The exoplanet hunter HARPS: unequalled accuracy and perspectives toward 1 cm s^{-1} precision

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ABSTRACT

We present results from the first two years of operations of the HARPS spectrograph installed on the ESO 3.6m telescope at La Silla Observatory, Chile. This instrument, primarily built to detect extrasolar planetary systems, was designed to achieve the highest radial velocity precision ever thanks to high mechanical and environmental stability, stable illumination, accurate wavelength calibration and tracking of instrumental drifts. HARPS has demonstrated a long-term accuracy at the 1 m s^{-1} level and below, exploring a new regime in RV precision. We present recent improvements in the wavelength calibration process, including the creation of a new ThAr reference atlas and the use of a much larger number of lines to fit the wavelength solution. We have also investigated the intrinsic stability of ThAr calibration lamps and show that they are able to provide a long-term wavelength reference at or below the 1 m s^{-1} level. Other instrumental error sources such as guiding accuracy and photon noise are discussed and a global error budget is presented. These efforts to further improve the RV precision are also part of a broader study to build a ultra-high accuracy spectro-velocimeter for the ESO OWL telescope, the CODEX project. The aim of this instrument is to reach an accuracy of 1 cm s^{-1} over timescales of at least ten years. This requires to push down the limits of present-day calibration techniques and to explore new technologies able to provide ultra-precise Doppler measurements.

Keywords: HARPS, radial velocities, extrasolar planets, wavelength calibration, ThAr lamps, CODEX

1. INTRODUCTION

Since the discovery of the first extrasolar planet around a solar-type star in 1995[1], intense efforts have been made to continuously improve the accuracy of radial velocity (RV) measurements. Indeed, the so-called RV technique, which measures the tiny RV wobble of a star induced by orbiting bodies, has proven to be the most efficient way of detecting low-mass companions around FGKM main-sequence stars. More than 180 extrasolar planets have been discovered in this way over the past ten years[2,3], opening a completely new field in astronomy. Because the RV technique is especially sensitive to massive planets on close orbits, Jupiter-like giant planets have been found first, followed by Saturn-mass objects orbiting within a few AUs of their parent star. Over the past two years, improvements in RV precision down to the 1 m s^{-1} level, together with the accumulation of data points, have led to the detection of planets in the Neptune-mass range and below (7-20 Earth masses). This means that we are now able to study planetary bodies which are mainly rocky in composition, the so-called 'super-Earths'. Low-mass telluric and icy planets are likely to be found more and more frequently by the ongoing RV surveys in the coming years, often as part of multiple planetary systems. Undoubtedly, past and future discoveries in the extrasolar planet domain will profoundly influence our comprehension of planet formation and evolution, and will put our own Solar System into a broader context, shedding new light on the fundamental question: 'Is the Solar System typical among the other planetary systems existing in the Universe?'

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In this paper we want to focus on the recent improvements of the RV technique and discuss its present capabilities and limitations. Two different methods have been developed to obtain high-precision radial velocities. The so-called iodine technique[4] uses an iodine absorption cell in the light path to superimpose a dense absorption spectrum onto the stellar spectrum, thereby providing a stable wavelength reference against which the position of stellar lines can be accurately measured. The advantage of this technique is that in principle all instrumental effects affecting the radial velocities are 'seen' in the same way by the iodine and stellar spectral lines, so that a careful modeling of the observed spectrum will yield a RV measurement free of instrumental bias. The major disadvantage of the technique, however, resides in the complex and ill-posed modeling of the combined star+iodine observations, which involves deconvolution algorithms and therefore requires high signal-to-noise data. The iodine technique has presently demonstrated a precision of ~3 m s^{-1}.

The other method permitting high-precision RV measurements is the simultaneous reference technique[5], which requires a fiber-fed spectrograph equipped with a second fiber to record a reference ThAr spectrum simultaneously with the stellar observation. This instrumental design has been successfully implemented on the ELODIE and CORALIE spectrographs, which have demonstrated a precision of ~7 m s^{-1} and ~3 m s^{-1} respectively. Building on acquired experience, the concept has been refined and upgraded to further improve the achievable accuracy, leading to the construction of the HARPS spectrograph mounted on the European Southern Observatory 3.6m telescope at La Silla Observatory, Chile. Performances and results of this instrument will be the main subject of this paper. In the last section we briefly discuss the possibility to achieve RV precisions at the cm s^{-1} level in the frame of the CODEX project.

