European Organisation for Astronomical Research in the Southern Hemisphere

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title — Category: **C–7**

Earth twins in the habitable zone of solar-type stars

2. Abstract

Five years of sub-m s^{-1}s radial-velocity measurements of quiet stars in the HARPS-GTO planet-search programme have unveiled the tip of a large population of Neptune-mass and super-Earth planets present around ∼30 % of G and K dwarfs of the solar neighborhood, within 0.3 AU from the central star. These findings support recent results of synthetic planet-population models that also predict the existence of a large population of Earth-mass planets at all separations. We propose in this ambitious large program to directly probe the presence of Earth twins in the habitable zone in a sample of 20 close-by solar-type stars, through radial velocities obtained with the high-resolution optical spectrograph CODEX on the European Extremely Large Telescope (hereafter E-ELT). The high resolution and long term stability of CODEX coupled with the large collecting area of the E-ELT provide an unequaled facility for measuring stellar radial velocities at the few cm s^{-1} level. Simulations show that stellar noise (p-mode, granulation, activity) can be averaged down to this level for the quietest dwarf stars. The scientific goals of the proposal are 1) to detect Earth-mass planets in the habitable zone around solar-type stars and thus build-up a list of suitable targets for future space missions aiming at characterizing their atmosphere; 2) to determine the frequency of Earth twins around neighboring stars; 3) to derive statistical properties of low-mass planets, priceless constraints for planet-formation models; and 4) to characterize the multi-planet aspect of systems with Earth twins.

3\.

Run	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	HRS	1400h	any	g	$\leq 0.8''$	CLR	v

4. Principal Investigator: **S. Udry** (Geneva Observatory, CH, stephane.udry@unige.ch)

CoI(s): C. Lovis (Geneva Observatory, CH), D. Naef (Geneva Observatory, CH), L. Pasquini (ESO, ESO), on behalf of the CODEX collaboration (Several institutes, OTHER)

5. Is this proposal linked to a PhD thesis preparation? State role of PhD student in this project

6. Description of the proposed programme

A) Scientific Rationale:

Discovering Neptunes and super-Earths with radial velocities: the HARPS experience.

From giant planets to super-Earths with radial velocities.

The discovery 14 years ago of an extra-solar planet orbiting the solar-type star 51 Peg (Mayor & Queloz 1995, Nature 378, 355) has encouraged the launch of numerous new search programs, leading now to a steadily increasing number of exoplanet detections. About 350 other planetary companions have been found to orbit dwarfs of spectral types from F to M and more massive evolved stars (Fig.1). Their properties provide important constraints for planet formation models. The majority of the exoplanets have been found through the induced Doppler spectroscopic variations on the primary star, the so-called radial-velocity (RV) technique. Because of the limitations inherent to the RV technique, most of the candidates detected so far are giant gaseous planets, similar in nature to Jupiter. However since 2004, research teams using the RV technique have been making the headlines several times for their discoveries of low-mass extrasolar planets, some of which having only a few times the mass of the Earth (Fig. 1). These discoveries were made possible thanks to the sub-$\mathrm{m\,s^{-1}}$ precision reached by HARPS-type instruments.

The HARPS high-precision programme.

