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HARPS

Scientific Proposal

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Contents

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F. Pepe was responsible for the technical proposal. That document also contains chapters done by A. Blecha, D. Queloz and L. Weber. J. Schmitt has described the possibility of employing the AAA in connection with HARPS. In the pre-study phase F. Wildi has explored the possibility of a Fabry-Perot calibration method for HARPS and helped to define the instrumental baseline. The seeing data of La Silla have been analysed by F. Bouchy who also made an evaluation of the gain expected from a tip-tilt correction on the 3.6-m telescope. D. Queloz and J.-P. Sivan made contributions to the technical and scientific definition of HARPS during the whole initial phase of the project. The three optical design studies contained in the technical proposal have been prepared by A. Baranne (Observatoire de Marseille), B. Delabre (ESO) and D. Kohler (Observatoire de Haute-Provence).

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1 General Presentation

1.1 ESO's "Announcement of Opportunity"

Faced during the past year with the increasing interest of the astronomical community in extra-solar planetary search, ESO has decided to intensify research in this domain. ESO has therefore announced (ESO 1998a) the construction of HARPS (High Accuracy Radial velocity for Planetary Search) which will be an instrument dedicated to the search of extra-solar planets by means of radial-velocity (RV) variations. The required RV accuracy is $1\,\mathrm{ms}^{-1}$.

HARPS will be located at the 3.6-m telescope at the ESO Observatory of La Silla (Chile). This project includes the allocation of a minimum of 100 nights/year of telescope time during 5 years, and allows therefore the applicants to draw up an adequate observational programme.

This offer represents a unique opportunity to push the hardware to the limit while collecting a large sample of new data which will serve as the testing ground for all new planetary formation theories.

1.2 The Search for Extra-solar Planets

Observationally, the last three years have been no less than extraordinary. After a number of years of searching for sub-stellar mass companions orbiting solar-type stars, the first signs of discouragement were appearing (Walker *et al.* 1995; Zuckerman *et al.* 1995). With the discovery of brown dwarf Gliese 229B (Oppenheimer *et al.* 1995; Nakajima *et al.* 1995) and the indirect detection the same year of the Jupiter-mass planet 51 Peg B (Mayor & Queloz 1995) followed within months by the discovery of 2 new giant extra-solar planets by the Lick Observatory group (Marcy & Butler 1996, Butler & Marcy 1996), the search for these objects entered a new era (Marcy & Butler 1998 and references therein).

The discovery of 51 Peg B by Mayor and Queloz (1995) has sparked a flurry of new activities worldwide. Although the existence of extra-solar planets was rarely challenged, the actual detection of these objects has not only tremendously energized the scientific community but also confirmed the ideas that planet formation must be a rather ordinary and common process.

To date, 16 planetary companions with minimum masses smaller than 5 times the mass of Jupiter ($\mathrm{M_J}$) have been announced, outnumbering the planets in our own solar system almost two to one and their number is steadily increasing. The observational challenge is therefore no longer the detection of one or even a few more of these objects, for which we have already discovered that our current paradigm of planetary system formation is in need of serious revisions. The observational challenge lies now in the detection of *as many* systems

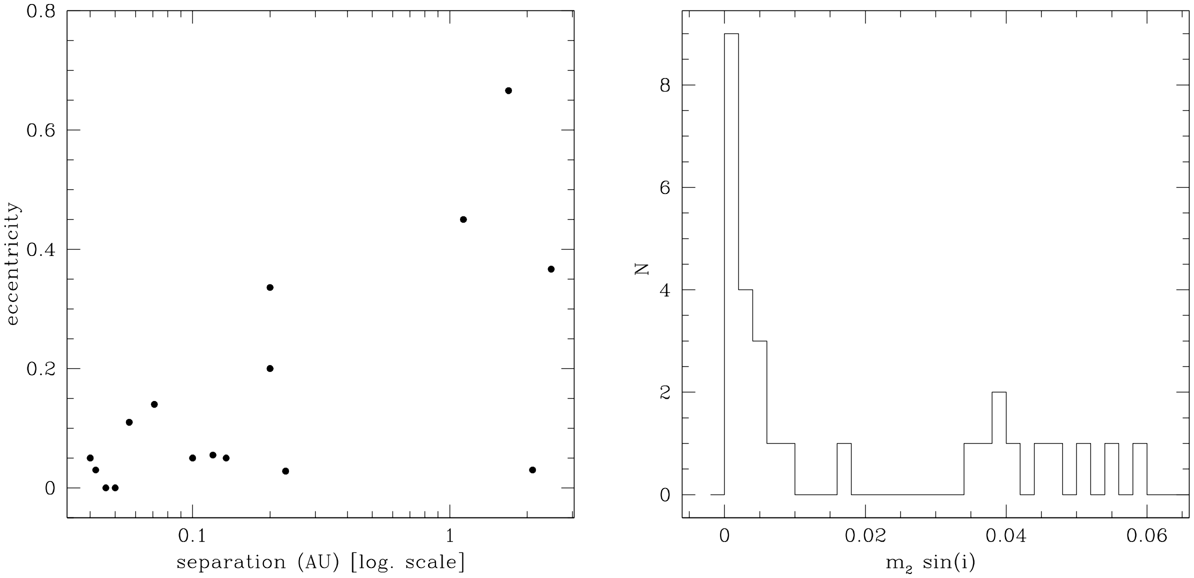

Figure 1: **Left.** Separation vs eccentricity distribution of the new extra-solar planetary systems. A large fraction of those orbit unexpectedly close their parent star. They also are found on orbits with various eccentricities. **Right.** Distribution of the projected masses (in $M_\odot$) of the low-mass secondaries of solar type stars. The extra-solar planets formed a huge peak below 5 Jupiter masses. Brown dwarfs are rare despite their easier detections

as possible to determine not only the fundamental physical processes underlying planetary formation but also a proper statistical distribution of orbital elements, planetary masses, frequency, etc. The necessity for such a large sample is best illustrated by considering the large diversity of the systems discovered so far.

The most remarkable feature of the newly discovered planetary systems is undoubtedly the variety of their orbital characteristics which challenges the conventional views of planetary formation. Amongst the most peculiar systems are those giant planets very close to their primary stars ($0.04 \leq a \leq 0.11\,\mathrm{AU}$) where they could probably not have formed (see Sect. 1.4). The orbits of these new planets are also a mix between circular and eccentric orbits. This opens the possibility that, at least for some objects, subsequent interactions with the disk or other planets has affected their original orbital parameters. The separation vs eccentricity distribution of the new exoplanetary systems is displayed in Fig. 1 (left). The planets also appear in single and binary stellar systems.

While the currently available sample of extra-solar planets is not yet very large, it already reveals some interesting results. The mass distribution of substellar companions to solar-type stars (Fig. 1, right) shows a huge peak below $5\,\mathrm{M_J}$ whereas there are only a few detections in the brown-dwarf domain although those are much more easily detectable at our precision level (Mayor *et al.* 1998a). This indicates the presence of two distinct populations probably

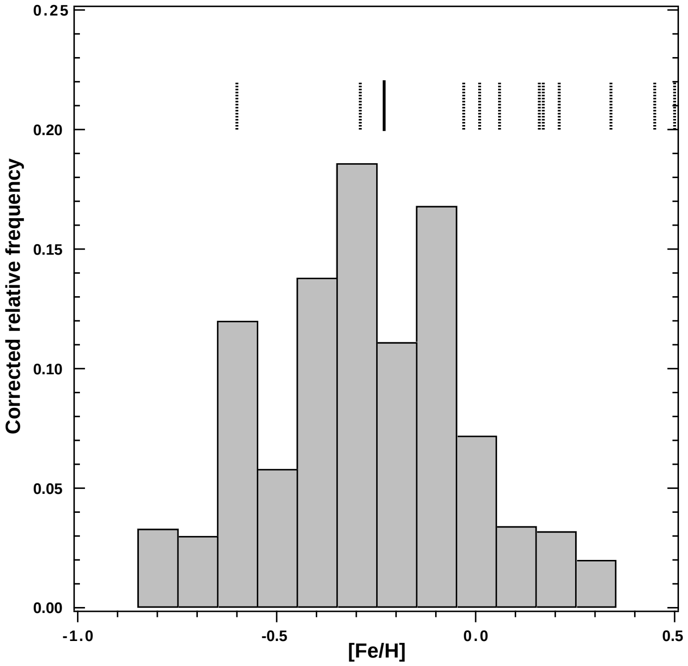

Figure 2: From Gonzales (1998). Distribution of [Fe/H] of stars of the solar vicinity. The positions in the diagram of stars with planets, indicated on top of the figure, show their high metallicity tendency

with different formation and evolution histories.

Stars with giant planets seem to be significantly enriched in heavy chemical elements when compared to the composition distribution of stars in the solar vicinity (Gonzales 1998; Fig. 2). This peculiarity (if confirmed by the studies of a much larger sample) may provide us with important clues to help us differentiate between the different planetary formation scenarios.

The distribution of orbital elements is a potential powerful tool to help us determine the physical processes underlying planetary formation. To disentangle the effects due to formation from those induced by subsequent evolution, a very good statistical sample is clearly needed. Thus, the field is moving from a *detection* to a *production* stage with all the groups involved in the *planet hunt* surveying larger star samples. In this context, the decrease of the detection bias favouring larger masses and smaller periods by improving the precision of the radial-velocity measurements – down towards 1 ms^{-1}, as planned with the HARPS project – will be of prime importance.

Targets for the new instrument will naturally come from on going surveys like the ELODIE, CORALIE or Keck ones. In the same manner the results from higher precision radial-velocity surveys will then provide targets for the future interferometry programmes (VLTI) and space missions (SIM, GAIA, DARWIN).

