The Cool Tiny Beats Project - A High-cadence HARPS Survey Searching for Short-period Planets, Pulsations and Activity Signatures in M stars

Z. M. Berdiñas[1], P.J. Amado[1], G. Anglada-Escudé[2], on behalf of the CTB Team.

[1] *Instituto de Astrofísica de Andalucía - CSIC, Glorieta de la Astonomía s/n, 18008, Granada, Spain.*

[2] *School of Physics and Astronomy, Queen Mary University of London, 327 Mile End Rd., United Kingdom.*

Abstract. The Cool Tiny Beats Project (CTB) is an Earth survey designed to observe a sample of M dwarfs with high-resolution and high-cadence. Data obtained with the HARPS and HARPS-N spectrographs will try to resolve three fundamental aspects related with nearby M stars and their planetary systems: i) characterization of compact planetary systems with sub-Earth mass objects, ii) detection of pulsations and asteroseismic studies, and iii) time-resolved analysis of stellar activity and its Doppler signatures. Program key lies in the observing strategy, which consists of monitoring each target for 3 consecutive nights (high-cadence). This strategy is pushing the HARPS instruments to their limit, and allowing not only to join three scientific cases under the same data sets, but also to check the HARPS performance in the intranight range. By the time 13 M dwarfs were observed for 36 high-cadence nights spread over 5 runs. Here we present the first CTB survey results.

1. Introduction

Photometric spacial missions as Kepler have revealed some new short period signals (from 0.5 to 3 days) in M stars systems, which have been identified as close-orbiting planets. Some examples are the systems Kepler-42 or KOI-1843 (Muirhead et al. 2012; Ofir & Dreizler 2013). Spectroscopy surveys have also discovered several short-period planets on M dwarfs systems as GJ 667C or GJ 581 (Anglada-Escudé et al. 2013; Mayor et al. 2009). GJ 581 was considered to be a 5-planet system until planets d and g were eventually retracted by the HIRES team and a study from Robertson et al. (2014) probed that signals associated with the d and g potential habitable planets were in fact masked stellar activity from the host star. Robertson's team studied the precise radial velocity (RV) Doppler shifts in the sodium D and H-alpha absorption lines, obtained with the HARPS and HIRES spectrographs, to model and subtract from the data the anti-correlation dependence observed between the RVs and the activity of the star. This study evidence the importance of going deeper in the star knowledge in order to fit the planets signal accurately. In the near future comparative studies of high-resolution spectra in the optical and NIR will allow to easily elucidate if the planet signal has in fact a magnetic or asteroseismology origin. New optical - NIR high-resolution RVs spectrographs as CARMENES (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs), (Quirrenbach et al. 2012; Amado et al. 2013) or HPF (Habitability Planet Finder), (Mahadevan et al. 2012) will open the NIR window for the RVs spectrographs.