Among the different surveys conducted by the HARPS consortium within the GTO time, the one aiming at finding the lightest possible exoplanets has been dedicated the largest fraction of the observing time (50 %). The "high-precision" HARPS-GTO subprogram is targeting close to 400 bright, non-active FGK dwarfs, selected from the large volume-limited CORALIE planet search sample, to which had been added the stars with already known planets. Figure 1 shows examples of low-mass planetary systems coming from these surveys: HD 69830 (Lovis et al. 2006, Nature 441, 305) and HD 40307 (Mayor et al. 2009, A&A 493, 639). In each case, at least three low-mass planets have been found with minimum masses similar to or smaller than Neptune, among them five below $10\,M_\oplus$, making them super-Earths which are very probably mainly solid (icy and/or rocky). Other examples are provided by HD 181433 with a super-Earth ($7.6\,M_\oplus$) in a 3-planet system and HD 47186 with a Neptune-mass planet ($22.8\,M_\oplus$), with a Saturn-mass companion (Bouchy et al. 2009, A&A 496, 527). Undoubtedly, all these exciting discoveries are important steps towards the first detection of a true Earth twin. After 5 years of observations, a lot has been learned about the RV behaviour of the stars surveyed by HARPS. The most stable ones exhibit RV dispersions at the level of 80 $\mathrm{cm\,s^{-1}}$ over several years, very close to instrumental limitations. Many others show variability at the 2-3 $\mathrm{m\,s^{-1}}$ level that often turns out to be due to orbiting low-mass planets. Most of these objects are actually found in multi-planet systems, leading to complex, low-amplitude RV curves. This is well illustrated by the HD 69830 and HD 40307 systems. The total RV dispersion before fitting any Keplerian model amounts to $3.7\,\mathrm{m\,s^{-1}}$ for HD 69830 and $2.9\,\mathrm{m\,s^{-1}}$ for HD 40307, whereas the post-fit rms dispersion of the residuals is only $\sim 0.8\,\mathrm{m\,s^{-1}}$ in both cases. This clearly demonstrates the need for the sub-$\mathrm{m\,s^{-1}}$ precision and for a large number of measurements (74 RVs for HD 69830 an 135 for HD 40307).

An emerging population of super-Earths and Neptune-mass planets.

The discovery of low-mass planets is especially important for the understanding of formation and evolution of planetary systems. Preliminary results from the HARPS program suggest that the already published discoveries only represent the tip of the iceberg. A recent census of planetary candidates among stars of the "high-precision" subprogram is revealing more than 40 possible low-mass planets ($m_2 \sin i < 30 M_\oplus$) orbiting in less than 50-60 days. Statistically, taking into account only the subsample with enough measurements to safely conclude on the existence or not of low-mass planets, this would mean that about 30 % of solar-like stars do possess such close-in ice giants and super-Earths. More than 80% of these light planets are in multi-planet systems. Although still to be confirmed, these preliminary numbers are a strong indication that a whole new population of low-mass objects is now emerging. This is supported by discoveries of similar low-mass objects at larger separations (a few AUs) using the microlensing technique (e.g. Bennet et al. 2008, ApJ 684, 663), and is also in agreement with the predictions of simulations of synthetic planet population (e.g. Mordasini et al. 2009, A&A in press, astro-ph/0904.2542; Ida & Lin 2008, ApJ 685, 584; Fig. 2). The latter theoretical approach is also predicting the existence of a large population of small-mass planets at all separations, and among them a large population of Earth-like planets at separations corresponding to the habitable zone around the star.

Limitations: instrumental, photon, and stellar noise.

The planetary minimum mass estimated from Doppler measurements is directly proportional to the amplitude of the reflex motion of the primary star. The detection of the lowest possible mass planets is thus intimately linked to the ultimate long-term precision achieved on the RV measurements of the star. Looking for the highest radial-velocity precision, we have to take into account several sources of noise. They can be classified into several broad categories: photon count, technical, and astrophysical. Each of these sources is essentially independent from the others and thus the actual precision eventually obtained on the measurements will be a quadratic combination of the different contributions. Each of them has thus to be smaller than the aimed precision (typically a few $\mathrm{cm\,s^{-1}}$; the effect of the Earth on the Sun is $9\,\mathrm{cm\,s^{-1}}$).

B) Immediate Objective: The main scientific goals of the proposed observations are: i) to detect

6. Description of the proposed programme (continued)

Earth-mass planets in the habitable zone around solar-type stars and thus build-up a list of suitable targets for future space missions aiming at characterizing their atmosphere; ii) to determine the frequency of Earth twins around neighboring stars; iii) to derive statistical properties of low-mass planets, priceless constraints for planet-formation models; and iv) to characterize the multi-planet aspect of systems with Earth twins. In order to achieve these goals, we propose to conduct a ultra-high radial-velocity precision survey of a sample of 20 bright Solar-type stars using the E-ELT/CODEX instrument. Investigating 20 targets, we expect to detect at least 7 planetary systems. We will fully characterize them (number of planets, orbital properties, minimum masses...). Ideally, we would prefer to survey a larger sample but 20 stars seems to be a reasonable compromise between statistics and requested telescope time. The key issue of such a challenging programme is the achieved precision. Apart from the instrument itself, the achieved radial-precision, and thus the detection capability of the survey, critically depends on the sample definition and on the observing strategy.