1.3 High-precision Radial-Velocity Measurements

All[1] the new planetary systems around solar-type stars have been indirectly detected by monitoring the radial-velocity change of the star on its orbit around the centre of mass of the star-planet system. Such radial-velocity variations are very tiny (the Doppler shift of the star spectrum is of the order of a few 10^{-4}Å) and thus require a specifically designed instrumentation to be accurately measured.

The basic ingredients for high-precision radial-velocity measurements ($\leq 10\,\mathrm{ms}^{-1}$) are a high-resolution spectrograph with a large spectral window, a very stable velocity reference and a fine data reduction process. Two basic techniques are presently used by the few groups in the world capable of reaching such a long term high-precision level. In one technique the absorption lines of a Iodine cell, superimposed to the stellar spectrum, are used as the zero velocity reference and the velocity is derived by spectrum fit (Marcy, Butler *et al.* at Lick, Keck and AAT; Cochran *et al.* at McDonald Observatory). The other technique uses a two-fibre fed echelle spectrograph, one fibre for the star and the other illuminating a reference Thorium-Argon lamp, allowing the follow up of any instrumental drift. Both stellar and reference velocities are calculated by numerical cross-correlation of the stellar and lamp spectra with corresponding templates (Mayor *et al.* with ELODIE and CORALIE; Noyes *et al.* with AFOE). A promising combined variant using a Fabry-Perot instead of the Iodine cell is under development but has not proven its efficiency yet.

Finally, we can mention that other very promising - although not yet successful - techniques to search for extra-solar planets are under development: astrometry on the primary star, transit of the planet in front of the star, microlensing[1], etc. Some of those will greatly benefit from high-precision radial-velocity measurements: the combined information from spectroscopic and visual data will rapidly provide real masses for planets; radial velocities will discriminate planets from brown dwarfs, white dwarfs or low mass stars among objects of similar sizes responsible for transits.

1.4 Formation and evolution of planetary systems

While the last three years have been a real observational bonanza, we must admit that these discoveries have put our theoretical understanding of the formation of these objects to a severe test. In conventional giant planet formation models (Pollack *et al.* 1996), the accretion of H/He by the solid core occurs only after its has reached a critical mass. Boss (1995a, 1995b) had argued that this nucleation of a H/He rich Jovian planet around a rock and ice core could be achieved in a protostellar disk only at or beyond the ice point. For the conditions presumed to exist in the early protosolar nebula this corresponds to a temperature

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[1] With the exception of one possible detection of a low-mass planet detected by microlensing (Ries *et al.* 1999)

of about 160 K or a distance between 4 and 6 AU. Remarkably, *all* the currently detected objects are within 4 AU of their star with seven, the so-called "hot Jupiters", inside a radius of 0.12 AU! Although there is clearly a strong observational bias against detecting distant planets, it is significant that *none* of these newly discovered objects should exist according to conventional formation theory.

The standard initial conditions for planetary formation are generally taken to be the so-called minimum mass solar nebula, a 100 AU disk having a total mass of order 0.02 $M\odot$ (Hayashi 1981; Shu *et al.* 1994). Accretion disks of similar masses (Beckwith & Sargent 1996) are indeed found around many T-Tauri stars (Strom 1994) of ages less than 10^7 years (Zuckerman *et al.* 1995). Both masses and ages are model dependent and therefore could be quite uncertain. In any case, in such disks the mass within 0.12 AU is significantly less than a Jupiter mass making giant planet formation in this region virtually impossible. To add to the conundrum, even if there was sufficient mass available, the young 51 Peg B for example would fill its Roche lobe and be prevented to form (Guillot *et al.* 1996).

The presence of giant planets at close orbital distances requires significant modifications and/or extensions to the standard formation model. The observed characteristics of disks around young stars could imply a diversity much larger than currently accepted in initial conditions. Ruzmaikina (1998) has argued that the collapse of a slowly rotating cloud having low turbulence could result in the formation of much more compact disks with much higher surface densities than the minimum mass solar nebula. Simple arguments can be used to indicate that rocky material can condense at 0.05 AU and therefore core accumulation could proceed as in the standard model. Wuchterl (1993, 1996) has shown that once a core with critical mass exist, runaway H/He accretion is indeed possible even at such close distances.

Interestingly, the two-step core accretion model for the formation of the giant planets in our solar system rests mainly on the fact that these planets are believed to have ice and rock cores of the order of 3 to 10 $M_\oplus$ for Jupiter and 1 to 13 $M_\oplus$ for Saturn (Chabrier *et al.* 1992). These numbers come from the modeling of the interior of the planets and basically depend on our knowledge of the hydrogen equation of state at high pressure which is still somewhat uncertain. With such large cores, these planets turn out to be enriched in heavy elements compared to solar and thus, they could not have formed from direct gravitational collapse. While this may be a valid requirement for the formation of our own giant planets, it may not have to be the case for all planetary systems. Direct gravitational collapse (see for example Boss 1997) could provide an attractive alternative especially since its characteristic timescale is considerably shorter than the one associated with the conventional core accretion model.

Moving already formed planets from the ice point or further out to close distances provides an alternative to *in situ* formation. This can happen as a result of gravitational scattering in a multiple giant planet system. Numerical simulations of such processes have shown (Weidenschilling & Marzari 1996; Rasio & Ford 1996) that not only is it unlikely that scattering will result in such small semi-major axis but that significantly eccentric orbits are to be expected. This process is therefore unlikely to account for the majority of objects which are in close to circular orbits large enough for tidal circularization to be inefficient.

Planetary migration can also occur through gravitational interactions between planets (or growing planets) and the gaseous disk or at later stages the disk of planetesimals. While this idea was already present in the literature for a long time (Goldreich & Soter 1966), and applied mainly to discuss gaps in circumstellar disks (Goldreich & Tremaine 1980; Ward & Hourigan 1989; Lin & Papaloizou 1986, 1993), the discovery of giant planets at small radii has forced us to recognize that these interactions may be a key ingredient in the formation of planetary systems (Lin *et al.* 1996). The migration timescale of a planet is a function of the characteristics of the disk as well as the mass of the planet as long as its mass is smaller than the critical value required to open a gap in the disk. Larger planets migrate on a timescale given by the viscous evolution time of the disk. Astonishingly, the time required by a planet ($\mathrm{M} > \mathrm{M}_{\oplus}$) to move a distance of 5 AU as a result of these interactions in a typical disk is computed to be of the order of 10^6 years or less, considerably shorter than the typical 10^7 years lifetime of disks (Zuckerman *et al.* 1995). Such short transport timescale are supported by the observational determination of typical mass accretion rates ($dM/dt \approx 3 \times 10^{-8}$ $\mathrm{M}_{\odot}$/years) in T-Tauri stars (Hartmann *et al.* 1997). This rate implies a typical time ($\tau \approx \frac{M}{dM/dt}$) of 10^6 years for a mass of 30 $\mathrm{M}_{\mathrm{Jup}}$ within 5 AU. A consequence of such large scale efficient migration is that survival of planetary systems may be a rather uncertain outcome (Ward 1997) unless a stopping mechanism exists preventing the planets from falling into their star (Lin *et al.* 1996; Rasio *et al.* 1996; Lubow 1996, Trilling *et al.* 1998).

Our current theories of the star formation process (see, e.g. the review of Shu *et al.* 1987) still lack a fundamental understanding of disk physics. While viscous dissipation is usually proposed as driving the evolution, this theory requires large viscosities to account for the short lifetime of disks around young stars (Zuckerman *et al.* 1995) and predict spectral energy distributions that are not observed. Various alternate mechanisms have been proposed among which figure spiral instabilities in the disk itself leading to gravitational torques driving the evolution over a few rotation timescales of the outer disk edge (Shu *et al.* 1990 and references therein).

We have performed a number of numerical simulations of the evolution of two-dimensional isothermal disks similar to the ones studied analytically by Adams *et al.* (1989) with masses $0.05 \leq M_{disk}/M_{*} \leq 1$ (Nelson *et al.* 1998). To disentangle numerical artifacts from true physical evolution, we used two drastically different but complementary numerical techniques (PPM and SPH). We have found that the instabilities predicted analytically are indeed present together with a host of higher order modes. Spiral patterns of increasing complexity with decreasing disk mass are seen in all simulations. In some cases, the instabilities are sufficiently vigorous to trigger local gravitational collapse. More recent calculations in which the disk was allowed to radiate (Nelson *et al.* 1999) show however that these local condensations are a consequence of the isothermal assumption.

We have studied the extend of radial migration of planets due to gravitational interactions with the disk and the central star. We model the migration by computing the net torque exerted on the planet by the disk and the spinning star. We also compute the internal structure of the planets as a function of time, mass and semi-major axis using models developed by Guillot *et al.* (1996). The mass transfer rate is obtained assuming a steady state and following Cameron & Iben (1986) and Benz *et al.* (1990).

These calculations (Trilling *et al.* 1998) show that planets can be divided in three categories depending on their mass and disk characteristics: (1) planets that migrate too quickly and lose all their mass, (2) planets which migrate inwards, lose some of their mass but survive at small radii and, (3) very massive planets that do not migrate very far at all.

2 Intrinsic stellar limitations to planet search with radial-velocity techniques

So far the discovery of extra-solar giant planets has essentially relied on the detection of radial velocity variations of solar-like stars. Since radial velocity variations can also be induced by motions of the photosphere due to pulsation and/or stellar activity-related variations like rotation of star spots or convective inhomogeneities and their temporal evolutions, it is very important to be able to distinguish between them. A quantification of those effects is possible by comparing, in the large planet-search surveys, the weighted radial-velocity dispersion (corrected from the mean internal error and orbital contribution from the known planets) with stellar characteristics like spectral type, rotation and magnetic activity (Saar *et al.* 1998; Mayor *et al.* 1998b; Queloz 1998). The amplitude of the radial-velocity variations associated with intrinsic phenomenons may reach a few tens of ms^{-1} and can possibly inhibit (when non-coherent) or confuse (on a few rotational or pulsation periods) planet detection (the semi-amplitude of the Jupiter perturbation on the Sun velocity is $\simeq 12.5\,\mathrm{ms}^{-1}$).

