

SETTING NEW STANDARDS WITH HARPS

By OCTOBER 1ST, 2003, ESO'S NEW AND UNIQUE PLANET-HUNTING MACHINE HARPS (HIGH-ACCURACY RADIAL VELOCITY PLANETARY SEARCHER) HAS BECOME OPERATIONAL. THE MEASUREMENTS MADE DURING THE COMMISSIONING PHASE AND THE FIRST WEEKS OF OPERATION ARE OF OUTSTANDING QUALITY. IN THIS ARTICLE WE REPORT AMONG OTHER EXAMPLES ON THE FIRST EXTRA-SOLAR PLANET DISCOVERED WITH HARPS AND ON THE DETECTION OF TINY STELLAR OSCILLATIONS. THE RESULTS PRESENTED DEMONSTRATE THAT HARPS IS CURRENTLY THE MOST PRECISE DOPPLER-MEASUREMENTS MACHINE IN THE WORLD. WITH THIS ACQUISITION ESO PLACES ITSELF AT THE HEAD OF A SCIENTIFIC DOMAIN, WHOSE INTEREST HAS CONTINUED TO GROW DURING THE PAST YEARS.

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THE HARPS PROJECT was born in May 1998 when ESO issued an Announcement of Opportunity asking for the design, construction, and procurement of an instrument dedicated to the search for extrasolar planets and aiming at an unequalled precision of 1 m/s. In response to ESO's call the Observatoire de Genève together with the Physikalisches Institut der Universität Bern, the Observatoire de Haute-Provence, and the Service d'Aéronomie du CNRS have formed a Consortium which realized, in collaboration with ESO, this ambitious project in only three and a half years. The instrument was installed by the Consortium on ESO's 3.6-m Telescope at La Silla in January 2003 and first light took place on February 11th. HARPS was commissioned during the periods 70 and 71. During period 71 a first GTO run of seven nights had been allocated for the Consortium as well. These observations have already produced many exciting results.

The instrument was handed over to ESO La Silla by the end of September 2003 and made available to the Community for period 72. Together with the 3.6-m telescope HARPS is now delivering fantastic scientific frames to the observers. But this is not the only data product of HARPS. The powerful HARPS pipeline provides any observer with extracted and wavelength calibrated high-resolution spectra, as well as the precise radial velocity of the observed star. The observer will thus leave the Observatory with fully reduced spectra. Additional information on how to observe with HARPS can be found at <http://www.ls.eso.org/lasilla/sciops/harps/>.

AN UNEQUALLED FACILITY FOR RADIAL-VELOCITY MEASUREMENTS

HARPS is a fibre-fed, cross-dispersed echelle spectrograph. Two fibres, an object and a reference fibre, feed the spectrograph with the light from the telescope and the calibration lamps. The fibres are re-imaged by the spectrograph optics onto a mosaic of two 2k4 CCDs, where two echelle spectra of 72 orders are formed for each fibre. The covered spectral domain ranges from 380 nm to 690 nm. The resolution of the spectrograph is given by the fibre diameter and attains a value of about $R=115,000$. At this resolution each spectral element is still sampled by 3.2 CCD pixels. A summary of the main HARPS features is given in Table 1. For a detailed description of the instrument we refer to the article published in Pepe et al. (2002) and to the HARPS Users Manual.

HARPS is an ordinary spectrograph with outstanding efficiency and spectral resolution. The main characteristics of HARPS is however its extraordinary stability. The ThAr-reference technique is able to measure and correct the tiniest instrumental drifts; nevertheless a lot of effort was put into making the spectrograph intrinsically stable, in order to avoid

Table 1: HARPS spectrograph characteristics

Optical design	fibre-fed, cross-dispersed echelle spectrograph
Technique	simultaneous ThAr Reference
Number of fibres	2
Fibre aperture on sky	1 arcsec
Collimated beam diameter	208 mm
Covered spectral range	380 nm to 690 nm
Spectral resolution	$R=115,000$
Spectral format	72 echelle orders 61.44 x 62.74 mm
CCD chip	mosaic, 2xEEV2k4 pixel size=15µm
Sampling	3.2 pixels/SE
Min. inter-order	33 pixels