2. CHARACTERISTICS AND PERFORMANCES OF HARPS

HARPS is a high-resolution (R=110,000) cross-dispersed echelle spectrograph[6,7]. It is fed by two optical fibers, one carrying the stellar spectrum and one carrying the ThAr spectrum for simultaneous referencing or, alternatively, the sky spectrum. The spectrograph is located inside a vacuum vessel in a thermally stabilized enclosure. This ensures that the pressure in the spectrograph always remains below 0.01 mbar and temperature fluctuations are kept within 0.01 K. Thanks to this high environmental and mechanical stability, instrumental drifts during the night never exceed 1 m s^{-1}, except in exceptional circumstances such as earthquakes. Also critical for RV precision is the illumination of the spectrograph, which must be as stable as possible. On HARPS a high stability is guaranteed thanks to the light-scrambling properties of the fibers and an accurate telescope guiding software.

Radial velocities are obtained from the extracted spectra by cross-correlation with a stellar template using the highly accurate wavelength calibration obtained at the beginning of each night. Then, the correction for the (very small) instrumental drift is performed. Present performances of HARPS are best illustrated by the published orbital solutions for the planets it has discovered so far. The HARPS GTO time is divided into several sub-programs, one of which is devoted to the high-precision follow-up of a sample of nearby stars. In this sub-program, the stars have been chosen for being non-active and slow rotators, and integration times are sufficiently long to minimize photon noise and the influence of stellar oscillations. Table 1 lists all planets discovered with HARPS in this sample with their orbital properties and the O-C residuals around the best-fit Keplerian curves. These results show that we are reaching a long-term precision at the level of 1 m s^{-1} and even better in favourable cases. The data analysis is still ongoing to determine which effects will ultimately limit the achievable precision on the radial velocity. Disentangling noise and systematics from instrumental and stellar origin is not an easy task and requires a large data set to be able to make useful comparisons and search for correlations. We will review the main error sources in the following sections and present recent developments to minimize their impact.

Table 1. List of the planets discovered with HARPS around stars of the high-precision sample (as of May 2006). The rms of the O-C residuals around the best-fit orbits show that the HARPS long-term precision is at the 1 m s^{-1} level, and probably even below.

Name	$m_2 \sin i$ [$M_\oplus$]	P [days]	Year of discovery	O-C [m s^{-1}]	Reference
μ Ara d	14.0	9.55	2004	0.9	8
HD 93083 b	118	144	2005	2.0	9
HD 101930 b	95.4	70.5	2005	1.8	9

HD 102117 b	44.5	20.7	2005	0.9	9
HD 4308 b	14.9	15.56	2006	1.3	10
HD 69830 b	10.2	8.67	2006	0.8	11
HD 69830 c	11.8	31.6			
HD 69830 d	18.1	197			

Before going further, we first present the most recent discovery made with HARPS, with illustrates very well the present capabilities of the instrument. Three Neptune-mass planets have been found orbiting the nearby K0V star HD 69830[11]. The best three-Keplerian fit to the RVs yields orbital periods of 8.67, 31.6 and 197 days and minimum masses of 10.2, 11.8 and 18.1 $M_\oplus$ (Earth masses). This is the first multiple planetary system without a massive gaseous giant planet, and the first one with a Neptune-mass object within the habitable zone of its star. The RV semi-amplitudes range from 3.5 to 2.2 m s^{-1}, the smallest ever measured. Fig.1 shows the phase-folded radial velocity curves for each planet, and Fig.2 shows the combined RV curve as a function of time. The global r.m.s. of the residuals around the best-fit solution is 0.81 m s^{-1}, and becomes as small as 0.64 m s^{-1} when considering only the more recent, higher-quality data points. Most interesting is the third panel of Fig.2, in which the data points were binned to yield one measurement per observing run (~10 consecutive nights). The residuals around the fit show a dispersion as low as 0.2 m s^{-1} (for the higher-quality data points), which indicates that, when averaging over a sufficient number of observations, we might be able to detect extrasolar planets of ~3 $M_\oplus$ at 1 AU. Obviously, this exciting possibility needs confirmation and a better understanding of the limiting factors influencing RV precision. But it seems reasonable to assume that most of the perturbing effects (such as stellar oscillations and activity-related jitter) can be efficiently averaged out when binning the data over timescales that are comparable to the characteristic timescales of these effects (minutes to hours for stellar oscillations, tens of days for stellar rotation). In summary, the RV technique has not said its last word yet in the field of extrasolar planets and we are confident that HARPS data will unveil many more Neptune-mass planets and below in the near future.