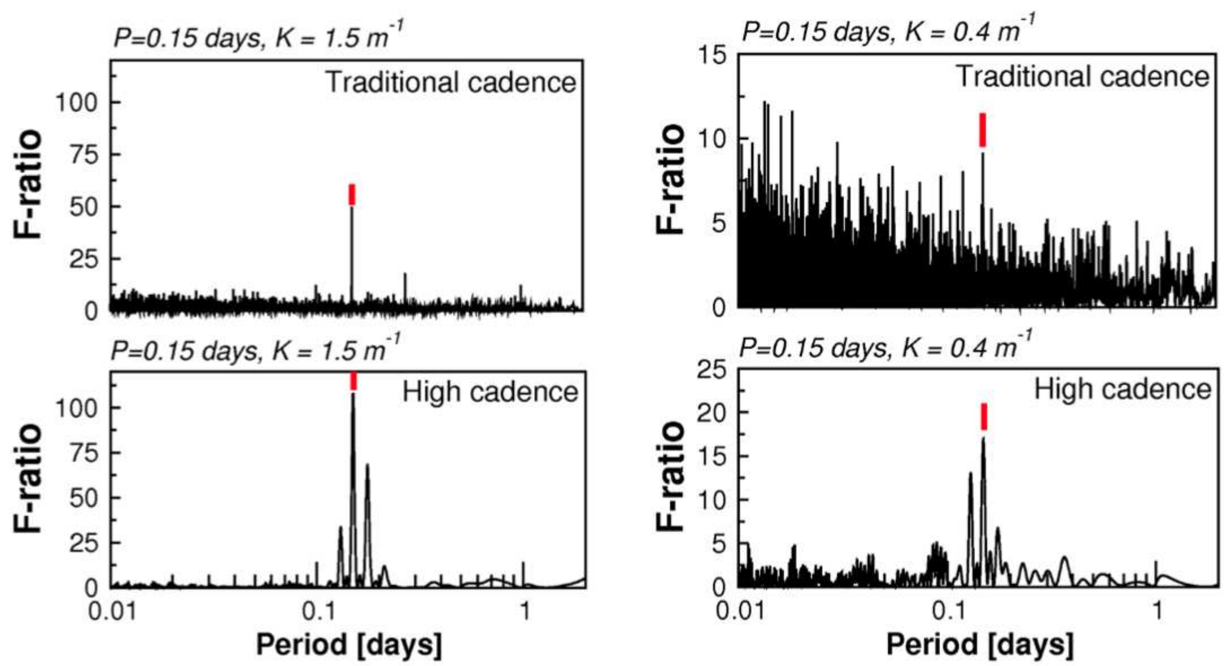

Figure .1: Comparison of the periodogram recovered for a short-period synthetic signal (P = 0.15 days) with amplitudes K = 1.5 $m\,s^{-1}$ (left) and K = 0.4 $m\,s^{-1}$ (right) using traditional-cadence (upper panels) and high-cadence (lower panels). While the 1.5 $m\,s^{-1}$ is detectable in both cases, a 0.4 $m\,s^{-1}$ amplitude cannot be detected with traditional-cadence.

The CTB is an ongoing program carried out with the most precise instrumentation for RVs determinations nowadays. This program can provide the first minimum mass determinations of sub-Earth sized objects, dynamical characterization and first population studies of these peculiar systems. Pulsations in M dwarfs have recently been theoretical predicted (Rodríguez-López et al. 2012, 2014) but none have been yet observed. Such a detection will enable the use of asteroseismic techniques on very cool stars. Time-resolved stellar activity analyses combined with wavelength dependent Doppler measurements will provide important clues to elucidate the connection between Doppler variability, activity and stellar magnetic fields. High-cadence (continuously monitoring each single target for almost three consecutive nights using exposures times from 300 up to 900 s) is a strong requirement to look for the theoretically predicted pulsations with periods ranging from a few minutes to a couple of hours which make the traditional cadence not useful for the lower amplitude signals (See Fig .1). High precision Doppler measurements are obtained with HARPS-TERRA (Anglada-Escudé & Butler 2012), a new technique developed by our group which allows to improve the precision on the radial velocity determination.

2. GJ 725A and the FWHM issue. *(Results from HARPS-N)*

GJ 725A is a nearby M3V (Jenkins et al. 2009) at 3.5 pc (Dieterich et al. 2012) with brightness 8.91 in V (Jenkins et al. 2009) and 4.432 in K (Cutri et al. 2003). The estimated mass is 0.36 $\pm$ 0.05 M$\odot$(Zakhozhaj 1979) and the metallicity spectroscopically measured in the K-band is -0.49 (Rojas-Ayala et al. 2012) indicating that is metal poor compared with the Sun. GJ 725A is slightly brighter than his binary companion GJ 725B. GJ 725A was selected for being a nearby bright M star with no planets or magnetic activity reported until the date, being a perfect target for asteroseismology studies. It was observed in 2013A (30th Jun 1st-2nd Jul, 229 spectra) and 2013B (13-17 Aug, 400 spectra) and a very clear strong 1 day controversial Doppler signal was detected from the first spectra.