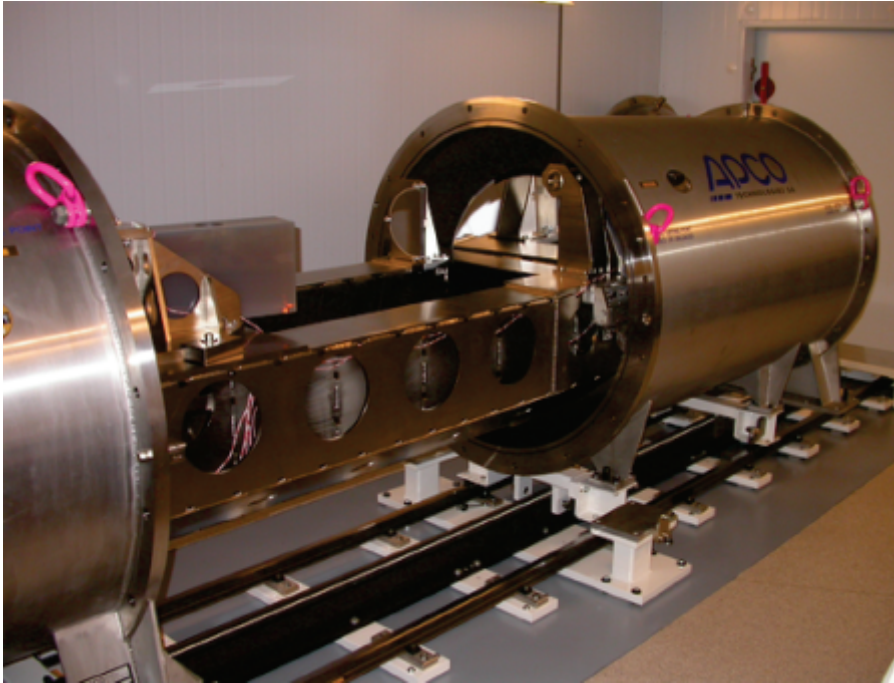


Figure 1: The HARPS spectrograph inside the air-conditioned room at La Silla just before being closed and evacuated.

as far as possible any kind of second-order instrumental errors. As a consequence, we have decided to operate the spectrograph in vacuum (see Figure 1), since ambient pressure variations would have produced huge drifts (typically 100 m/s per mbar). The operating pressure is always kept below 0.01 mbar such that the drifts never will exceed the equivalent of 1 m/s per day.

Not only the pressure but also the temperature is strictly controlled. In fact, a two-stage air-conditioning around the vac-

uum vessel controls the air temperature to 17°C with a long-term stability of the order of 0.01°C. Because of the huge thermal inertia of the vacuum vessel and the excellent thermal insulation between spectrograph and vessel provided by the vacuum, the short-term temperature stability obtained is even better. Over one day we have measured variations of the order of 0.001 K rms. An example of the excellent control is given by the behaviour of the echelle grating temperature plotted in Figure 2a.

Figure 2: a) Temperature of the echelle grating over 24 hours recorded at two different days. b) Drift of the spectrograph during a ThAr series of several hours proving that the spectrograph is extremely stable and that the simultaneous ThAr reference is able to track and correct tiniest instrumental drifts.