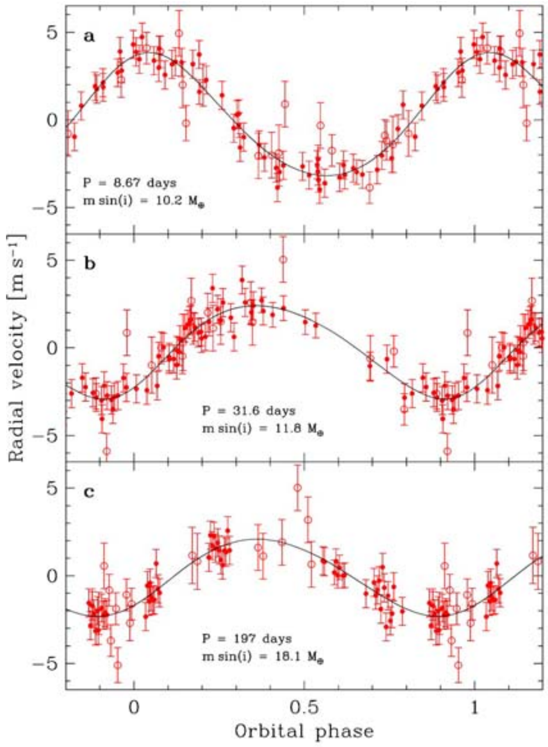

Fig. 1. Phase-folded radial velocity curves for the inner (**a**), intermediate (**b**) and outer planet (**c**) in the HD 69830 system. In each case, the contribution of the two other planets has been subtracted. The orbital periods are 8.67, 31.6 and 197 days, respectively. The RV semi-amplitudes range from 3.5 to 2.2 m s^{-1}, corresponding to minimum masses of 10.2, 11.8 and 18.1 $M_\oplus$.

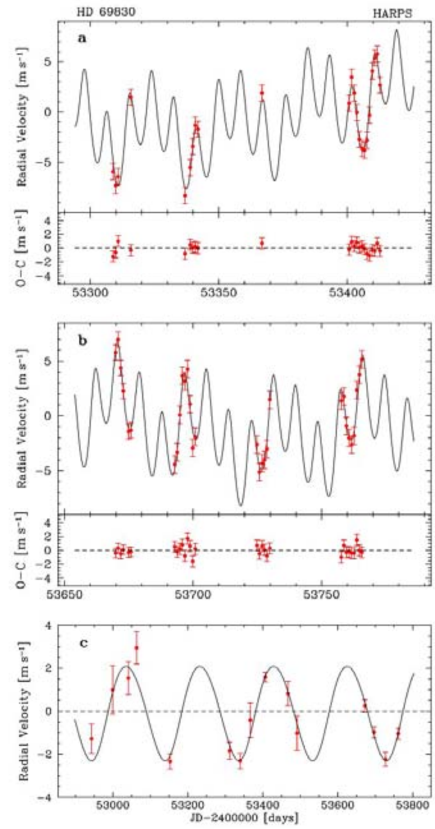

Fig. 2. Radial velocity curve as a function of time. **a** and **b**, close-up views showing the cumulative signal of three planets. The short-period planet (*P*=8.67 days) shows up as a high-frequency modulation, whereas the intermediate planet (*P*=31.6 days) is revealed through the varying values of successive minima and maxima. The outer planet (*P*=197 days) is not easily seen on these magnified views, but its presence becomes clear when removing the signal of the inner planets and binning the data points (one per observing run), as shown in **c**. Note that only high-quality RV measurements are able to fully resolve this system. The weighted r.m.s. of the residuals around the best-fit model is 0.81 m s^{-1} and becomes as low as 0.64 m s^{-1} when considering only the more recent, higher-quality data points.