Stellar activity is the empirical impetus driving models of dynamo activity. In magnetic dynamo models, stellar activity is produced by the interaction of magnetic fields in or immediately below the subsurface convection zone with the motions of rotation and convection (e.g. Noyes *et al.* 1984, Baliunas *et al.* 1985). Saar *et al.* (1998) have shown a clear relation between stellar activity, estimated by R'_{HK}, the fractional Ca II HK flux corrected for the photospheric flux, and the level of non-orbital radial-velocity variations (Fig. 3, right). The same trend is observed with $v \sin i$, the projected rotational velocity (Fig. 3, left), what is expected, on the one hand, because of the coupling of high activity and rapid rotation in the magnetic dynamo model and, on the other hand, because of the line broadening due to stellar rotation that degrades the radial-velocity precision.

From this study it comes out that a substantial part of the initially selected sample, mainly the bluer ($B-V \leq 0.6$) and redder ($B-V \geq 1.3$) colour ranges, presents radial-velocity variations exceeding the long term accuracy claimed for the survey. Thus, in order to avoid the spurious velocity variations due to activity and false planetary detections associated with periodic radial-velocity changes induced by spots over a rotational period, a careful preselection of the star sample is mandatory when setting up a planet search programme. In addition to evolved stars known for their frequent intrinsic radial-velocity variations (pulsation or jitter), young rapidly rotating active dwarfs should be left over. From the ELODIE and CORALIE results, an empirical limit at $v \sin i = 4\,\mathrm{kms}^{-1}$seems adequate at their precision level. When available, an activity estimator (R'_{HK}) better than projected rotational velocity (confused by inclination effects) should be used. Such a selection will discriminate against F and early G dwarfs (rotation) and late M dwarfs (activity) but favour K dwarfs contrarily to the Lick star sample examined in Saar *et al.* (1998; their Fig. 1, left).

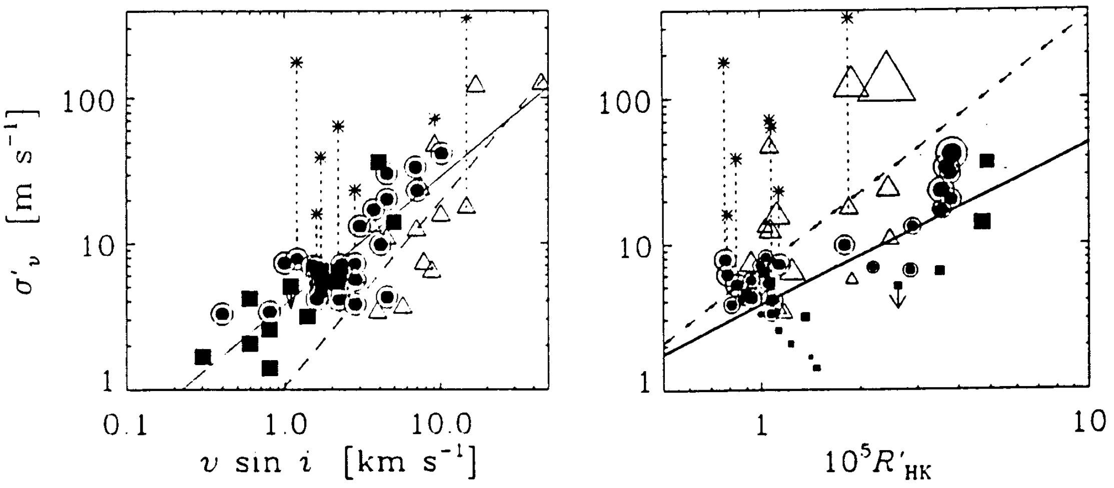


Figure 3: From Saar *et al.* (1998). **Left.** Radial-velocity dispersion (corrected from internal errors) vs rotational velocity. **Right.** Radial-velocity dispersion vs stellar activity

For large samples, the *a priori* stellar rotation and activity characteristics are not always available. However, already after the first measurement (at least for techniques with large spectral windows), an *a posteriori* check may be done. As an illustration, Fig. 4 displays the Ca II HK absorption lines, measured with ELODIE, in the case of a chromospherically active star (HD 166435) for which a stellar activity-related emission line is superimposed in the middle of the line (upper panel) and in the case of a "quiet" star showing no additional special feature (lower panel).

In case of periodic radial-velocity changes, stellar intrinsic variations have to be ruled out by checking the invariability of the bisector of the spectral lines (or cross-correlation function) and the invariability of the star luminosity, expected for velocity variations due to orbital motions. The star HD 166435 (Mayor *et al.* 1998c) varying with a period of a few days turned out to also phtometrically vary with the same period and so did the bisector of the cross-correlation function. The planetary explanation had thus to be rejected even if the variation period seemed to stay stable over several cycles. Such *a posteriori* verifications are fundamental taking into account that the lower limit of the radial-velocity jitter related to stellar activity, down to a 1 ms^{-1} precision, is still unknown.

This preselection strategy was already applied to the ELODIE and CORALIE samples for which projected rotational velocity and *large-amplitude* binary information were available from 20 years of CORAVEL lower-precision measurements.

We shall see in Sect. 6.2 that the number of stars meeting the required criteria for a high-accuracy planet-search sample selection is still very large, even if we restrict ourselves to the HIPPARCOS catalogue, incomplete for *faint* stars, but which gathers an unequalled

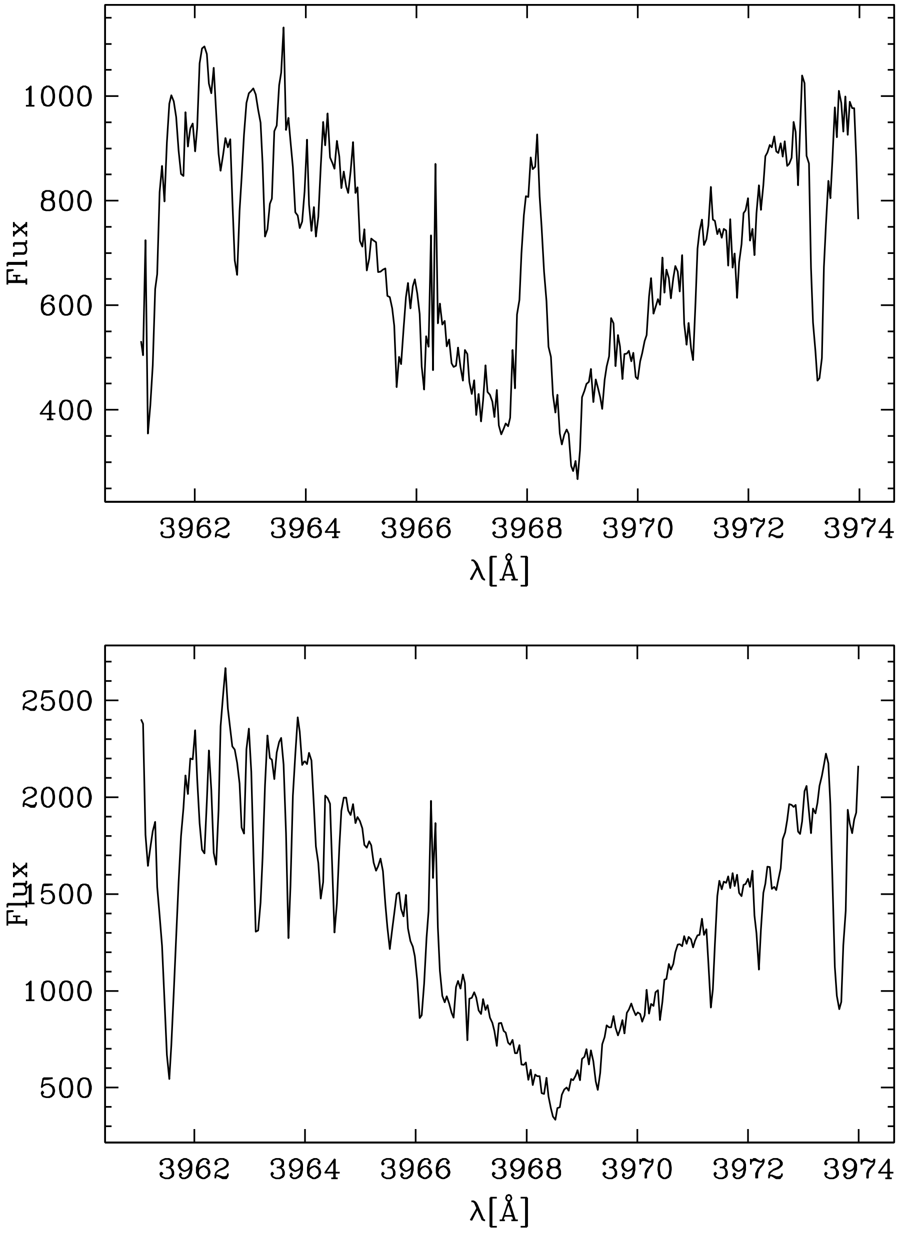


Figure 4: Ca II HK absorption lines measured with ELODIE. *Upper panel.* For a chromospherically active star (HD 166435) for which a stellar activity-related emission line is superimposed in the middle of the line. *Lower panel.* For a "quiet" star showing no additional special feature

set of useful stellar information.