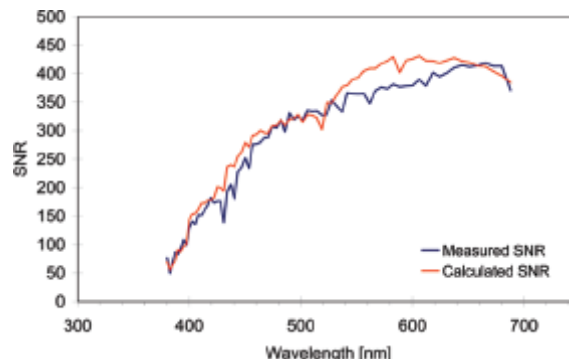
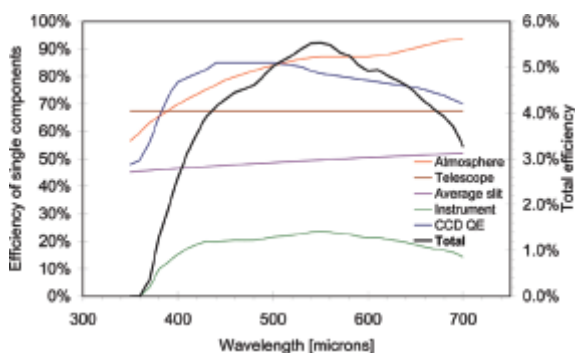
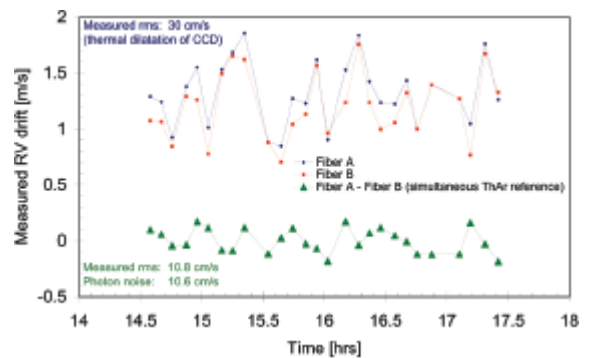
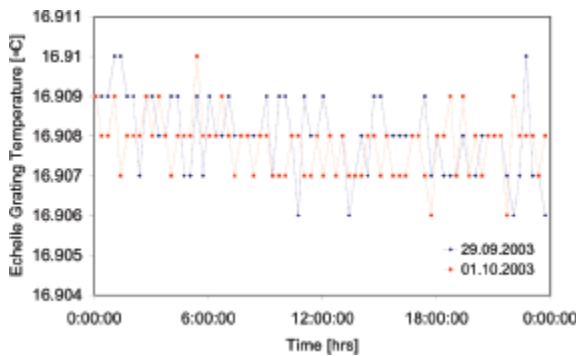


Figure 3: a) Total efficiency of HARPS (right-hand ordinate) and efficiency of single components (left-hand ordinate). b) Comparison of the measured SNR with the values calculated by means of the Exposure Time Calculator. For comparison we performed a 71s exposure on HD10700 ($m_v=3.5$) at an airmass of 1.1. The DIMM monitor was indicating a seeing of 0.9 arcsec.

The extraordinary stability translates directly into the stability of the radial velocity measurements. This is most impressively shown by the measurement series presented in Figure 2b. Both fibres have been exposed repetitively with the ThAr calibration light and the drift – expressed in m/s – was computed as a function of time. During several hours the total drift remains well below 1 m/s and the measurement is dominated by “noise”. This noise is introduced by the CCD whose temperature varies by ± 0.02 K and produces microscopic dilatation of the chip. In fact, both fibres show the same behaviour and when subtracting one fibre from the other this “noise” disappears and we obtain the dispersion values expected from the photon-noise level of the simultaneous ThAr reference. These measurements prove that the simultaneous ThAr reference technique is perfectly able to track instrumental drift at a level of 0.1 m/s rms.

HARPS has been optimised for radial-velocity efficiency, i.e. to obtain in the shortest possible exposure time the most precise radial-velocity measurement. However, this requirement is not necessarily synonymous with optical efficiency. For example, spectral resolution is an important factor in reducing the photon noise of the radial-velocity measurement but is often in competition with the optical efficiency of the spectrograph or with the size of the instrument and the telescope. On the other hand the instrumental errors must also be low, at least as low as the goal for the photon-noise equivalent. The

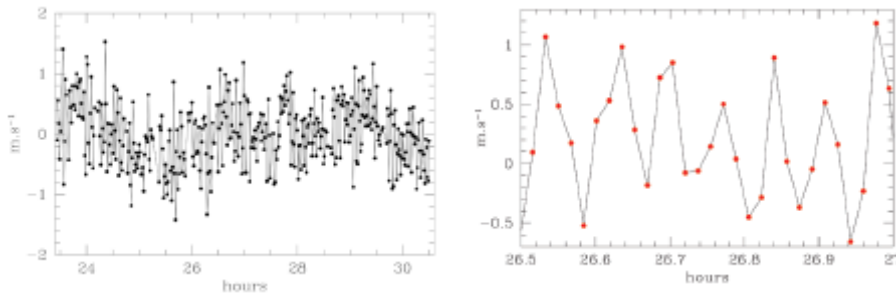


Figure 4: a) Series of 7 hours and 420 exposures on α Centauri B proving the extraordinary short-term precision of HARPS. b) Zoom of figure a) to illustrate the presence of a periodic signal produced by the stellar pulsation.