Definition of the sample: For the definition of the sample to be used for this program, the idea is to build up from the experience, results and data gained during the HARPS-GTO and ESPRESSO programs. The sample will consist of a set of 20 slowly-rotating, non-active, radial-velocity constant and bright G and K dwarfs. Precise activity indexes and rotational velocities are available thanks to HARPS and ESPRESSO observations allowing us to build the best possible sample for such a program. Targets with bright (less than 7-9 magnitudes fainter) close (closer than $\simeq 3$ arcsec) visual companions will be excluded from the sample in order to avoid possibly seeing-dependant contamination.

Observation strategy: As mentionned before, several error sources do affect radial-velocity measurements. From the E-ELT spectroscopic exposure time calculator, we estimate that photon noise errors below $5\,\mathrm{cm\,s^{-1}}$ can be obtained in less than 15 minutes for stars brighter than $m_{\mathrm{V}} = 10$. Monte-Carlo simulations have been performed for checking our ability to damp the impact of astrophysical error sources. For example, Dumusque et al. (2009, in prep.) have simulated the impact of stellar pulsation and granulation in a realistic way (see Fig. 3). They have obtained the typical timescales and RV amplitudes of these effects. They have also determined an optimal observing strategy in terms of precision and observing time availibility that will allow us to average these effects out down to a few $\mathrm{cm\,s^{-1}}$ level. These simulations so far do not include the effect of stellar activity (i.e. spots) so these results correspond to the case of spotless stars (like the Sun at the moment). We propose to use this optimal observing strategy which can be summarized like this:

i) the exposure time of an individual velocity measurement will be 15 minutes (divided in multiple exposures if necessary to avoid saturation) in order to average out the stellar seismic noise (typical timescale: a few minutes)

ii) 3 individual velocity measurements per target per night separated by about $\simeq$ 2 hours for averaging out the granulation effect (typical timescale: from 0.15 to several hours).

iii) The same strategy is repeated every second night during a 10–day observing run and one observing run per month in order to sample well the stellar rotation period (typical timescale: weeks for non-active stars and days for more active ones).

iv) We will use the entire yearly visibility period of our targets ($\simeq$ 7 months per year) during at least two years in order to sample well the period interval corresponding to the habitable zone (e.g. one year for a G dwarf, less than one year for K dwarfs).

Apart from damping noise sources of astrophysical origin, this observing strategy will provide us with ultra-high precision RV data sets for every target that will have a temporal sampling sensitive to periods from less than one day to more than a year allowing the characterization of very low-mass planets at separations from 10^{-2} AU to beyond the habitable zone around their host star. The rather large number of observations per target will be sufficient for disentangling multiple low-amplitude Keplerian signals. Our experience suggests that of the order of 20 data points (epochs) per planet in the system are required for a well constrained orbital fit.

C) Telescope Justification: The presence of the Earth around the Sun changes the velocity of the Sun by about $9\,\mathrm{cm\,s^{-1}}$. In order to detect and characterize such a tiny variation on solar-type stars, we need an instrument capable of reaching such a precision ($<< 10\,\mathrm{cm\,s^{-1}}$), and stable over several years. Another important point is the signal-to-noise (S/N) required to reach such a precision. The RV precision inversely scales with the S/N of the spectra. With CODEX on the E-ELT, we reach $4\,\mathrm{cm\,s^{-1}}$ on a V=7 in 1 minute, or on a V=10 in 15 minutes (based on the E-ELT spectroscopic Exposure Time Calculator). The needs in stability, precision and large collecting area make E-ELT/CODEX the unique instrument in the world to reach the ambitious goal of this programme.

D) Strategy for Data Reduction and Analysis: The online CODEX DRS pipeline delivers calibrated high-resolution spectra and high-precision radial velocities. The optimum pipeline is developed in the frame of the CODEX project. The ultra-high precision of individual velocities will then be combined in an optimal way to efficiently average down the different contributions of the stellar limiting noise. The observational strategy had been design with similar goals (Texp long enough to dump stellar oscillation effects, several measurements per night to average granulation effects, and regular observations to cover the activity time scale).

