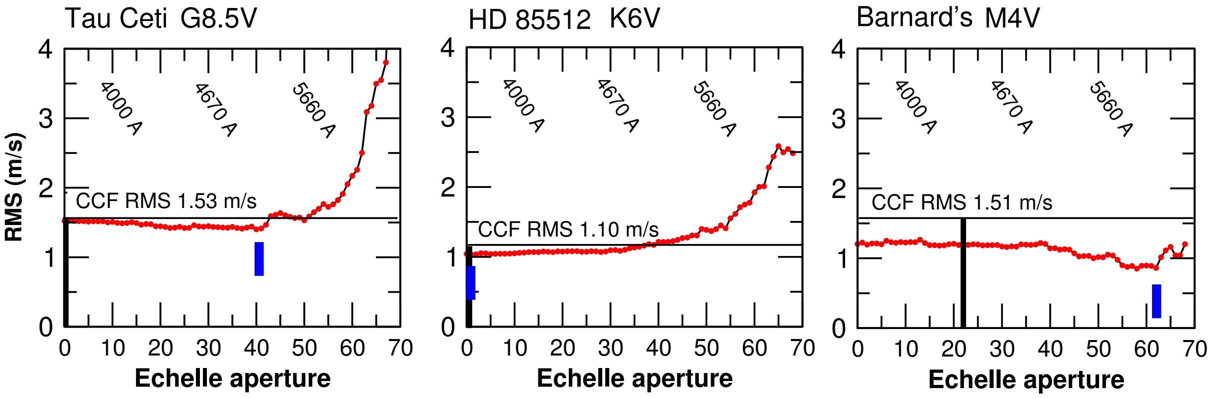

Fig. 2 (online colour at: www.an-journal.org) Measured rms as a function of the bluest échelle aperture used to derive RV measurements for three relatively inactive dwarf stars. The rms of the CCF measurement provided by the HARPS-DRS is illustrated as a horizontal black line. The black vertical line indicates the bluest echelle order employed by the HARPS-DRS to derive Doppler measurements (e.g., for M dwarfs, HARPS-DRS only uses down to the 22nd échelle aperture). The minimum of the rms is marked with a short blue vertical line. Except for the K dwarf, both the G and the M dwarf show a clear minimum.

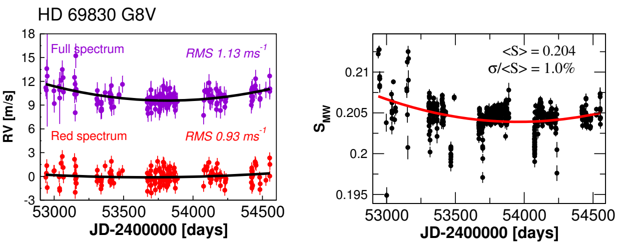

Fig. 3 (online colour at: www.an-journal.org) *Left*: residual radial velocities after subtracting the three planets reported by Lovis et al. (2006) using the full spectrum (top violet points) and the red half of the HARPS wavelength range only (bottom red points). The black line is a parabolic fit to the measurements in both cases. *Right*: S-index measurements on the same spectra. The red line is also a parabolic fit to the S-index data illustrating the clear correlation with the RVs derived from the full HARPS spectral range.

69830, HD 88512, α Cen A and B) internal errors can be as low as 0.3, the rms of the residuals is typically between of 0.8 and 2.0 m s^{-1}. This indicates that HARPS Doppler measurements are mostly dominated by systematic effects rather than photon noise (stellar or instrumental). This illustrates that higher instrumental stability is often more desirable than a large collecting area. In overview, further work is on-going to separate the instrumental from the stellar noise, identify the physical origin of the wavelength dependent jitter and design strategies to filter it out without perturbing the time coherence of true Doppler signals.

As shown in next sections, in addition to the study of stable stars, the enhanced precision of the HARPS-TERRA measurements are also being used to examine archival data for additional low amplitude signals.

4 New systems

4.1 Three signals in GJ 667C

In September 2011, the HARPS-TERRA analysis of 143 public spectra on the M dwarf GJ 667C revealed the presence of 3 candidate planets around this star. The first one was was a 5 $M_\oplus$ super-Earth in an orbital period of 7.2 days and had already been announced in 2009 but the precise orbit was not known at the time. Two additional (unreported) signals were also spotted at periods of 91 and 28 days. Given that the last public observations were taken back in 2008, it looked like the previous CCF observations were not convincing enough to claim a clean detection and that the star was abandoned. The phase sampling of the two longer periods was not ideal either, so we obtained additional RV measurements using the PFS/Magellan spectrograph (20 RVs) and combined them with lower precision but longer time-baseline HIRES/Keck observations (21 RVs). The combined analysis of the three data sets confirmed the three signals with high confidence and the candidate planets were finally announced in February 2012.