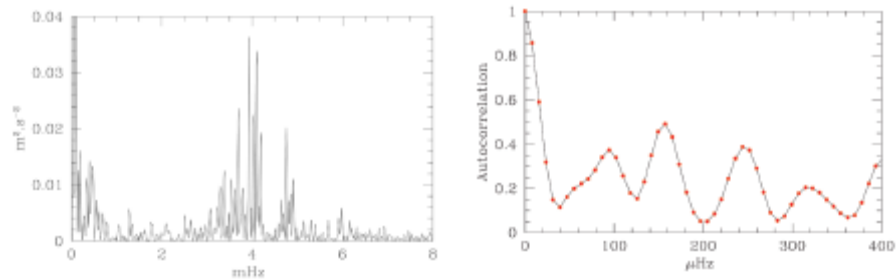


Figure 5: a) Power spectrum of α Cen B. The acoustic modes corresponding to the 4-minutes oscillation are clearly identified and emerge well above the noise. b) Autocorrelation of the power spectrum of α Centauri B.

design of HARPS is consequently the result of an accurate trade-off between all the relevant factors. Despite various compromises regarding for example the fibre diameter (1 arcsec on the sky) and the fibre-feed itself, the optical efficiency obtained is remarkable. Figure 3a shows the calculated total optical efficiency of the instrument and some of its subsystems. These values have been adopted in the current version of the HARPS-Exposure Time Calculator (ETC) which serves to estimate the SNR obtained during an exposure. In Figure 3b we compare the results obtained using the ETC with real measurements on the star HD 10700.

HARPS DELIVERING PRECISION NEVER REACHED BEFORE

During the HARPS commissioning we monitored the star α Centauri B, which is a K-type star substantially smaller than our Sun. During 7 hours we collected a total of 420 spectra with typical SNR of 500 each at $\lambda=550$ nm. The radial-velocity measurement sequence plotted in Figure 4a indicates a dispersion of 51 cm/s but the zoom shown in Figure 4b shows that this dispersion is completely dominated by 4-minutes stellar oscillations. In fact, the power spectrum of this sequence shown in Figure 5 clearly exhibits a series of peaks around 4 mHz, corresponding to individual acoustic modes of the star, with amplitude in the range 10-20 cm/s. The positive interference of several oscillation modes may lead to amplitudes much larger than the amplitude of single modes. From the power spectrum we estimate

that the average contribution of modes to the total dispersion reaches 0.44 m/s. By quadratic subtraction of this value from the measured dispersion we obtain a noise level of 0.26 m/s, which is in good agreement with the value extrapolated from the mean white noise level measured in the high frequency range between 6 and 8 mHz in the power spectrum. The photon noise on a single measurement is of 0.17 m/s, which leaves less than 0.2 m/s for all other possible error sources (ThAr noise, guiding errors, influence of the atmosphere, instrumental errors).

The long-term precision of the instrument cannot be checked easily because it requires a long time base on one hand, and the knowledge of stable stellar sources on the other hand. Especially the latter point represents a new challenge since the intrinsic stability of the stars has never been studied at this level of precision before. Nevertheless we have been able to gain some indication of the long-term precision of HARPS by observing the star HD 83443 which has a planetary companion with well known orbital parameters. Figure 6 shows a total of nine radial-velocity data points, some of them collected during the first commissioning period in February 2003, and some others about 4 months later during the second commissioning held in June 2003. All the data fit well the calculated orbit whose parameters are fully consistent with the previously known solution. The obtained dispersion (O-C) is only

1.7 m/s and partly due to photon noise. The residual noise is a combination of calibration errors (< 0.5 m/s) and effects due to the star itself, which can be due to pulsations, activity and jitter. It is also worth noting that the HARPS vacuum has been broken between the two commissioning runs.

We conclude that the short-term precision (1 night) of HARPS is well below 1 m/s. Even on the time scale of a commissioning period (2 weeks) we have been able to measure standard stars which showed radial-velocity dispersions of 1 m/s including photon noise. The same level of precision is obtained on HD 83443 over a time scale of 4 months. Apart from photon noise a major contribution to the residuals probably comes from the star itself (pulsations, activity, jitter). Only an in-depth, long-term study will allow us to identify the relative importance of the various error sources.