3 Instrument Efficiencies

Table 1: Comparison table of instrument overall efficiencies. The coefficient Q_{night}/Q_{HARPS} represents the efficiency of the instrument to reach a given photon-noise precision per observing night, compared to HARPS, taking into account the telescope size, spectral band width ($\lambda\lambda$), resolution and transmission differences between the spectrographs. The used technique for radial-velocity measurements is indicated by *Iodine* for the Iodine cell method and by the number of fibres for the ThAr simultaneous method. Q_{year}/Q_{HARPS} corresponds to the same value integrated over 1 year taking into account the time allocation for planet search only

Instrument	Telescope diameter [m]	Spectrograph resolution	Technique	$\lambda\lambda$ [Å]	$\frac{N_{night}}{year}$	$\frac{Q_{night}}{Q_{HARPS}}$	$\frac{Q_{year}}{Q_{HARPS}}$
HARPS (ThAr)	3.60	100000	2 fibres	3000	100	1	1
HARPS (Iodine)	3.60	100000	Iodine	3000	100	0.16	0.16
CORALIE	1.20	50000	2 fibres	3000	200	0.01	0.02
FEROS	1.52	50000	2 fibres	5000	-	0.10	-
AFOE	1.50	56000	2 fibres	1500	100?	0.04	0.04
CES link	3.60	200000	Iodine	40	-	0.04	-
Hamilton (Lick)	3.00	100000	Iodine	1200	50?	0.12	0.06
HIRES (Keck)	10.0	80000	Iodine	1200	24	0.92	0.25
UCLES (AAT)	3.90	≥60000	Iodine	1200	20	0.10	0.02
UVES (VLT)	8.20	100000	Iodine	1200	-	0.86	-
UVES+FLAME link[a]	8.20	40000	5+1 fibres	3000	-	6.60	-

[a] Supposing one the fibres illuminated by a ThAr calibration lamp

The choice of the method of high-precision radial-velocity measurements proposed for HARPS, i.e. the simultaneous ThAr technique, is motivated in details in the *Technical Proposal* document. Its main advantage compared to the Iodine cell method resides in its smaller need in stellar photons to reach the desired photon-noise precision. The differences between the two methods translate into a factor of about 6 on the stellar flux: a factor of 2 coming from the absorption by the Iodine and a factor of 3 coming from the band width difference (Table 1). On the same facility and in the same integration time, the simultaneous ThAr method will thus allow us to measure stars more than two magnitudes fainter than stars observable with the Iodine technique. This has implications on the definition of the future observing programmes with HARPS (Sect. 6.2).

To compare the general efficiency of existing or under development experiments of high-precision radial-velocity measurements, we can define efficiency coefficients which integrate the technical specifications (telescope size, spectrograph transmission, resolution, used method, spectral window) and telescope time allocations. Table 1 gathers the corresponding information for the main available or soon available instruments. For comparison, a variant of HARPS with the Iodine cell technique is also considered in the table. It directly emphasizes the advantage of the ThAr simultaneous technique.

The coefficient Q_{night}/Q_{HARPS} represents the efficiency of the instrument to reach a given photon-noise precision per observing time unit (e.g. per night), compared to HARPS. It takes into account the band width, resolution and transmission differences between the spectrographs. The values in the table show that HARPS will be even more efficient than the spectrographs installed on 8-m class telescopes (whose long term accuracies, furthermore, do not reach the $1\,\mathrm{ms}^{-1}$ limit, at least for existing instruments). Only the VLT with the FLAME fibre links (and ThAr calibration lamp) would be better, mainly because of the multi-fibre configuration.

The HARPS supremacy is further enhanced when defining a coefficient per year, Q_{year}/Q_{HARPS}, integrating over the annual telescope time allocated for planet-search programmes on each instrument. That makes HARPS several times more efficient than any comparable experiment thanks to the large number of nights associated with the programme.

The efficiency coefficients are estimated without taking into account the overhead time for measurement setup which further enhance the position of HARPS (and CORALIE) with respect to larger photon collectors, for the brighter star observation. The star apparent magnitude is not considered either. For very faint stars (low S/N), the detector noise becomes important with regards to the stellar signal and large mirrors are then fundamental. This will make UVES unique for such observations.

4 Present Programmes of Extra-solar Planet Search

4.1 ELODIE/CORALIE surveys and successes

In collaboration with the groups from the Observatoire de Marseille and the Observatoire de Haute-Provence (OHP) the Geneva Observatory Planet-search group has built two spectrographs which are optimized for high-precision radial-velocity measurements (Baranne et al. 1996):

– the ELODIE spectrometer: CNRS instrument on the 193-cm telescope at the OHP;

– the CORALIE spectrometer: Geneva Observatory instrument installed on the L. EULER 1.2-m telescope at La Silla (Chile).

The spectrograph ELODIE achieves a precision that improved from about $12\,\mathrm{ms}^{-1}$ at the time of its installation to $8\,\mathrm{ms}^{-1}$ as a result of a "double scrambler" implementation on the optical fibres and a better thermal control of the spectrograph. In October 1995 it allowed the first detection ever of a planet orbiting a solar-type star, 51 Pegasi (Mayor & Queloz 1995). Since then, we have detected with ELODIE two additional giant planets at OHP. One is the companion of the very low-mass star Gl 876, a M4V star with 0.3 $M_\odot$ (Delfosse et al. 1998a). It is the closest known planetary system. This planet had been discovered and announced independently by the Lick/Keck observers (Marcy et al. 1998). The other planet has the largest period (P = 4.4 years) known for a non-solar planetary companion and is in orbit around the star 14 Herculis (Mayor et al. 1998c). We can also mention the important contribution of that survey to the discovery of companions with $m_2 \sin i$ in the mass range of brown dwarfs (Mayor *et al.* 1996).

At La Silla the new spectrometer CORALIE has been tested since June 1998. Already in its very first month of activity this new instrument has made a decisive contribution to the discovery of a planet around Gliese 876 (Delfosse et al. 1998a). Since then, two additional planets have been discovered with this instrument. The first one, announced through an ESO press release (ESO 1998b) end of November 1998, orbits the primary component of a spectroscopic binary system in 15.8 days. The second, orbiting the star HD 75289 with a period of 3.5 days, belongs to the "hot Jupiter" family and is therefore a good candidate for a transit search. With a mass of 1.4 times the mass of Saturn, it is the lightest extra-solar planet found to date. The phase-folded observed radial-velocity curve is shown in Fig. 5. The announcement of this discovery will be made beginning of February 1999.

The precision actually achieved with CORALIE is $\leq 3 - 4\,\mathrm{ms}^{-1}$ on a daily time scale and $\sim 6\,\mathrm{ms}^{-1}$ from night to night. The higher efficiency of CORALIE compared to ELODIE stems mainly from the higher resolution and the improved detector (smaller pixel size and higher sensitivity). Although the thermal control of our spectrograph has not yet reached the expected level of stability, it is nevertheless worth mentioning that the measurements obtained with our small 1.2- and 1.93-m telescopes are competitive in comparison to the

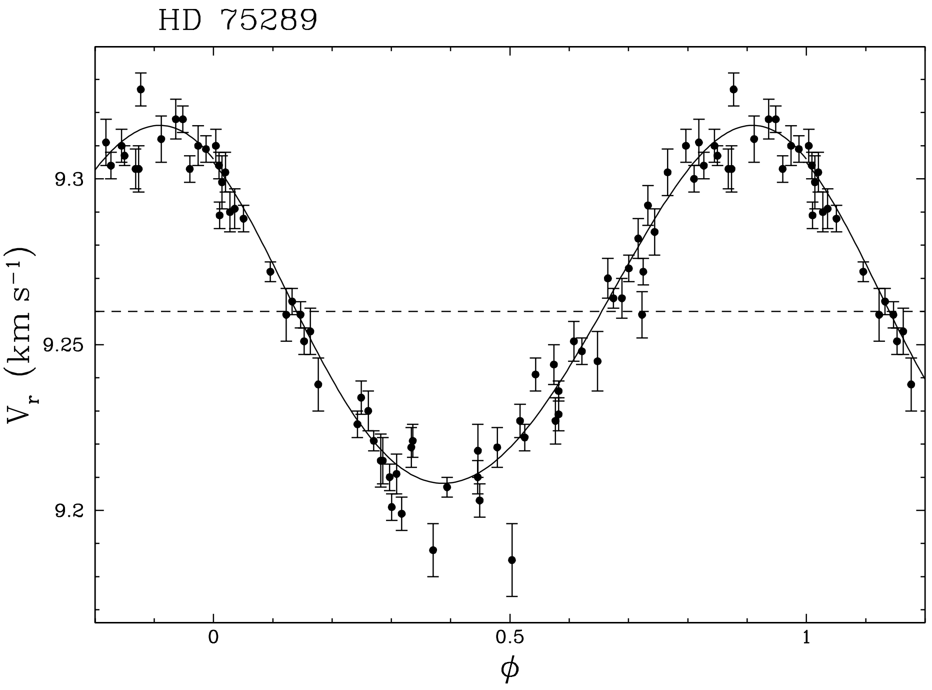


Figure 5: Phase-folded radial-velocity curve, measured with CORALIE, of the star HD 75289. The inferred planetary companion which circularly orbits the star in 3.5 days has a minimum mass 1.4 times the mass of Saturn

measurements obtained by Marcy and Butler with their 3- and 10-m telescopes at Lick and Keck Observatories.

The very encouraging results obtained with ELODIE and CORALIE demonstrate that we have not yet reached the limit of the technique. Higher precision radial-velocity measurements (down to 1 ms^{-1}) are still possible mainly by improving the stability of the spectrograph in addition to increasing the resolution.

To explore more deeply the possible formation scenarios for planets and brown dwarfs, the orbital element distributions of both populations have to be determined much better. There are basically two ways to improve the statistics. First, to get detections more rapidly and to remove detection biases in the distributions (towards high masses and short periods), the precision of the radial-velocity surveys has to improve. This is the major impetus behind the HARPS project. Second, the sample size of the surveys may be enlarged. This is under way. We are now following a large number of stars with ELODIE and CORALIE. The different programmes are divided up as follows:

– Our programme for extra-solar planet search carried out since April 1994 at the OHP consists of a sample of 320 solar-type stars (Mayor *et al.* 1999). Some 80 stars, which represent 25%(!) of the total sample, exhibit significant radial-velocity variability (previously undetected long-period spectroscopic binaries, brown-dwarf companions, giant planets and intrinsic stellar variability) letting us expect new discoveries as the time base of the survey extends.