3. IMPROVEMENTS IN WAVELENGTH CALIBRATION

We have recently performed a careful examination of the ThAr spectra recorded with HARPS to better characterize the wavelength calibration accuracy and to investigate what are the fundamental limitations of ThAr lamp spectra. First of all, we examined the stability of the spectrograph over timescales of months by measuring the position of individual ThAr lines on the CCD. At this stage, we are only interested in absolute positions (in pixels) on the CCD detector, without performing any wavelength calibration. For our tests we choose a set of 64 ThAr spectra spanning about one month, during which the spectrograph is expected to have remained very stable. We select a subsample of strong, unblended Th lines that we fit with Gaussian functions on each of the 64 spectra. We then compare the r.m.s. dispersion in position with the expected standard deviation due to photon noise (see Fig.3). It turns out that both quantities remain equal all the way up to the saturation limit (~300,000 electrons peak intensity), where they reach a minimal value of 0.002 pixel, corresponding to 1.6 m s^{-1} in radial velocity. At higher flux levels, the dispersion tends to slightly increase due to the unstable behaviour of saturated lines. These results show that 1) the spectrum has not drifted by more than ~0.002 pixel (r.m.s.) over the one-month period considered here and 2) the best precision that can be achieved on a single line in a single ThAr exposure is ~1.5 m s^{-1}, limited by the saturation of the CCD. We also tried to characterize other systematic effects related to CCD properties and data reduction, such as pixel inhomogeneities, imperfect spectrum extraction and flat-fielding. All these effects seem to remain below 0.002 pixel and are therefore very difficult to identify on individual lines. In conclusion, we have found that the precision at which the position of ThAr lines can be measured on the CCD is always photon-limited except for the strongest lines, where saturation limits the achievable accuracy at ~1.5 m s^{-1}.

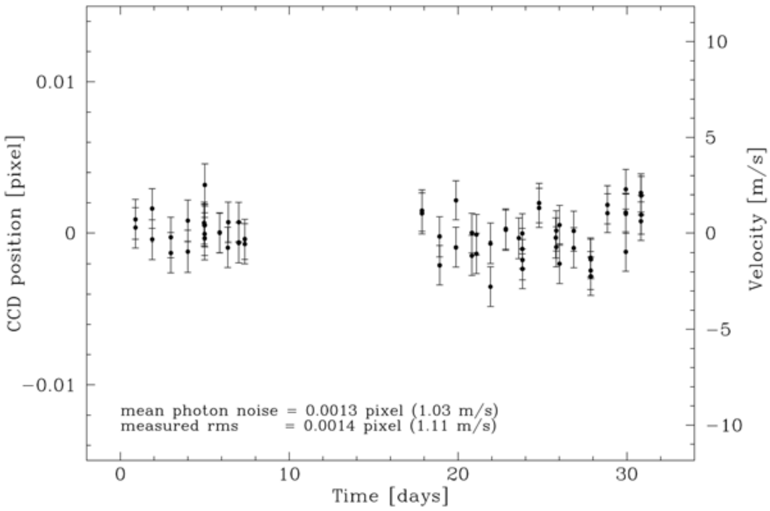

Fig. 3. Measured absolute position of a typical, strong Th line on the CCD as a function of time. The dispersion of 1.4 milli-pixels corresponds to 1.1 m s^{-1} in radial velocity and is photon-noise limited. This shows that the spectrograph remained extremely stable over about one month.

In the next step of our analysis, we carefully examined the ThAr spectra taken with HARPS and noticed that a large number of lines are blended, leading to wrong estimates of line centroids that are not acceptable when highly accurate wavelength calibration is needed, especially if the relative line strengths of both components are variable in time. We therefore developed a procedure to simultaneously fit the position of lines that lie close to each other, and to reject lines that are too strongly blended to be reasonably fitted. We found that, in general, two lines of similar intensity have to be rejected if their separation is less than about half of the instrumental resolution, i.e. ~1.5 pixel in the case of HARPS.