CATCHING THE TINY MELODY OF A SOLAR-LIKE STAR

Stars, which are spheres of hot gas, propagate very well in their interiors acoustic waves which are generated by turbulent convection near their surfaces. Frequencies and amplitudes of these acoustic waves, also called oscillation modes or p -modes, depend on the physical conditions prevailing in the layers crossed by the waves and provide a powerful seismological tool. Helioseismology, which monitors the oscillation modes of our Sun, has been used since the 1970's and led to major revisions in the "standard model" of the Sun and provided, for instance, measures of the Sun's inner rotation, the size of the convective zone and the structure and composition of the external layers. Solar-like oscillation modes generate periodic motions of the stellar surface with periods in the range 3 – 30 min., but with extremely small amplitudes. The corresponding amplitudes of the stellar surface velocity modulations are in the range 10 – 100 cm/s.

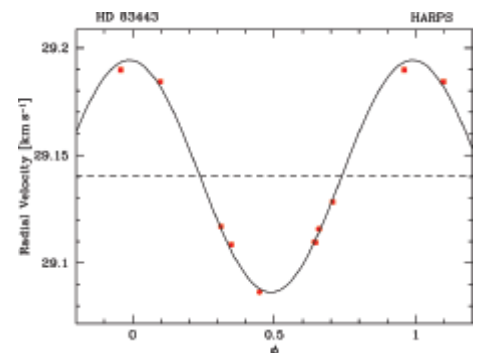


Figure 6: Radial-velocity data of HD 83443, which harbours a known extra-solar planet. The data fit well the calculated orbit with a weighted dispersion of 1.7 m/s.

Two years ago, we were able to detect with the CORALIE spectrograph an unambiguous oscillation signal of 31 cm/s amplitude of the star α Centauri A, a nearby solar twin (Bouchy & Carrier, 2001 & 2002). With these measurements several oscillation modes were separated and clearly identified.

The measurements made on α Centauri B with HARPS have lower frequency resolution because of the limited duration of the tests. To obtain the same resolution we would have had to observe the star for 13 consecutive nights. On the other hand the measurement obtained with HARPS are impressive mostly because of efficiency, cycle time and precision. Figure 4 illustrates clearly the detectivity obtained with HARPS: despite the small amplitude the 4-minutes stellar oscillation can be detected “by eye” directly in the time series, and they become even more evident in the Fourier Transform space shown in Figure 5a. Figure 5b shows the autocorrelation of the power spectrum. The plot clearly indicates that the peaks have a comb-like structure, with a main peak separation of about 160 μ Hz. This is the typical signature of oscillation modes of identical angular degree expected for solar-like stars. The intermediate peaks appearing in the figure correspond to the correlation between modes with angular degree $l=1$ and $l=0$ or 2.

Such a level of accuracy in the detection of solar-like oscillation modes has never been reached before. This result obtained with HARPS on a very short sequence (7 hours), clearly shows the unique potential of this instrument in the domain of asteroseismology. Long

sequences (several nights are needed to reach a sufficient frequency resolution to characterize individual p -modes) of high sampling radial-velocity measurements will permit to measure acoustic waves with amplitudes as tiny as a few cm/s.

DOWN TO THE STELLAR LIMIT

After the amazing results obtained on α Centauri B we have decided to monitor a small set of solar type stars. Figure 7 shows short sequences of radial velocity measurements obtained on these objects. On *each* of these sequences the stellar oscillations are clearly visible. Stellar parameters and observed oscillation modes are listed in the Table 2. As expected, these measurements clearly show that period and amplitude of the oscillation modes are directly related to the stellar properties. They demonstrate the full capability of HARPS for asteroseismology, not only on very bright stars.

These results show however also that the main limitation for HARPS will come from the stellar “noise” itself. The individual mode amplitudes of these stars are in the range 10–50 cm/s but their additive

interference leads to modulation of the Doppler time series of up to 10 times their value. This is clearly a limitation for high precision exoplanet surveys at the level of 1 m/s and requires us to define a precise strategy of target selection and observation. Short-period oscillations (4–8 min.) of small amplitudes, which occur in G and K dwarfs, can be easily averaged out with typical exposures times of 15 minutes. Sub-giants and giants, which can show larger amplitudes and longer periods, should however be carefully removed from the sample. This kind of precaution should permit us to detect exoplanets at the level of 1 m/s.