Radial velocity time series have an RMS of $\sim$11.5 $m\,s^{-1}$ per night in the first run and $\sim$17 $m\,s^{-1}$ in the second one, which leads to a 0.97 days period signal with a significant amplitude of 1.9 $m\,s^{-1}$ (see Fig .2). Close to 1 day period signals must be deeply analyzed as they could be related to night-to-night instrumental variations. In order to perform a thorough analysis we calculated periodograms of several indicators, such as the FWHM (Full Width High Maximum) or the BIS Span (Bisector Span) of the spectrum lines. FWHM measure symmetrical changes in the mean line-profile width and the BIS Span is related with the asymmetry of the the mean line-profile, which is calculated as the difference between the average velocity at the upper and at the lower part of the Cross Correlation Function (CCF). Spectrum lines changes (other that shifts which are measured by the RVs) are detected with the FWHM / BIS indices. These deformations of the spectral lines are usually associated with magnetic features happening on the stellar surface. Periodograms performed over the 2013B FWHM index report an unambiguous 1.01 days signal with K$\sim$44 $m\,s^{-1}$(see Fig .2). As a rule, activity features produce FWHM time variations with lower amplitude than the RVs but we are recovering 23 times higher amplitude in the FWHM index. This is not expected even in very active M dwarfs. The 0.9 days signal could not be the rotation period because other indicators as the CaHK (S-index) are not showing strong signatures. The only alternative explanation is to have a pole on case, which is very unlikely. Consequently, after discarding plausible magnetic effects, we suspect that this signal has an instrumental origin. In fact if we introduce the FWHM series as a correlation term in our RVs fit model, the 0.97 days signal is absorbed by the correlation. The trend of the FWHM with the airmass (AM)

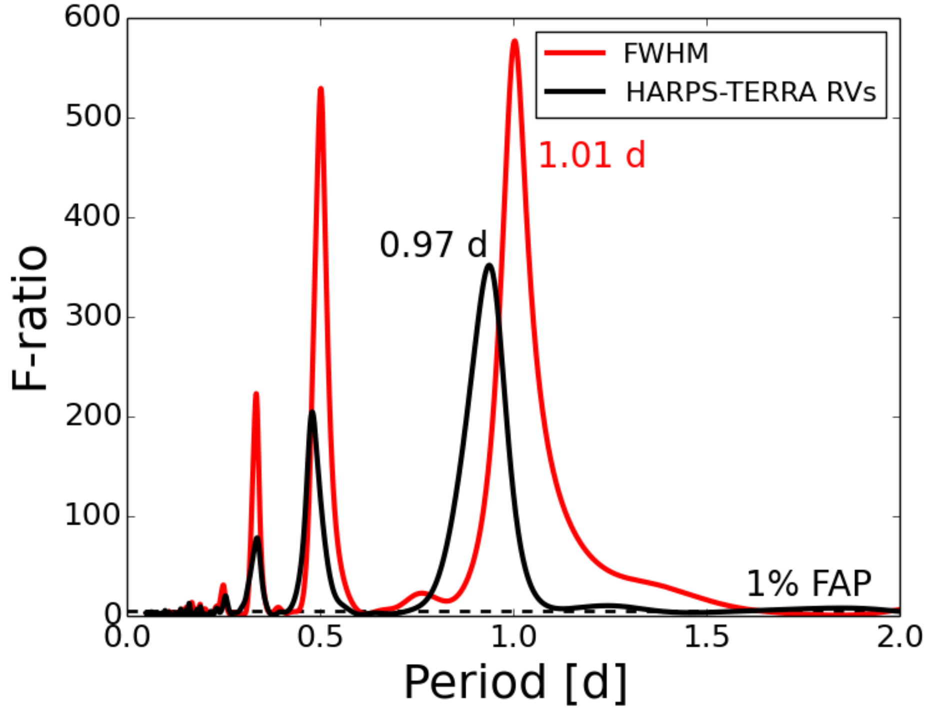

Figure .2: An unambiguous 1.01 days signal with amplitude of 44 $m\,s^{-1}$ is recovered in the FWHM time series (red periodogram). Black periodogram shows a signal of 0.97 days detected in the RVs series. RVs were obtained with the HARPS-Terra pipeline, i.e., they were independently measured from the FWHM values which were calculated with the DRS HARPS-N self pipeline. After discarding plausible magnetic effects, we suspect that this signal has an instrumental origin.

shown in Fig. .3 reveals indeed an instrumental issue still unresolved but probably related with an inefficient ADC (Atmospheric Dispersion Corrector) correction.