We also noticed that many lines in the HARPS spectra are simply not present in the reference atlas that we use to perform the wavelength calibration (Palmer & Engleman 1983, ref. 12, hereafter PE83). This atlas was derived from very high-resolution (R=600,000) scans obtained with the McMath-Pierce Fourier Transform Spectrometer and is the best presently available for Th at optical wavelengths. However, its limitations become obvious when analyzing HARPS spectra. First of all, it is much less sensitive than HARPS (except in the bluest part of the spectrum). This explains why so many lines detected with HARPS are not listed in the atlas. Secondly, the precision of the wavelengths given in the atlas ranges from ~100 m s^{-1} for the weakest lines to 15 m s^{-1} for the strongest ones. This has to be compared to the measurement precision on HARPS spectra, which is a factor of ~10 better. As a result, when fitting a wavelength solution through the measured positions of ThAr lines on a given spectral order, the residuals around the fit will be very large compared to the photon noise uncertainties and merely represent the systematic errors in the wavelengths given in PE83. This leads to somewhat unstable wavelength solutions that are not robust enough against flux variations or changes in the set of lines used in the fit.

For the above reasons, we decided to create a new Th and Ar atlas based on HARPS spectra to increase both the number of lines and the accuracy of the relative line positions, but still using the PE83 atlas as the absolute global wavelength scale. We started from the HARPS spectra by performing a systematic search for lines in all spectral orders. When lines were to close to each other to be fitted independently, we defined groups of lines to be fitted simultaneously. We checked the stability of each line by measuring its position on 64 different spectra and comparing the dispersion with the photon noise. At the end, we obtain a list of more than 8,600 usable lines spanning the whole wavelength range of HARPS

(3800-6900 Å). This is a factor of ~3 more than was previously available using the PE83 atlas. Then we take the average position of each line over the 64 spectra in order to reduce the photon noise as much as possible. Because of the overlapping between spectral orders, there are more than 10,300 detected lines in the 72 orders. Finally, we simultaneously fit 72 wavelength solutions on all spectral orders. This fit is performed by solving a huge linear least-squares problem where the unknowns are 1) the coefficients of the 72 polynomial wavelength solutions and 2) the systematics $\Delta\lambda$ for each individual line, representing the systematic error in wavelength in the PE83 atlas. The linear system of equations is set up in such a way that repeated lines (appearing on two different orders) are assigned one single $\Delta\lambda$. Each equation is properly weighted with the corresponding uncertainty on its residual (i.e. the corresponding photon noise on HARPS spectra and in the PE83 atlas). Additional constraints to the system take into account the fact that the global, weighted, distribution of the systematics $\Delta\lambda$ must be normal. As a result we obtain a global wavelength calibration for all orders together with new, corrected wavelengths for all detected lines. These new wavelengths are internally (i.e. relative to each other) much more accurate than the original PE83 wavelengths. However, the global, absolute wavelength scale is still the one of PE83. We presently estimate that we reach a relative precision of ~5 m s^{-1} for most of the lines, which is a factor of 3 to ~20 better than in PE83. At the end of this process we have obtained a new ThAr atlas giving updated wavelengths for more than 8,600 lines, about half of which lack a previous identification. Most of these are likely to be Th lines, but some of them will be from Ar and other elements. In a future step, we plan to try to distinguish between both categories by installing other calibration lamps on HARPS (such as ThNe) and comparing their spectra to those of the ThAr lamps.

In the final step of this process, the use of the new ThAr atlas has been implemented in the HARPS data reduction software (DRS). As a result, the fitted wavelength solutions have become much more stable, especially at the edges of the spectral orders. Residuals of the line positions around the fit now follow the photon noise statistics and are no more dominated by the large systematics present in the PE83 atlas. We presently estimate that these efforts have allowed us to reduce the global uncertainty in the wavelength calibration (RV zero point) from ~0.8 m s^{-1} down to ~0.2-0.4 m s^{-1}. The exact number is not precisely known yet because of the difficulty in distinguishing between the various error sources affecting high-precision RV measurements.