OBSERVING FAINT OBJECTS

The OGLE-III programme, involved in an extensive ground-based photometric survey for planetary and low luminosity object transits, has recently announced the detection of transiting candidates around stars located in the direction of the Galactic centre. The radii of these objects were estimated to be in the range between 0.5 and 5 Jupiter radii, meaning that some of these objects are probably in the planetary domain. In order to measure the mass of these objects, and then determine their real nature, a radial velocity follow-up is necessary.

In order to test the limiting magnitude of HARPS, we observed the faint candidate OGLE-TR-56 ($m_v=16.6$). One hour exposure allowed us to reach a signal-to-noise ratio between 3 and 4 corresponding to a photon noise uncertainty on the radial velocity of about 30 m/s. The five RV measurements presented in Figure 8 demonstrate the full capability of HARPS to find and characterize hot Jupiters around stars as faint as OGLE-TR-56. We have fitted to these data points a sinusoidal curve with fixed period as given by the photometric study. The measured amplitude is however much different and in contrast to the results published by Konacki et al. (2003). A complete analysis of these measurements will be required in order to determine whether this RV modulation is due to a planetary companion or to a binary system blended and

Figure 7: Summary plot of the radial-velocity of stars for which we have made long observations series. All of them show clear indications of star pulsation.

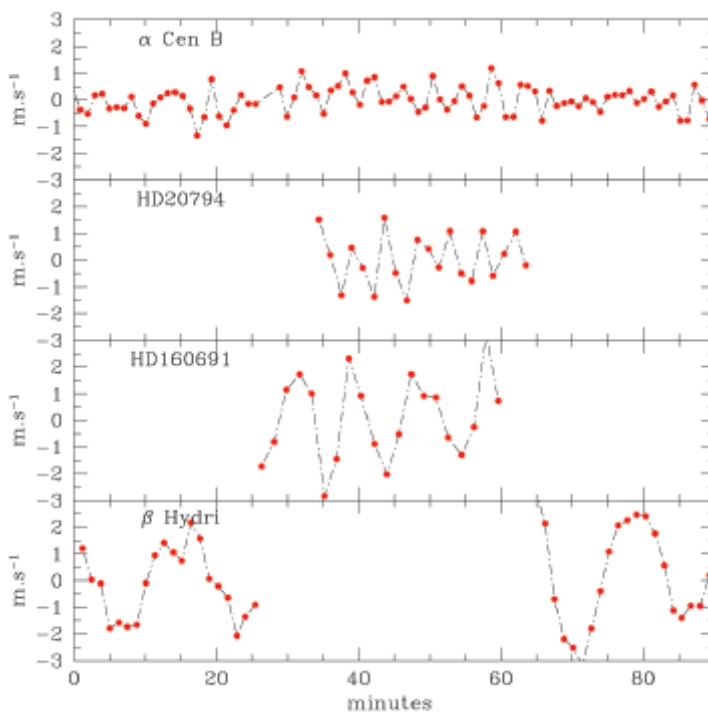


Table 2: Stellar parameters and oscillation modes properties

Star	Spectral type	Period	Peak to Peak modulation	RMS Dispersion
α Cen B	K1V	4 min.	1.5 m/s	0.5 m/s
HD20794	G8V	5 min.	2.5 m/s	0.8 m/s
HD160691	G5IV-V	9 min.	5 m/s	1.7 m/s
β Hydri	G2IV	16 min.	5 m/s	1.7 m/s

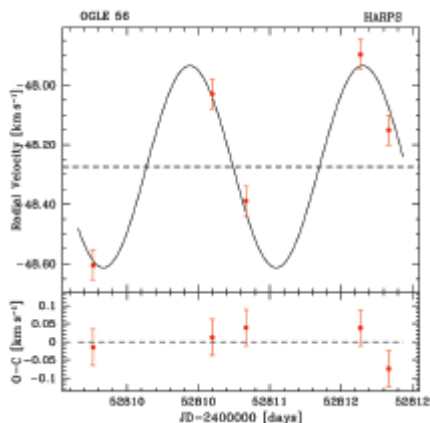


Figure 8: Radial-velocity of OGLE-TR-56 measured with HARPS. Despite the faint magnitude of the object, the dispersion of the data points around the fitted curve is only 30 m/s.

masked by the main star. This kind of study has a huge interest for the future radial-velocity follow-up of exoplanets detected by the satellite COROT.