– A similar survey for the M dwarfs closer than 9 pc to the Sun (about 120 stars) is also carried out with ELODIE. Even if the primary goal of this survey is to determine the binary frequency among very low-mass stars (Delfosse *et al.* 1998b, 1999), it has the capability of detecting giant planets as illustrated by the recent discovery of the planetary companion of Gl 876 (Delfosse *et al.* 1998a).

– In the southern sky, a volume-limited sample of about 1650 G and K dwarfs of the solar vicinity was selected from the HIPPARCOS catalogue among which about 1000 stars are good targets for the CORALIE planet search programme i.e. they display no CORAVEL radial-velocity variations at a 300 $\mathrm{ms^{-1}}$ precision level, no large activity or rotation (which correlate with intrinsic radial-velocity variations) or had no previous measurements. The 3-year survey of this sample will help to define a "clean" programme sample for HARPS to explore at a precision unreachable with CORALIE. **HARPS will be the unique instrument to explore a sample of stars below a 5 $\mathbf{ms^{-1}}$ velocity variation level.**

4.2 Concurrent Programmes in the Southern Sky

Several concurrent programmes are carried out in both hemispheres. The more important ones, aiming towards the less explored southern sky, are the followings:

– With one of the 10-m Keck telescope in Hawaï, Marcy *et al.* follow 430 stars at a $\sim 5\,\mathrm{ms^{-1}}$ precision level. The Hawaï latitude allows them to observe stars in the southern sky above $\delta = -30°$. The weakness of their programme is the *small* number of nights per year dedicated to the survey (20 nights/year). They thus bring a special attention to the most equatorial part of the sky, allowing a follow up of the detected candidates from the Lick Observatory where they carry out, with a similar precision, a survey of 300 stars (Fischer *et al.* 1999), some of which belonging to the two programmes. The fruitfulness of their strategy is illustrated by the recent announcements of 5 new extra-solar planets: HD 217107 and HD 195019 (Fischer *et al.* 1999), HD 210277 and HD 168443 (Marcy *et al.* 1999), and HD 187123 (Butler *et al.* 1999).

– In the more southern sky, this team, around P. Butler, has also set up a planet-search programme with the AAT in Australia. They monitor 150 stars but with only 20 nights per year of allocated time. The reached precision for radial-velocity measurements seems to be slightly higher than 5 $\mathrm{ms^{-1}}$.

The two mentioned programmes concurrent to HARPS in the southern hemisphere, if very good according to the obtained radial-velocity precision (although not reaching the HARPS hopes), lack the substantial observing time allocation, mandatory to be very efficient from a *statistical* point of view.

In addition to the Lick, Keck and AAT surveys, (handled by the same team). Several other programmes are carried out in the northern hemisphere. They mainly monitor small numbers of stars (≤ 100) at a moderate precision (10-15 $\mathrm{m\,s^{-1}}$).

5 Detection probability and observing strategy

One of our main scientific goal with the HARPS project is to provide a large and statistically significant observational data base from which (with the help of theoretical models) the key physical processes underlying planetary formation can be inferred.

As with any large astronomical survey, the scientific interpretation of the results rests for a large part on a rigorous statistical description of the data set. Of great interest is therefore not only an optimum measurement scheduling but also the knowledge of the *a priori* detection probability of planets as a function of physical parameters such as planet mass, semi-major axis of its orbit, distance to the sun, etc. This probability is the key ingredient to determine the fraction of stars in the solar neighborhood having planetary companions as well as the statistical significance of trends that may be observed in the data.

To address these issues, we are developing a method based on a Monte Carlo approach which allows us to determine the planet detection probability for a given observing strategy on a given telescope with a given instrument. For the sake of brevity, we only summarize our approach here which is based on the formalism developed by Nelson & Angel (1998). A given set of radial velocities under the form $v(t_i) \pm noise$ is generated by the computer and fitted by a family of functions $f_P(t)$, where P is a variable period used as a parameter. It turns out that the norm of f_P shows a peak when the period matches that of the actual system. To assess whether this peak is the signature of a real signal or simply due to noise, its height is compared to a reference function $f_{ref}(P, N_{obs}, P_{obs}, X_{proba}, \sigma_{noise})$ given by theory. This function depends on the total number of observations N_{obs}, the duration of the survey P_{obs}, the probability of detection X_{proba} and the noise contained in the data. The comparison of the height of the peak and the theoretical function gives the probability that the signal is real and not due to noise.

Practically, a given planetary system is generated and "observed" under a large number of inclinations with respect to the line of sight. These inclinations are drawn randomly with a uniform deviate. The noise function has two components. Firstly, an *intrinsic noise* which is itself the sum of instrumental contributions (resolution, stability, etc.) as well as intrinsic stellar effects (intrinsic jitter or activity). The second source of noise is due to *photon noise* which depends on the brightness of the source, the telescope, etc. The actual intrinsic precision of HARPS will only be known after tests, but we adopted a nominal value of $1\,\mathrm{ms}^{-1}$. Intrinsic stellar variations probably prohibit any better accuracy. To illustrate the benefits associated with such a high resolution, we also considered a $10\,\mathrm{ms}^{-1}$ intrinsic noise. Photon noise is calculated from the expected signal to noise ratio obtained from photon statistics. The resulting radial velocity error for a given signal to noise is obtained by scaling results obtained for ELODIE and CORALIE to HARPS.

To illustrate the typical results we obtain with this approach we present Fig. 6 which displays the detection probability of planets by HARPS given an intrinsic noise of $1\,\mathrm{ms}^{-1}$ and

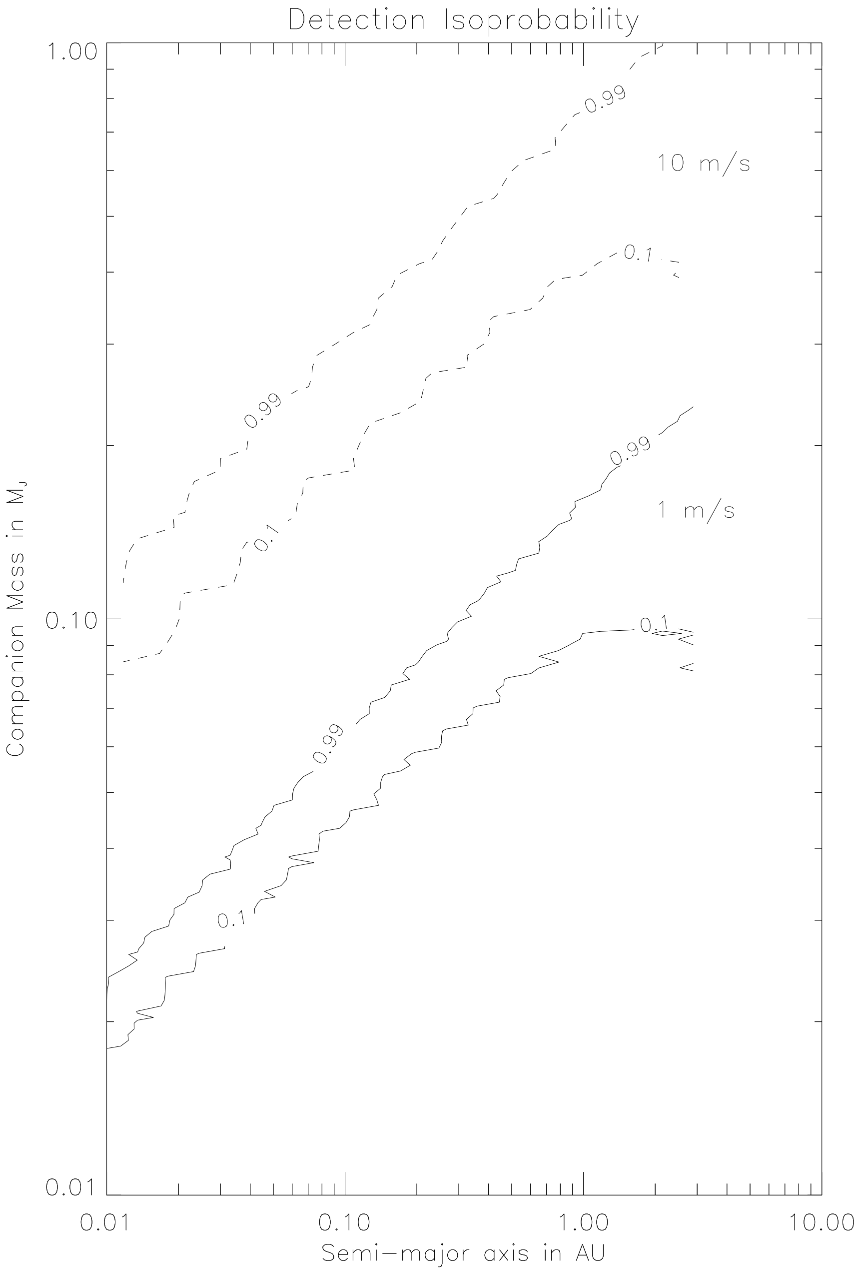


Figure 6: Isoprobability contours of detecting a planet on a circular orbit around a solar-like star located at 50 pc with 10 measures distributed uniformly over a period of 5 years. An intrinsic noise $\sigma_{intrinsic} = 1\,\mathrm{ms}^{-1}$ (solid lines) and $\sigma_{intrinsic} = 10\,\mathrm{ms}^{-1}$ (dashed lines) was assumed

$10\,\mathrm{ms}^{-1}$ and various companion masses and semi-major axis. The star was assumed to be solar-like and located at 50 pc and planets to be on circular orbits. We assumed 10 measures of 5 minutes each distributed uniformly over a period of 5 years.