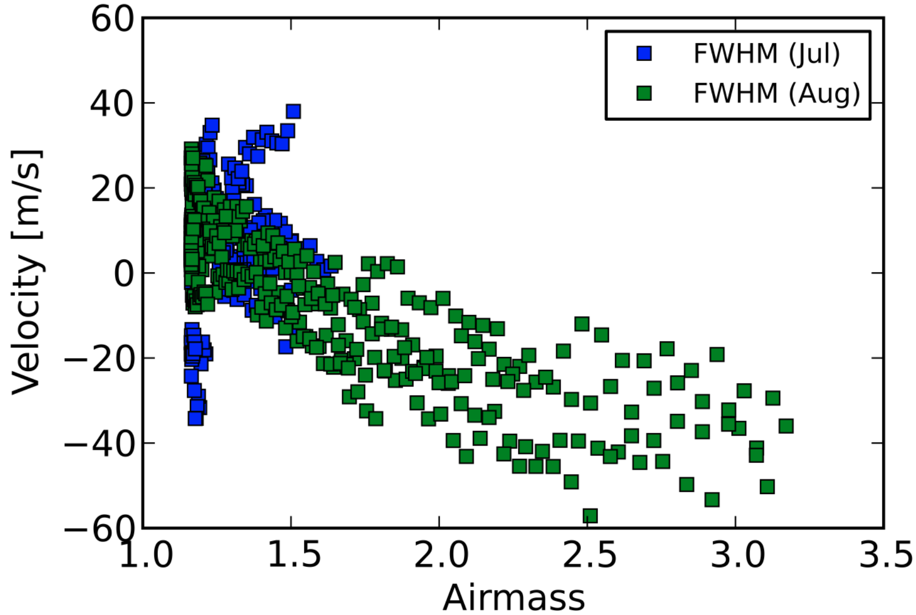

Figure .3: Correlation between the variability in the FWHM of the spectral lines with airmass clearly indicates a correlation with some instrumental effect. FWHM velocity mean value have been subtracted. Further observations will be useful to confirm this trend with the airmass as the main precursor of the FWHM variability. For AM higher than 2.0 data get more dispersed and the linear correlation coefficient is lower. This is because the HARPS-N ADC does not correct for AMs higher than this value. Nevertheless the trend is still clear at lower AMs (specially on the August run -green squares-).

3. GJ436: planet or pulsation? *Results from HARPS-N*

GJ 436 was our benchmark M dwarf during the 2013A run. In this case the FWHM mean RMS is 18.08 m/s indicating that high amplitudes in the FWHM may be a general case. The star was selected because the long-cadence periodograms (HARPS-S) show very significant peaks in the sub-day time-domain (see Fig. .4, bottom panel). We used 141 HARPS/ESO spectra available through the ESO archive and our new high cadence observations. GJ 436 is a nearby star hosting a transiting Neptune mass planet with a 2.64 days orbit (see Fig. .5, left panel).

The two full nights obtained in March 2013 confirm the presence of an extra sub-day period planet. Unfortunately the preferred period is not unique (0.56 days or 0.32 days; see Fig. .4, upper panel), even when the signal is strongly significant in the sub-day period domain. If we select the 0.56 days signal as real, the resulting signal (K∼1.1 m/s, 0.9 M⊕; see Fig. .5, central panel) is consistent with the UCF.1.02 transiting candidate (R∼0.65 R⊕, M∼0.28 M⊕) suggested by Stevenson et al. (2012) using Spitzer photometry. The search for a third periodicity suggests the presence of a 4.5 hours Doppler signal (FAP∼5%; see Fig..5, right panel) which could be consistent with stellar pulsations. Our fitting procedure also adjusts the jitter (excess noise) of each dataset as a free parameter. While the low-cadence