THE HARPS EXOPLANET PROGRAMME

The HARPS Consortium GTO programme will be devoted exclusively to the study and characterization of exoplanets, in continuation of a planet-search programme initiated 10 years ago (Queloz & Mayor, 2001). For a large, volume-limited sample we will do a first screening in order to identify new “Hot Jupiters” and other Jovian-type planets. Increasing the list of “Hot Jupiters” will offer a chance to find a second star with a planetary transit among relatively bright stars. Better statistics are needed to search for new properties of the distribution of exoplanet parameters.

This part of the programme already started in July 2003 within the first GTO period assigned to the Consortium. In this short run of only 9 nights HARPS unveiled all its characteristics, its optical efficiency, the unique precision and, in particular, the outstanding efficiency of the reduction pipeline. In fact, we have collected about 500 spectra and radial

velocity measurements of several hundred stars. Many of them show a varying radial velocity, sometimes with a clear periodicity. In the case of HD 330075 the signal is most probably due to an exoplanet orbiting this star in 3.37 days. The radial-velocity curve of HD 330075 is shown in Figure 9. Precise photometric measurements carried out on the SAT Danish Telescope and by the Swiss-Euler Telescope have shown the absence of a photometric transit, which would have allowed us to determine the radius and the orbital inclination of the planet. Nevertheless, these measurements have also demonstrated that the photometric variability is low, and that we can exclude therefore the radial-velocity variation to be produced by stellar activity. This makes HD 330075 the first HARPS extra-solar planet candidate.

Only a few of the hundred detected planets have masses less than the mass of Saturn, and due to the present precision of radial velocity surveys the distribution of planetary masses is heavily biased (or completely unknown) for masses less than half the mass of Jupiter. We will take advantage of the very high precision of HARPS to search for very low mass planets. For a sample of pre-selected non-active solar-type stars we will be able to explore the domain of the mass-function for planetary masses less than the mass of Saturn down to a few Earth masses for short periods.

A systematic search for planets will be made for a volume-limited sample of M-dwarfs closer than 11 parsecs. Such a survey of very low mass stars will give us a chance to derive the frequency of planets as a function of the stellar mass. These objects are of prime importance for future astrometric studies to be carried out with the VLTI or space-mission like SIM.

Stars with detected giant planets exhibit an impressive excess of metallicity in contrast to stellar samples without giant planets (Santos et al., 2001). The excess of metallicity does not seem relat-

ed to the mass of the convective zone and probably finds its origin in the chemical composition of the primordial molecular cloud. To add new constraints to the link between star chemical composition and frequency (or properties) of exoplanets, we will carry out two additional programmes: The first programme is a search for exoplanets orbiting solar-type stars with notable deficiency (for most of them $[\text{Fe}/\text{H}]$ between -0.5 and -1.0). Among the existing detections of exoplanets only two or three have been found with metallicity in that range. We aim at being able of estimating the frequency of exoplanets in that domain of metallicity and, if possible, to compare their characteristics (masses, orbits) to planets orbiting metal rich stars. The second programme aims at exploring the link between stellar metallicity and properties of exoplanets. Visual binaries with solar-type stars of almost identical magnitudes have been selected. We will search for exoplanets orbiting one of the components of these systems. For those including giant planets a detailed chemical analysis will be done for both stellar components to search for possible differences in their chemical compositions.

Follow-up radial velocity measurements for stars with planetary transits detected by the COROT space mission will be made with HARPS. Photometric transits provide an estimate of the radius of the transiting planet as well as the orbital period and phase. Complementary ground-based spectroscopic measurements with HARPS will constrain the planetary mass and then the planet mean density. The main scientific return for the planetary programme of the COROT mission will come from the combination of the photometric and radial velocity data.

ACKNOWLEDGEMENTS

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Figure 9: First HARPS extra-solar planet candidate HD 330075. The planet has a minimum mass of $0.8 M_J$ and orbits the star in 3.37 days at a distance of 0.044 AU from its parent star, and belongs therefore to the category of Hot Jupiters. The induced radial-velocity variation has a semi-amplitude of 107 m/s. The total dispersion with regard to the orbital solution is $(o-c)=2.5$ m/s, and includes photon noise, stellar pulsation and possible jitter.