6. Attachments (Figures)

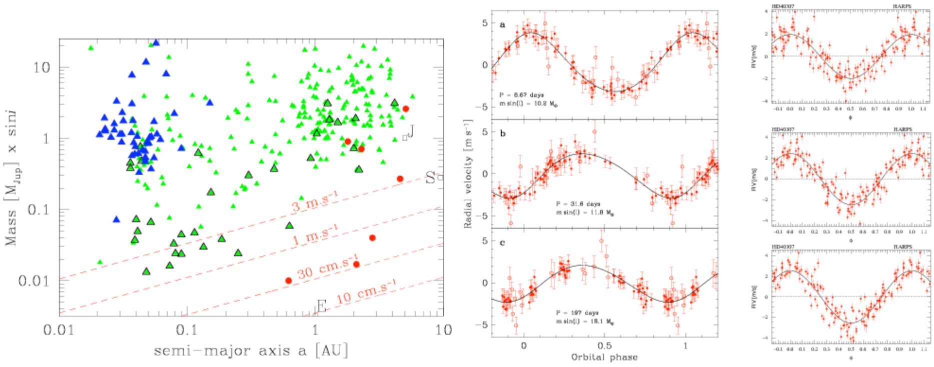

Fig. 1: **Left:** Mass-separation diagram of the more than 350 known exoplanets. The triangles refer to exoplanets found by radial velocities. The dark triangles refer to transiting exoplanets. The circles refer to exoplanets found by microlensing. The bold triangles correspond to planets discovered with HARPS. Lines of radial-velocity semi-amplitude of 3, 1, 0.3 and 0.1 ms^{-1} are shown, assuming a 1 $M_{\odot}$ primary star (adapted from Bouchy et al. 2009, A&A 496, 527). Examples of multi-planet systems detected with HARPS: three Neptunes in HD 69830 (Lovis et al. 2006, Nature 441, 305, **Middle**) and three super-Earths around HD 40307 (Mayor et al. 2009, A&A 493, 639, **Right**).