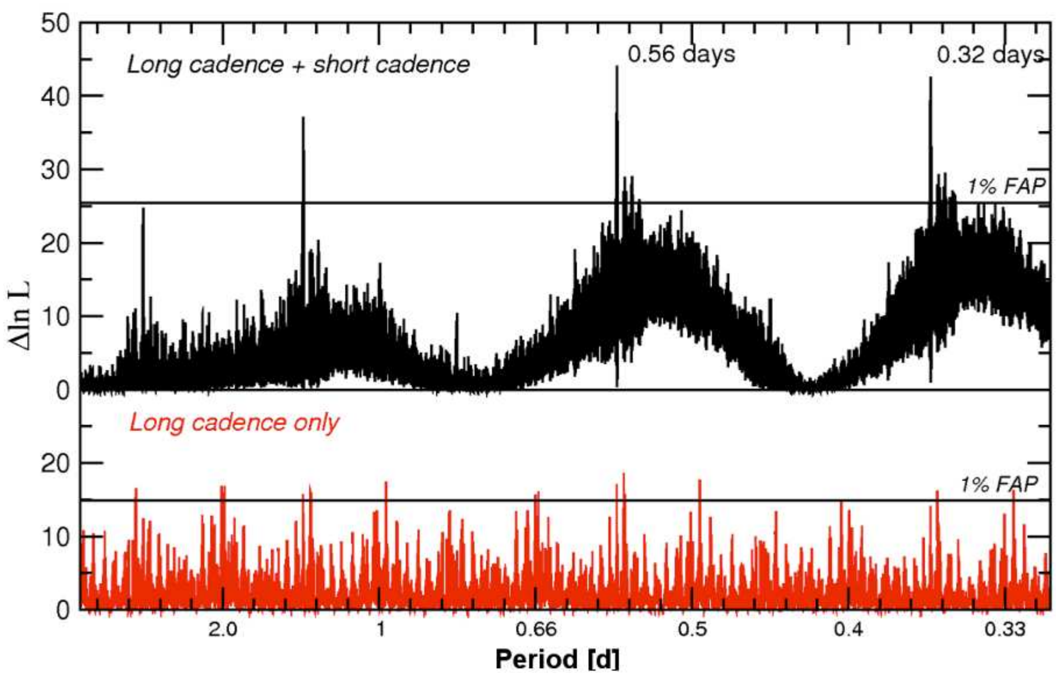

Figure .4: Periodogram of the residuals after adjusting the well-know hot Neptune b planet. Black plot includes two nights of high-cadence observations. While the preferred period is not yet unambiguously determined (0.56 days or 0.32 days), it is clear that a Doppler signal is strongly present in the sub-day period domain. Red periodogram is calculated with low-cadence data over the years denoting the importance of the high-cadence sampling to recover sub-day signals.

observations had an excess noise of 1.5 m/s, the jitter in the high-cadence run was only 0.9 $m\,s^{-1}$ (RMS 1.9 and 1.4 $m\,s^{-1}$ respectively after subtracting the two first signals). Detailed simulations assuming simplistic noise models (assuming 1 $m\,s^{-1}$ precision) indicate that our sensitivity limit is around K= 0.3 $m\,s^{-1}$. Extra telescope time have been already awarded to break the period solution duplicity and get a robust detection of the sub-day Earth mass planet. Besides, these results support our proposed observational strategy in identifying sub-day period signals.

4. The Kapteyn's star planetary system. *Results from HARPS*

Kapteyn's star belongs to the galactic halo and shares with its group (Kapteyn's group) a retrograde velocity of rotation of -290 $km\,s^{-1}$ around the Galactic centre (Eggen 1996). Current formation scenarios suggest that it belonged to a satellite dwarf galaxy which was engulfed by the early Milky Way(Klement 2010).

CTB data, in combination with HIRES and PFS data, made possible to report two new planets orbiting the ancient halo star (Anglada-Escudé et al. 2014): Kapteyn b, a 48 days-period planet inside the habitable zone of the star with a mass at least five times the

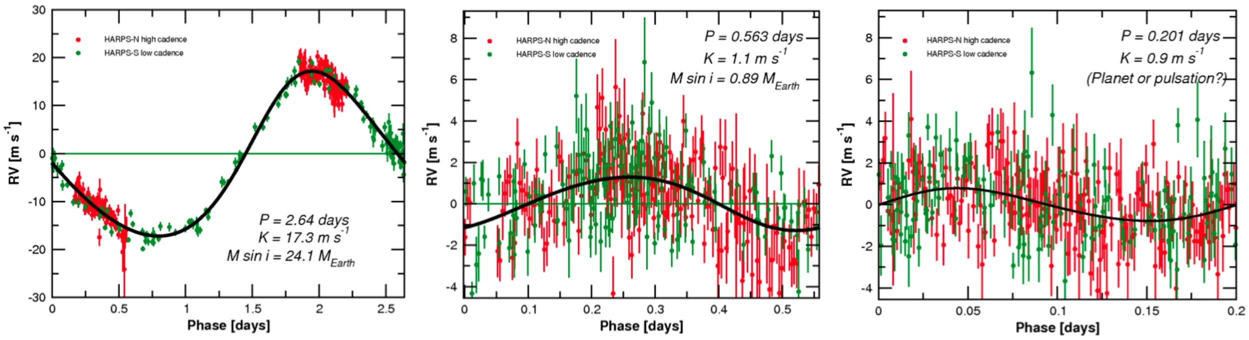

Figure .5: Left panel represents the phase folded diagram to the know GJ 436b Neptune planet. Central panel corresponds to a full Keplerian fit at 0.56 days. Right panel shows the residuals to the 0.56 days signal phase folded to a 0.20 days signal. The 0.20 days signal is rather significant but its False Alarm Probability (FAP) is still higher than 1% of the frequencies being explored. More data will allow unambiguous confirmation of the signals.