In the meantime, (Bonfils et al. 2011) (whose team has been in charge for the actual HARPS observations), reported the same 28 days candidate (GJ 667Cc) and a first preliminary description of the candidate was also given. The same three candidates and a more detailed orbital analysis of the system were also provided by Delfosse et al. (2012) using $\sim$40 additional HARPS observations taken between 2009 and 2012. While the third candidate (with an uncertain period of 74 to 105 days) is still controversial due to a similar period detected in two activity indicators (S-index and FWHM of the cross-correlation function), GJ 667Cc (period of 28.1 days and a minimum mass of about $\sim 4\,M_\oplus$) is the most robustly detected candidate orbiting well within the liquid water habitable zone of a nearby star and, compared to other candidate as GJ 581d or HD 88512b, it requires no assumptions about its cloud coverage (Selsis et al. 2007) to be considered potentially habitable.

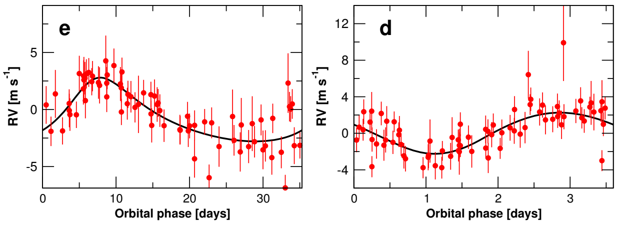

Fig. 4 (online colour at: www.an-journal.org) Radial velocity curves phase folded to the period of the new planet candidates: GJ 676Ad 3.60 days (*left*) and GJ 676Ae 35.5 days (*right*).

4.2 Two additional candidates around GJ 676A

A planetary system with a massive gas giant candidate and a long period trend extending the time-baseline of the observations was first reported by Forveille et al. (2011). Using HARPS-TERRA, the re-analysis of 40 public spectra available in October 2011 showed improved precision compared to the CCF measurements and a few promising peaks in the periodogram of the residuals. With the full set of 75 observations processed with HARPS-TERRA (full set finally released by May 2012), we were able to identify two new candidates in the super-Earth mass regime (Anglada-Escudé & Tuomi 2012). Besides improved HARPS-TERRA precision, the analysis required the refinement of the detection methods to deal with parameter correlation in multi-planet fits and the candidates were both confidently detected using Bayesian methods (e.g., Tuomi 2012) and new periodogram approaches. Anglada-Escudé & Tuomi (2012) also showed that 50 HARPS-TERRA measurements would have been enough to report the same candidates using the same Bayesian detection criteria. The system holds the record in terms of mass range (form 4.4 $M_\oplus$ to more than 5 $M_{\rm Jup}$) and period range (from 3.6 to more than 4000 days) in a single star and has a general architecture reminiscent of our own Solar System : two long period gas giants and lower mass planets in shorter period orbits. Given that the habitable zone remains unoccupied and that the star is remarkably quiet, a few more measurements could reveal potentially habitable worlds around it.

High multiplicity? With this new systems, there are now 3 planetary systems with (at least) four planets around M dwarfs: GJ 876, GJ 581, and GJ 676A. In comparison, *only* 12 M dwarfs are reported to have a single planet around them. Even if only tentative, this shows evidence of high multiplicity of planets around low mass stars. That is, the probability of finding one more planet is significantly larger than the probability of finding the first. If this trend is confirmed, it can have profound implications in our understanding of planet formation in the planetary low-mass regime.

5 Conclusions

We show that precision RV in the optical are significantly more precise that what can currently be done in the nIR thanks to a greater instrumental stability at all time-scales. For the M dwarfs, and due to their redness, most of their Doppler information is concentrated in the 20 % red-most fraction of the HARPS spectrum, highlighting the importance of moving towards the red/near infrared to enable the efficient follow up of many other late type stars. The same data analysis techniques allowed us to identify apparent radial velocity offsets that are wavelength dependent. Therefore, the best strategy to robustly detect low amplitude candidates seems to be the comprehensive analysis of the Doppler measurements on a wavelength range as broad as possible.

HARPS-TERRA measurements allowed the convincing detection of the potentially habitable zone candidate GJ 667Cc with 20 % less observations than those required using the CCF technique. A similar increase in precision allowed the convincing detection of two low mass candidate planets in short period orbits around GJ 676A. The abundance of low mass planets around M dwarfs promises a bright future to spectrographs under construction with red/nIR capabilities such as GIANO-TNG and CARMENES/CaHa. Given the number of spectrographs in construction and on-going transit searches, finding a nearby potentially habitable world transiting in front of its parent star is likely to happen in the next few years.

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