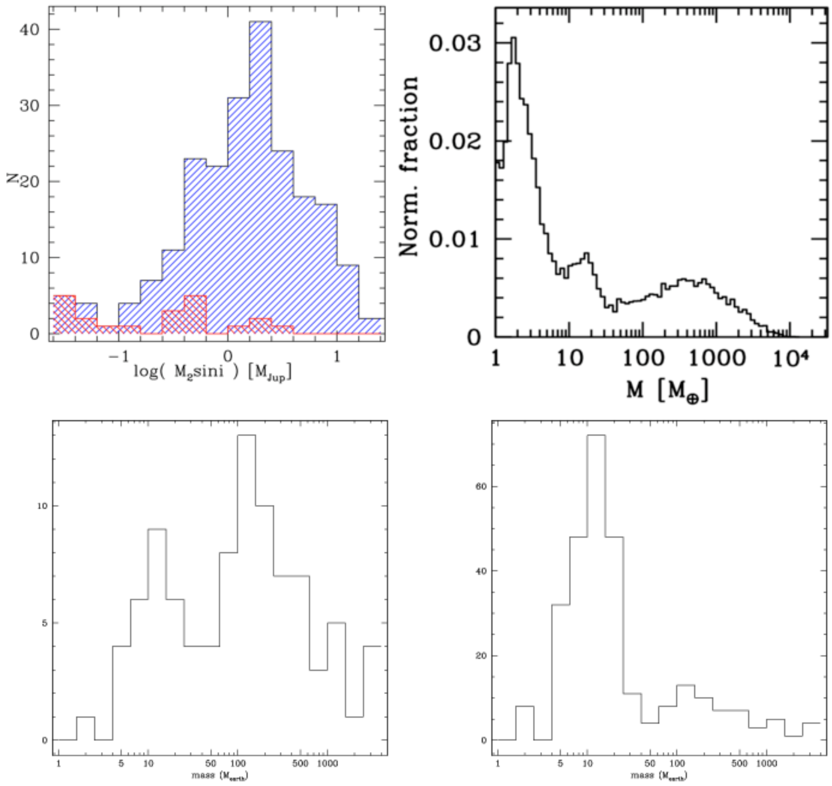

Fig. 2: **Top left:** Mass distribution of known extrasolar planets. The red-shadded is the HARPS contribution. A new low-mass population is emerging on the left side of the diagram. **Top right:** This new population is also predicted by models of synthetic planet populations (from Mordasini et al. 2009, A&A in press, astro-ph/0904.2542). **Bottom left:** Mass distribution of known exoplanets with periods shorter than 100 days. **Bottom right:** Same distribution with a normalization taking into account the fact that the sample out of which very low-mass planets are detected (i.e. the HARPS high-precision sample) is about 8 times smaller than the total number of stars in exoplanet search samples.

6. Attachments (Figures)

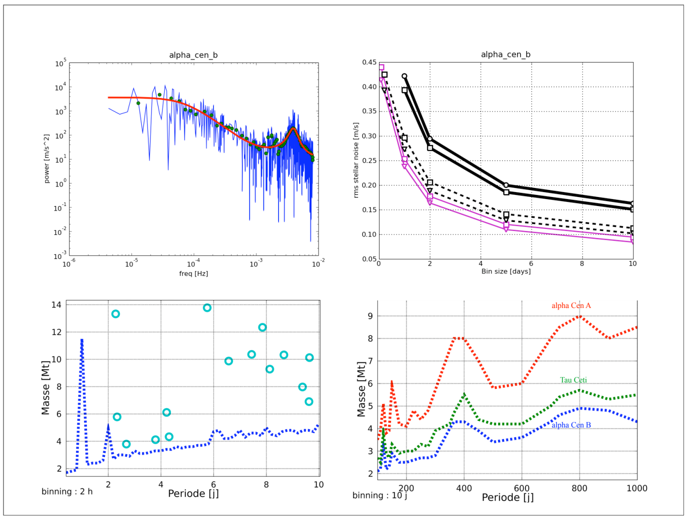

Fig. 3: Simulations aiming at optimizing the observing strategy for low-mass planets detection (from Dumusque et al. 2009, in prep.) **Top left:** Power spectrum of real α Cen B radial velocities obtained over 8 hours of consecutive observations and fitted noise model including photon noise, p-mode and granulation (bold line). **Top right:** *rms* of the synthetic RV data generated from the noise model for different observing strategies and averaged over various bins lengths in days. **Bottom:** Simulated detections limits in the planetary mass-separtion space, for optimized binning applied to a real observation calendar (the one of HD 69830), for short period planets around α Cen B (left, 2 h bins) and planets close to the habitable zone around 3 different stars (right, 10 d bins).