Note that with $1\,\mathrm{ms}^{-1}$ intrinsic noise and this measurement strategy, all Saturn-like planets orbiting this type of star within 3 AU will be detected after 5 years of observing. The 3 AU limit being given not by the instrumental capabilities but by the 5 year observing period. Without this time limit, we would be complete out to about 5.5 AU. Comparatively, with $10\,\mathrm{ms}^{-1}$ we can only hope to detect all Saturn-like planets out to 0.08 AU regardless of an extension of observing time. Identical calculations but allowing for an eccentricity of 0.3 shows very little change in these results.

A related question consists in determining the optimum observing strategy to detect the planets most *efficiently*. For example, is it more efficient to begin the measurement of a given star with a relatively high frequency and subsequently lower it appropriately if no or little radial velocity variations have been observed? We are currently addressing this question using this formalism.

Finally, we would like to emphasize that *detection* is not equivalent to *orbit determination*. More measurements are needed to derive the orbital parameters, especially for small-amplitude or eccentric orbits. Therefore part of the foreseen measurements will have to be devoted to the orbit follow up of the detected candidates (Sect. 6.2).

6 Science with HARPS

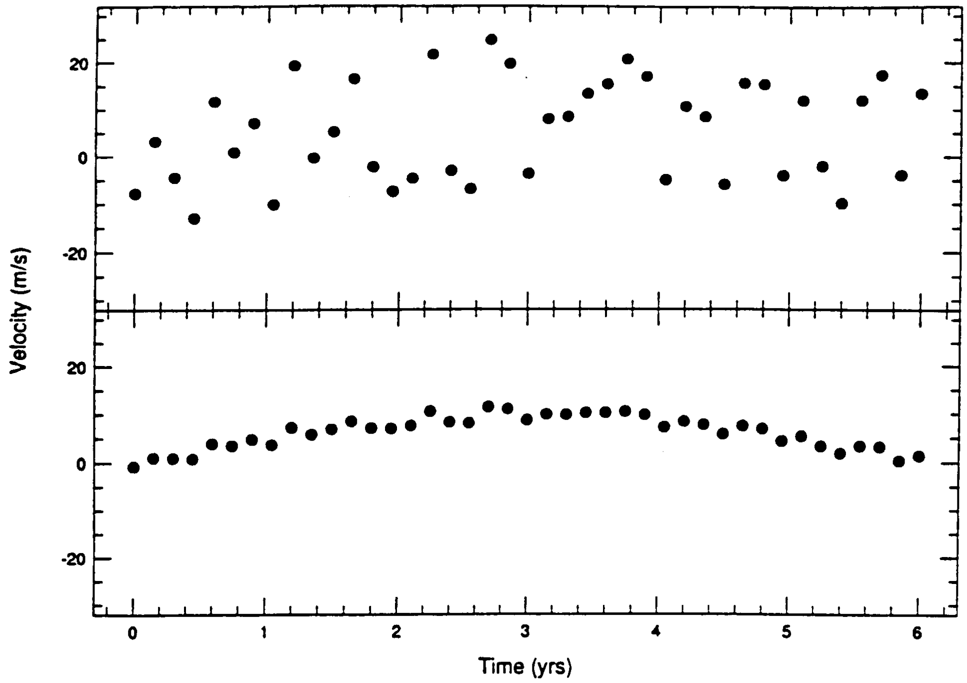
6.1 Scientific Motivations for HARPS

The improvement in the precision of radial-velocity measurements from 5-10 ms^{-1} down to 1 ms^{-1} will largely contribute to remove biases in the detection of extra-solar planets (see also above). As the amplitude of the radial-velocity variations scales with the mass of the planetary companion, a 1 ms^{-1} precision will permit the detection of very light "giant" planets (a few tenths of Saturn, although terrestrial planets will stay beyond reach). This is especially important in the case of planetary systems for which the influences of several companions add up blurring the observed signal for instruments with inadequate resolution. An illustrative example is given in Fig. 7 (taken from ESO 1997) displaying the simulated observed radial-velocity change of the Sun due to the presence of Jupiter and Saturn, measured over periods of 6 and 35 years with precisions of 10 and 1 ms^{-1}. The 1 ms^{-1} precision allows a Jupiter detection in 6 years and the Saturn effect is visible on a longer timescale. With the 10 ms^{-1} precision Jupiter is just accessible with a large time base whereas Saturn stays beyond reach.

Another illustration of the expected enlargement of the reachable parameter space of planetary orbits with HARPS is shown in the $(a,\log(m_2 \sin i))$ diagram displaying the star-planet separation vs the minimum planetary mass (projected mass)(Fig. 8). Detection limits at given radial-velocity precisions are indicated as well as expected detection limits from precise astrometric measurements, for a star at 10 pc. In the large "overlapping" region, precise real mass determinations are potentially available by combining the two techniques.

HARPS will thus bring a major contribution for the determination of good distributions of planetary orbital elements which are the key tools for a better understanding of the formation and the evolution of these systems. This is especially true thanks to the large telescope-time allocation (number of nights and time base for the survey) associated with the HARPS project that is fundamental to get a good detection rate and follow up of the orbits.

A natural by-product of the survey will be the determination of targets for the future interferometric programmes (VLTI) and space missions (SIM, GAIA, DARWIN).



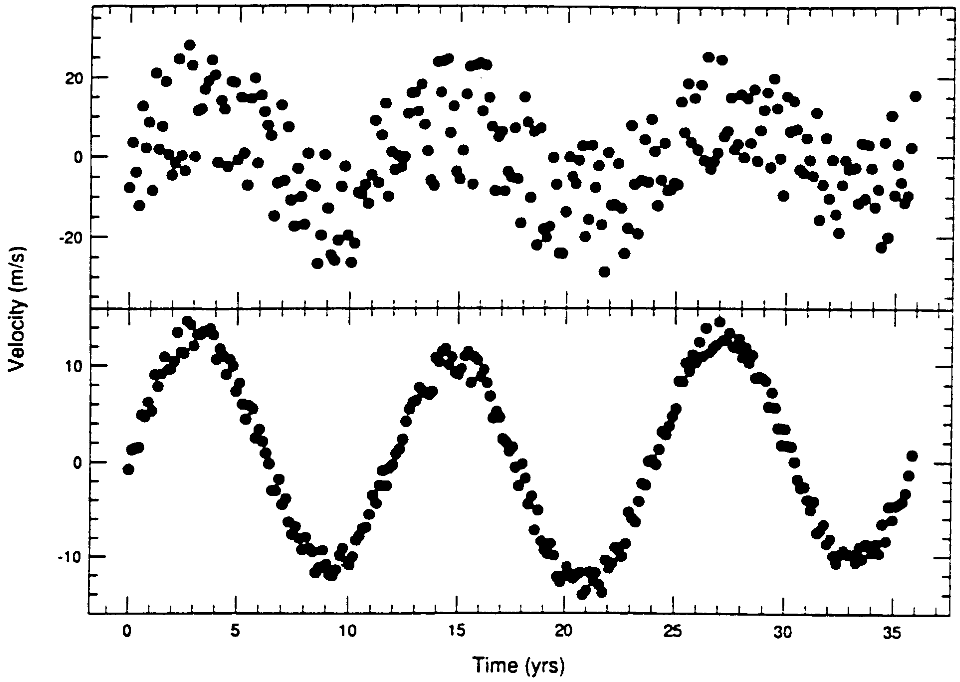


Figure 7: Simulated observations of the solar radial-velocity changes due to the perturbations of Jupiter and Saturn over periods of 6 (upper panels) and 35 years (lower panels), with precisions of 10 (upper diagrams in the panels) and 1 ms^{-1} (lower diagrams in the panels)