mass of the Earth; and Kapteyn c, a massive super-Earth with an orbital period of 121 days (see Fig. .6)

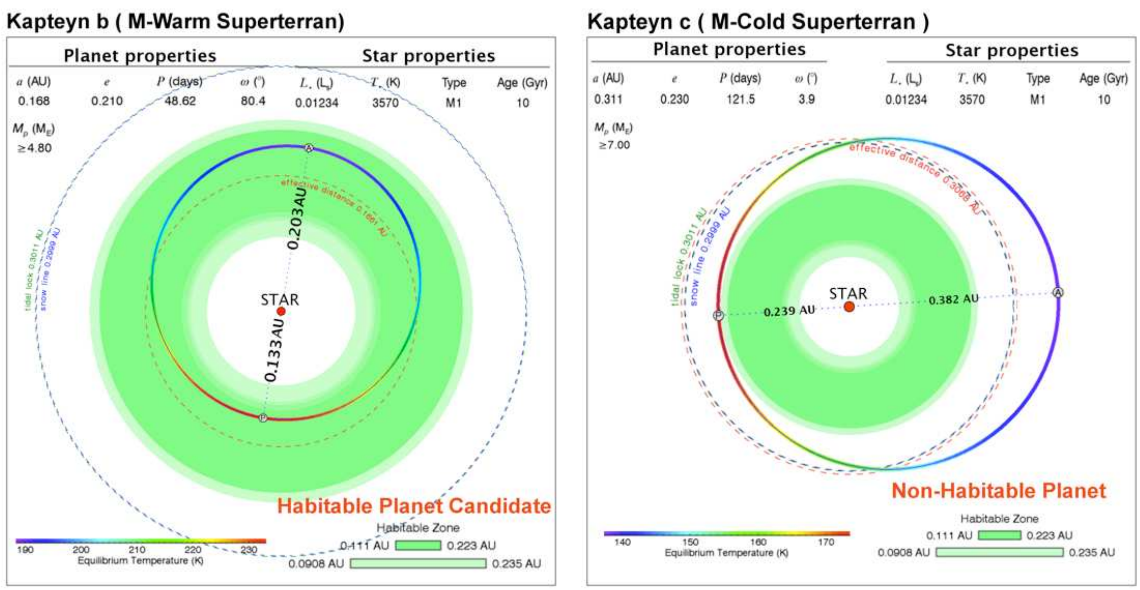

Figure .6: Orbits and physical parameters of the planets Kapteyn b and c.

The detection of this two planets orbiting the metal-poor old star is consistent with the hypothesis that low-metallicity stars are more prone to formate planets (Udry & Santos 2007) but also, and more impressive, raise the question of whether planets can survive to a intergalactic merging event in the early history of the Milky Way.

Acknowledgements. ZMB acknowledges financial support from MINECO through the Spanish grant FPI BES-2011-049647. ZMB, PJA and CRL acknowledge financial support from AYA2011-30147-C03-01 of the Spanish Ministry of Economy and Competivity (MINECO), co-funded with FEDER funds, and 2011 FQM 7363 of the Consejería de Economía, Innovación, Ciencia y Empleo (Junta de Andalucía). This study is based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Galileo Galilei Fundation of the INAF (Instituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. Observations were also made with ESO Telescopes under programmes ID 191.C-0505 and ESOs Science Archive Facility (req. number GANGLADA95087). We acknowledges the effort of the HARPS team program obtaining data within program 072.C-0488. Some data were obtained at the W.M. Keck Observatory made possible by the support of the W.M. Keck Foundation and operated among Caltech, University of California and NASA. This study uses also data obtained at Magellan, operated by the Carnegie Institute, Harvard University, University of Michigan, University of Arizona, and the Massachusetts Institute of Technology.

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