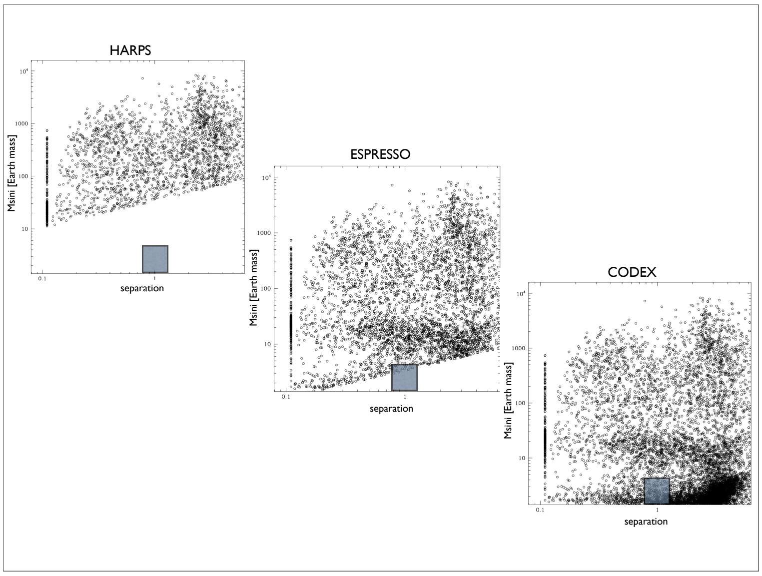

Fig .4: Expected planet population to be detected by Doppler spectroscopy with the HARPS/3.6m (precision of 1 m s^{-1}; left), ESPRESSO/VLT (precision of 10 cm s^{-1}; middle) and CODEX/E-ELT (precision of 1 cm s^{-1}; right) spectrographs, after applying observational limits for radial-velocity measurements on the predictions of planet population synthesis models with Solar-type primaries from the Bern group (Mordasini et al. 2009, in press, astro-ph/0904.2542). The detection criterium is set as the RV semi-amplitude being equal to twice the precision. Note that limitations due stellar noise are supposed to be solved by the averaging statistical approach (see text) and thus they are not taken into account in these estimates. The impact of the achieved RV precision is clearly seen.

7. Justification of requested observing time and lunar phase

Lunar Phase Justification: We have to avoid that direct or indirect Sun light reaches the detector with a contrast magnitude compared to the science target smaller than ~9. In order to avoid significant RV errors, one would have to avoid twilight observations, avoid observations during full moon, or when target is too close to the moon, avoid observations with cloudy sky and cirri. Grey or dark time is thus required.

Time Justification: (including seeing overhead) The global need in observation time is governed by the statistics required to obtain trustable answers to the scientific questions/objectives defined for the programme (i.e. number of sample stars), and by the number of observations and their temporal sampling needed for each star to average the intrinsic stellar jitter over the different variation time scales (minutes, hours, days and weeks). The total number of data points also needs to be sufficient for convincing multi-planet orbital fits to be performed. Finally, the total observing time span has to be long enough to allow the detection of planets in the habitable zone (e.g. longer than one year in the case of a G-type primary).

Following the considerations developed in the previous sections, an optimized survey would require 3 observations of a given star per night, repeated every other night during regularly scheduled 10-night runs (once a month) over the visibility period of the star (7 months per year, i.e. 7 runs per star per year). The typical exposure time for individual integrations would be 15 minutes (as mentionned in Box 8C, this is sufficiant for obtaining a photon noise error of the order of a few $\mathrm{cm\,s^{-1}}$ for any target brighter than $m_V = 10$) plus 5 minutes of overheads hence 1 hour per star per night or 5 hours per star per run or 35 hours (3.5 nights) per star per year. In order to be able to detect signals with a period close to one year, the same observing strategy has to be applied at least during two years, e.g. 7 nights (3.5 per year) per target taken during two different years. The surveyed stellar sample has to be large enough for obvious statistical reasons. We estimate that statistically useful conclusions on low-mass planet properties could be drawn from an initial sample of about 20 targets. The total number of requested nights would thus be $7\times20 = 140$ nights. As mentionned before, the minimal time span for a given target is two years but it would be posible to spread the total 140-night survey over more than two years. If successful, this initial exploratory sample will be extended and more observing time will be requested in order to improve the statistical significance and robustness of our findings. The positive statistical perspectives provided by the theoretical models of planet formation (Mordasini et al. 2009, A&A in press, Fig. 4) completely justify the required observational effort.

Calibration Request: Standard Calibration

8. Instrument requirements

– Extreme RV stability (2–5 $\mathrm{cm\,s^{-1}}$) over 10 yr
– Minimum energy in optical fibres: 80%
– Very stable fibre illumination
– Wavelength range required: 3800Å to 6800Å.
– Spectral resolution: $\geq 150\,000$
– FOV: a few arcsec
– Sky coverage: $\geq 90\%$

9. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	Codex1	00 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex2	01 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex3	02 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex4	03 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex5	04 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex6	05 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex7	06 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex8	07 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex9	08 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex10	09 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex11	10 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex12	12 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex13	13 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex14	14 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex15	16 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex16	17 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex17	19 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex18	20 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex19	21 00 00.00	-00 00 00.0	1.0	7.0			
A	Codex20	23 00 00.00	-00 00 00.0	1.0	7.0			

Target Notes: The best targets will come as output of the on-going HARPS/3.6m high-precision programmes and the future ESPRESSO/VLT surveys.