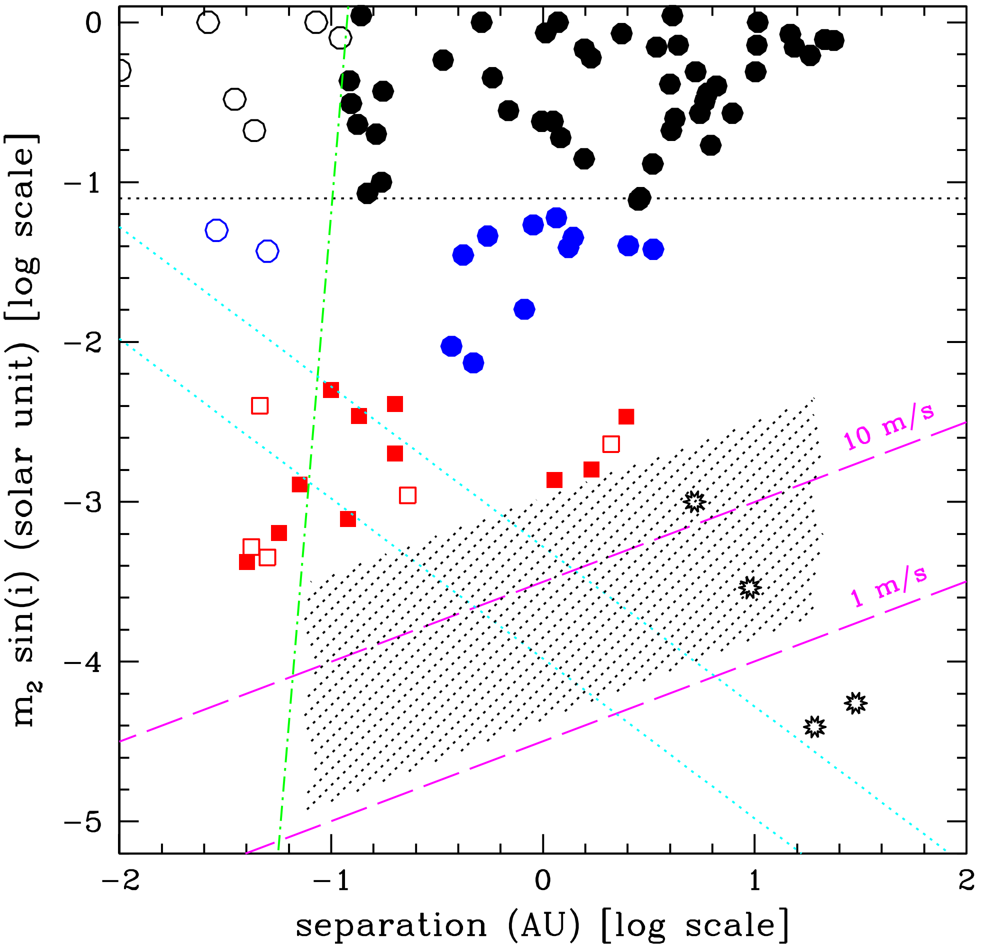


Figure 8: Distribution of projected masses of the companions of stars as a function of their separations ($f(a, m_2 \sin i)$). Stellar (black) and sub-stellar (blue) companions of G and K dwarfs of the solar vicinity are identified by open and filled circles for circular and eccentric orbits, respectively. The four giant planets of our Solar System (Jupiter, Saturn, Neptune and Uranus) are plotted with star-like symbols. The red squares represent the extra-solar giant planets. The horizontal dotted line at $\log(m_2 \sin i) = -1.1$ corresponds to the hydrogen-burning limit ($m_2 \simeq 0.08\,M_\odot$). On the left-hand side of the green dotted-dashed line, orbits are circularized by tidal dissipation (short periods). The inclined pink dashed lines indicate detection limits for radial-velocity surveys of different accuracies ($10\,\mathrm{ms}^{-1}$ and $1\,\mathrm{ms}^{-1}$). The radial-velocity search with HARPS will explore the hatched domain in the figure. The inclined dotted blue lines indicate the future possibilities of detection by precise astrometric techniques (differential interferometry) with 10 μarcsec and 50 μarcsec precision levels (reflex motion of a star at 10 pc)

6.2 Number of Potential Targets for HARPS

The most evident targets for our foreseen survey are the stars of the solar vicinity. The best existing source of potential targets is thus provided by the HIPPARCOS catalogue. In Fig. 9 we have plotted the HR diagram of HIPPARCOS stars with precise trigonometric parallaxes ($\sigma_\pi/\pi \leq 10\%$), south of $\delta = 20°$ (accessible from La Silla). On the main sequence alone we have a huge reservoir of about 3000 G dwarfs, 1500 K dwarfs and 350 M dwarfs. Very blue stars with $B - V \leq 0.5$ should not be considered as stellar rotation – related to stellar activity – prevents planet detections (see Sect. 2). All evolved stars ($\delta M_v \geq 1\,\mathrm{mag}$ with respect to the main sequence) have to be rejected due to their intrinsic variability. Finally, to provide targets for future interferometric measurements with the VLTI or further space missions, we have to give a preference to stars at close distances from the Sun.

The cumulative distribution of distances of such a defined sample (non-evolved stars with precise trigonometric parallaxes in the HIPPARCOS catalogue) is shown in Fig. 10. More than 3500 G- to M-dwarf stars are closer than 50 pc.

If we want to derive distributions of orbital parameters for a significant sample of stars, we have to limit the mean integration time for a single measurement to short exposures. Figure 11 (bottom) illustrates the cumulative distribution of the apparent magnitudes of G, K and M dwarfs with $\sigma_\pi/\pi \leq 10\%$, $d \leq 50\,\mathrm{pc}$ and $\delta \leq 20°$ in the HIPPARCOS catalogue. In the upper diagram of the same figure we have drawn the expected photon noise after a 5-minute integration time for G and K dwarfs (HARPS corresponds to the line at a $1\,\mathrm{ms}^{-1}$ precision) and after 15 minutes for M and halo stars. The photon noise is a function of the Signal-to-noise ratio (S/N), the band width ($\lambda\lambda$), the spectrograph resolution (R) and the spectral type of the target star via the contrast of the cross-correlation dip (H):

$$\varepsilon_{Vr} \simeq \frac{C(\lambda\lambda,\, R)}{S/N\, H}.$$

With an optimized numerical template, the typical contrast of the cross-correlation dip of G and M dwarfs is 0.15, but could be as high as 0.25 for K dwarfs. At the opposite, low metallicity stars could have quite small contrasts, as small as 0.05 or less for extreme deficient stars. We remark that by good seeing conditions almost all G and K dwarfs of the sample can be measured at $1\,\mathrm{ms}^{-1}$ with an integration time as short as 5 minutes.

It is also worth noticing that a less efficient spectrograph using a Iodine absorption cell (Sect. 3) and a limited range of wavelengths (1200 Å instead of 3000 Å) will have access to a much smaller stellar sample, for a given integration time. A loss of 2 magnitudes or more will drastically diminish the number of potential targets.

Some 350 M dwarfs could be measured at a reduced precision of $2\,\mathrm{ms}^{-1}$ with 15-minute integration time. This precision is maybe adapted to the measurements of these slightly variable stars. The exact level of the M-dwarf activity-related jitter is still unknown.

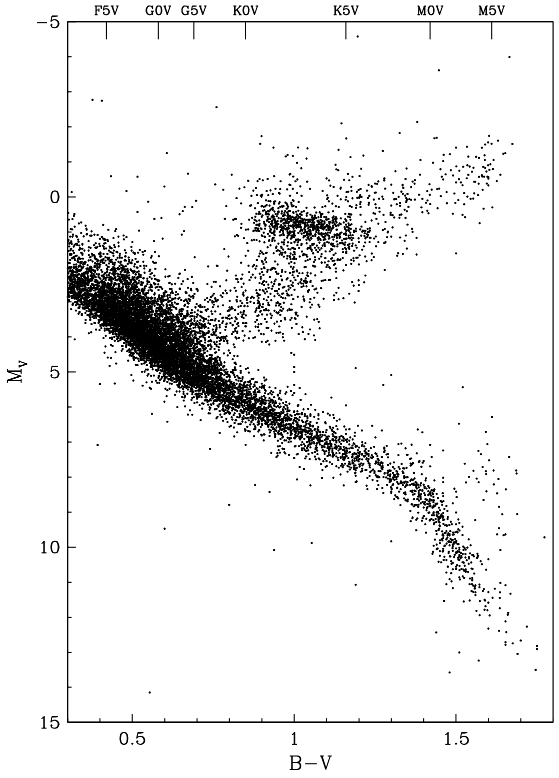


Figure 9: HR diagram for the stars in the HIPPARCOS catalogue with precise parallaxes ($\sigma_\pi/\pi \le 10\%$) and $\delta \le 20°$

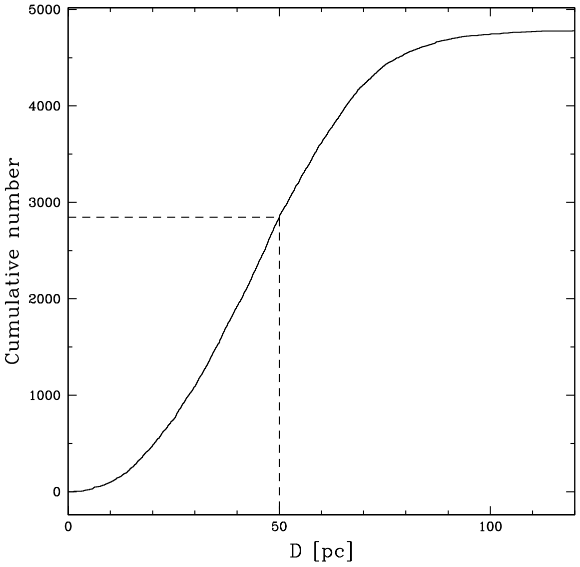


Figure 10: Cumulative distribution of distances for the non-evolved G, K and M stars in the HIPPARCOS catalogue with precise trigonometric parallaxes and $\delta \le 20°$