We also investigated the intrinsic stability of the ThAr calibration lamps we are using on HARPS. To do this, we compared series of spectra taken with different lamps during the same night. As the spectrograph is expected not to have drifted by more than ~1 m s^{-1} over such timescales, comparing the measured line positions between different lamps allow us to test the quality of these lamps as absolute wavelength references. An important result we have obtained is the demonstration of the intrinsic variability of Ar lines. Indeed, Ar lines change their positions by tens of m s^{-1} between lamps, showing that they are highly unsuitable for wavelength calibration. This is not completely unexpected since some authors had already noticed such wavelength changes in Ar lines[13]. These shifts could be explained by the various Ar pressures at which the lamps are operated. Indeed, external pressure has an influence on the energy levels in atoms and therefore on the transitions between these levels (pressure shifts). Fortunately, the Th atom appears to be much less affected by pressure shifts than the Ar atom. Indeed, the comparison of Th line positions between different lamps yielded small, unsignificant shifts at the 1 m s^{-1} level that could well be due to instrumental drifts, CCD limitations or imperfect data reduction. We are therefore confident that ThAr lamps are able to provide a stable, long-term wavelength reference at the 1 m s^{-1} level and below.

4. OTHER ERROR SOURCES IN HARPS MEASUREMENTS

In this section we briefly discuss the other main error sources that have to be taken into account to compute a realistic error bar on the RV measurements.

4.1 Photon noise

The most obvious noise source is the one coming from the finite number of photons collected in a stellar spectrum. On HARPS spectra, the photon noise is computed using the procedure described in ref. 14. The fundamental uncertainty on the radial velocity in a spectral chunk depends both on the number of recorded photons and on the intrinsic slope of the spectrum (i.e. its derivative). As a consequence, the spectrum of a slowly-rotating, metal-rich K dwarf contains much more Doppler information than the one of a metal-deficient F star (with the same visual magnitude). In numbers, for a

G2V spectral type, HARPS delivers a photon-limited RV precision of ~1 m s^{-1} in a one-minute exposure on a V=7.5 star (or in a one-hour exposure on a V=12 star). For later-type K dwarfs, the photon noise goes down to ~0.8 m s^{-1} under the same assumptions. This level of precision should be sufficient to allow for a good follow-up of the transiting planetary candidates detected by the COROT satellite, to be lauched at the end of 2006.

4.2 Guiding noise

The illumination of the spectrograph is one of the very critical aspects as far as RV precision is concerned. Changes in the light distribution at the fiber output directly translate into wavelength shifts on the CCD, and therefore into spurious RV variations. Particular attention has been paid to the light-scrambling properties of the HARPS optical fibers, so that the illumination at fiber output becomes as stable as possible. However, scrambling is never perfect and a good telescope guiding software is absolutely necessary. A specific guiding algorithm was developed for the ESO 3.6m-telescope, whose role is to continuously check that the fiber hole remains centered in the middle of the stellar image during science exposures. At the end of each exposure, the integrated guiding image is saved and the average position of the fiber hole is computed, allowing us to check the guiding quality for each observation. To give a numerical estimate of the impact of bad centering, we have measured a radial velocity shift of ~3 m s^{-1} if we force the star to remain at the edge of the one-arcsecond fiber. Fortunately, we estimate that the guiding software is presently able to control the position of the photocenter at the 0.05 arcsecond level, thus keeping the guiding noise below ~0.3 m s^{-1}.

4.3 Stellar oscillation noise

Solar-type stars show p-mode oscillations with characteristic periods of a few minutes and amplitudes of a few m s^{-1} (when observed in disk-integrated light). Many oscillation modes are simultaneously excited, so that the observed RV signal is the superposition of a large number of modes beating at slightly different frequencies. The characteristic periods and amplitudes tend to increase when going from K dwarfs to early-G dwarfs, and from main-sequence to subgiant stars. The present observing strategy with HARPS is to integrate over a few characteristic periods to average out these oscillations as much as possible. This should in most cases allow us to maintain the oscillation noise below 1 m s^{-1}.

4.4 Stellar activity-related jitter

Magnetic phenomena at the surface of solar-type stars are known to induce radial velocity perturbations due to the rotational modulation of dark spots for example. For young stars, these effects are so strong that they can induce RV variations of more than 100 m s^{-1}, thus preventing the detection of low-mass companions with the RV technique. Several diagnostics have been developed to measure the activity level of stars, the most famous being the CaII H&K chromospheric emission index, $\log(R'_{HK})$. Stars in the HARPS high-precision planet search sample are selected for showing low chromospheric activity and low rotational velocity, which should guarantee that stellar activity effects remain below a few m s^{-1}. A useful tool used to identify RV perturbations of stellar origin is the bisector span measurement, which characterizes the shape of spectral lines. With this indicator we expect to be able to trace stellar effects below the 1 m s^{-1} level, but obviously we are entering here a totally unknown domain and it is presently difficult to predict what will be the ultimate limitations on the RV measurements. Hopefully, the binning of data points over the stellar rotation period will allow to average out these effects.

5. THE CODEX PROJECT

ESO has recently initiated several studies related to the future instrumentation for the European Extremely Large Telescope (ELT). Among those was the CODEX project (COsmic Dynamics EXperiment), which aims at directly measuring the cosmological acceleration/deceleration of the Universe[15]. The basic idea behind this project is to observe the Lyman α forests seen in QSO spectra and precisely measure the redshift of each absorption system as a function of time. As the Universe evolves, the observed redshift of a given hydrogen cloud is changing slowly with time, reflecting the dynamics of the expansion of the Universe. A direct measurement of this redshift change would put strong constraints on the present cosmological models and yield independent measurements of various parameters such as the cosmological constant.

The expected magnitude of this cosmic signal is of the order of 1 cm s^{-1} per year, which is at least one order of magnitude smaller than the RV precision achievable today. Such a measurement is obviously challenging but should not be considered a priori impossible. Extrapolating from what we have learned with HARPS, we anticipate that a dedicated spectrograph, specifically designed for this purpose, could be able to achieve the required ultra-high Doppler accuracy. However, some technological developments will be necessary. We briefly review some of these below.

First of all, it seems clear that a new calibration system will be needed. Present calibration techniques, such as ThAr lamps, have some disadvantages that will not be acceptable any more at the 1 cm s^{-1} level. Varying physical conditions in the discharge probably induce some pressure shifts in the wavelengths at the sub-m s^{-1} level. Moreover, the large dynamics of line intensities represents a major problem since we need the largest possible number of lines (to have enough Doppler information) and at the same time we want to avoid strongly saturated lines that would pollute large chunks of the spectrum. Finally, ThAr lamps do not have enough lines in some parts of the spectrum to locally constrain the wavelength solution to sufficient accuracy. We therefore need to explore new calibration techniques. A "perfect" calibrator would have the following qualities:

- It should have a very large number of lines covering the visible wavelength range (up to one line per resolution element of the instrument);
- It should guarantee a very high long-term wavelength stability ($\Delta\lambda/\lambda < 10^{-11}$);
- The wavelengths of individual lines should be known to very high relative accuracy;
- The line intensities should all be about the same.

Such a system might well be available soon: indeed, a laser frequency comb, specifically designed for our purpose, could fulfil all the requirements above. Laser frequency combs generate emission line patterns regularly spaced in frequency. The frequencies of the pattern can be controlled by an atomic clock, whose intrinsic accuracy would provide the required long-term wavelength stability. All lines would be equally spaced by construction, and the line spacing itself can be adjusted to meet the limitations set by the spectrograph resolution. Although technical developments are needed to fully adapt this technology to the calibration of astronomical instruments, the laser frequency comb seems to offer a very promising and elegant solution to our needs in the CODEX framework.

The stability of the spectrograh illumination is another critical aspect to consider when aiming at 1 cm s^{-1} accuracy. This will require the development of a "perfect" light-scrambling system. Work is currently underway to provide optical fibers and light-injection systems with the required properties. Finally, some developments are needed on the detector side to better characterize the limitations of CCDs and closely control their behaviour. For example, heat dissipation during readout causes tiny temperature fluctuations and therefore dilatation of the CCD. This translates into spurious Doppler shifts at the ~10-30 cm s^{-1} level . An active system compensating for this heat generation could ensure that these shifts remain as small as possible, although the simultaneous reference technique already allows us to precisely track these drifts.

In conclusion, the work being presently done to improve the RV precision on HARPS and to understand the present limitations of the RV technique will be very useful in the framework of CODEX. Ultra-high accuracy RV measurements offer exciting perspectives in the domain of extrasolar planets as well as in cosmology, which are two of the major fields of present-day astrophysics. We will therefore continue our efforts to push down the limits of the RV technique.

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