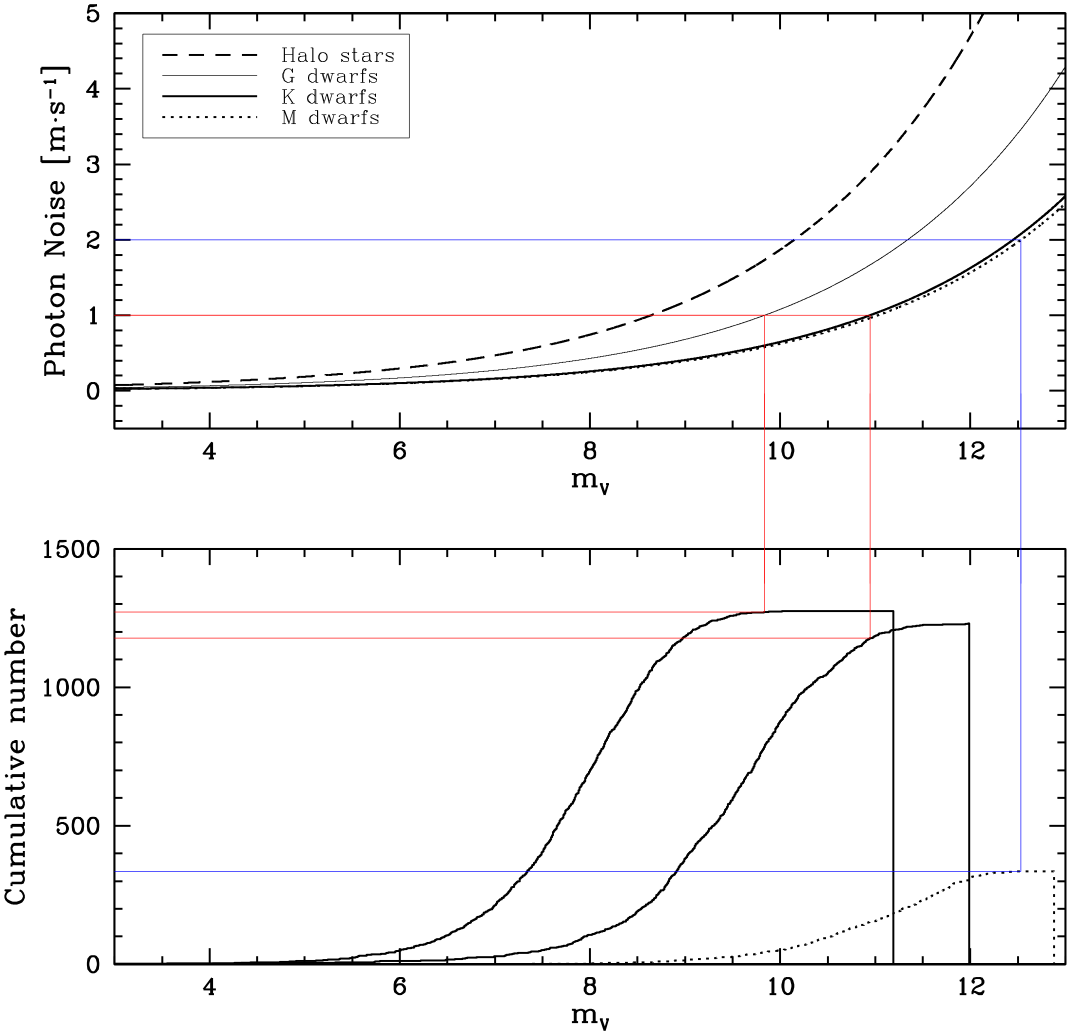


Figure 11: *Upper panel.* Photon-noise precision reached after 5-minute integration for G (solid line) and K (bold solid line) stars and after 15 minutes for M (dotted line) and halo (dashed line) stars as a function of the star magnitudes. *Lower panel.* Cumulative distributions of magnitudes of G, K and M dwarfs from the HIPPARCOS catalogue with $\sigma_\pi/\pi \leq 10\%$ and $\delta \leq 20°$

If we define a stellar sample after selection of only the non-active stars, we have a potential list of targets (G to M dwarfs, $d \leq 50\,\mathrm{pc}$) of more than 2000 stars accessible from La Silla ($\delta \leq 20°$).

If we admit an overhead of 5 minutes per telescope-spectrograph setting, we still have the possibility to get 5 measurements per hour. A rough estimate shows that on a 5-year programme about 15000 precise measurements will be done:

$$100 \text{ nights/year x } 5 \text{ years x } (2/3) \text{ x } 9 \text{ hours/night x } 5 \text{ mes./hour} \simeq 15000 \text{ mes},$$

the (2/3) factor standing for meteorological bad conditions.

If the stellar jitter really allows measurements at the 1-2 ms^{-1} level, the real breakthrough of the HARPS survey will be in the still unexplored region of small-amplitude velocity variations (and long periods; Fig. 8). The observing strategy will require about ten measurements per star on the full span of the survey (+ additional measurements for the follow up of detected variable stars). To have an unbiased detection at the extreme precision level of 1 ms^{-1}, we have to restrict the size of the programme sample to about 1000 targets.

Taking into account the existing large-size surveys in progress in the "southern" hemisphere at a precision of 5-10 ms^{-1} (Sect. 4), the HARPS survey has really to explore the domain only accessible at the 1 ms^{-1} level, taking advantage of the available information from the previous programmes.

Halo Stars

The magnitude distribution of halo stars combined with the very small contrast of cross-correlation dips of deficient stars drastically limit the radial-velocity precision for those targets. At a limited precision of 5 ms^{-1}, deficient stars as faint as $m_V = 12$ could be in the capabilities of HARPS, with 15-minute integration times (Fig. 11).

The already discovered exoplanets are found around rather metal-rich stars (Gonzales 1998, Fig 2). The frequency of giant planets to be found around halo stars could be very low. It is however not clear if this low frequency will also be the rule for less massive planets.

6.3 Orbital Parameters, Mass, Metallicity

The prime goal of this 5-year survey will be to built the $f(a,\, e,\, m_2,\, [Fe/H])$ distribution, the distribution of orbital elements as a function of the masses of the planets and the metal content of the parent stars. This function is expected to bring constraints on the formation mechanisms of giant planets. For example:

- We would like to have an unbiased distribution of the masses of hot Jupiters $f(a < 0.1\,\mathrm{AU},\, m_2)$, as a test of the orbital shrinking.

- We would like to determine the distribution of parent star metallicities as a function of planetary masses $f(m_2,\, [Fe/H])$. This function is maybe helpful to clarify the transition from giant planets to brown dwarfs. We could expect a better defined mass function (from an unbiased sample) and an upper limit for the mass of giant planets.

- We have mentioned the function $f(a,\, e,\, m_2,\, [Fe/H])$. We would try to get deeper constraints on formation mechanisms by searching signatures of chemical anomalies as a function of the planetary masses and orbital separations ($f(m_2,\, a,\, [\chi_i/H])$).

Existing extra-solar planets have been detected from radial-velocity variations larger than $40\,\mathrm{ms}^{-1}$ and corresponding masses as small as 0.4 Jupiter mass ($\mathrm{M_J}$). With HARPS, planetary masses as light as 0.1 $\mathrm{M_J}$ will be detectable.

6.4 Planetary Systems ($N_{\mathrm{planets}} \geq 2$)

A drift of the velocity of the star-planet system (γ-velocity) has been detected for three of the detected exoplanets: 55 Cnc (Butler *et al.* 1996), HD 166443 (Fischer *et al.* 1999) and Gliese 86 (ESO 1998b). These drifts result from the existence of a stellar companion. For the time being, the radial-velocity measurements have not revealed possible γ-drift due to a second planet.

All the planets detected in the southern sky (mostly expected from our CORALIE survey) will be followed with HARPS at higher accuracy and then scrutinized year after year to search for possible γ-drift.

6.5 Mean Density of 51 Peg-type Planets?

The short-period extra-solar planets have a significant probability to transit in front of the stellar disk. That probability is close to 10 % for the shortest periods. To date, already 6 exoplanets have been detected with periods less than 10 days (51 Peg, υ And, τ Boo, HD 187123, HD 217107 and HD 75289). The photometric monitorings at the predicted transit times have not revealed the expected 1 % drop of the stellar flux. A positive detection (to be expected with the increasing number of 51 Peg-type planets) will allow the direct estimate of the mass and radius of the planet. A direct measurement of the mean density ($\bar{\rho}$) of these *strange* exoplanets is therefore possible. With good photometry a determination of $\bar{\rho}$ with a precision better than 10 % is certainly feasible and offers a direct constraint on the structure of these extra-solar planets.

The possibility offered by HARPS of finding lighter exoplanets whose internal structure is governed by a complete different Hydrogen equation of state will bring, in the cases of short periods ("hot Saturn") revealing transits, strongly dynamizing observational constraints in a still largely unexplored field.

Complementary Observations to the COROT Space Mission

The space mission COROT (CNES, France) has been designed to allow an extremely precise photometric monitoring of a large sample of stars. The two driving goals of that mission are asterosismology on the one hand and the search for planetary transits on the other hand.

The photometric sensitivity is large enough to permit detections of planet masses much lower than the mass of Jupiter. Scaled on the frequency of short-period planets discovered by the Doppler surveys, a hundred or more planetary transits are expected from the COROT mission. Most of these stars will be K dwarfs with magnitudes between 11 and 15.

A photometric transit is not a proof by itself of the presence of an exoplanet, the radius of a Jupiter being rather similar to the radius of a brown dwarf or of a M star at the very bottom of the main sequence. The determine the mass of the companion, we have to measure the radial-velocity variation of the star. From the masses and the radii of the detected candidates we will access the mean densities of a sample of about 100 giant planets or more: an exceptional source of information for the physics of the interior of giant planets.

The efficiency of HARPS is perfectly suited for such follow up observations. A 15-minute integration of a 15th magnitude star will give a signal-to-noise of about 10. For a K-dwarf such a moderate S/N is sufficient to get errors on the radial velocities of about $5\,\mathrm{ms}^{-1}$. Such a precision is quite sufficient to derive precise velocity curves for low-mass stellar companions or brown dwarfs and also efficient to have a fair estimate of the planetary mass. 25 HARPS measurements of a 15th magnitude star with a short-period exoplanet of mass of $0.2\,\mathrm{M_J}$ will be sufficient to estimate the planetary mass to a 5% accuracy.

6.6 Do not forget the Brown Dwarfs

The HARPS survey will be oriented towards the detection and study of giant planets. However, we can also expect a few detections of brown-dwarf candidates ($\sim 7\,\mathrm{M_J} < m_2 \sin i < 75\,\mathrm{M_J}$). These rare objects are of interest to precise the lower limit of their masses.

Already now, brown dwarfs offer the first possibilities of combining astrometric and radial-velocity measurements to get the orbital plane inclination and thus real mass determinations. Interestingly enough, most of brown-dwarf candidates exhibit a non-negligible astrometric reflex motion, seen by the HIPPARCOS mission. A majority of these systems have a rather low orbital inclination and therefore a stellar (instead of substellar) companion at the bottom of the main sequence! This study carried out in collaboration with F. Arenou and J.-L. Halbwachs reveals a significant gap in the mass distribution between stars and giant planets (Mayor *et al.* 1998d).

7 Science with HARPS not devoted to the Search and Study of Extra-solar Planets

HARPS has been designed and optimized for an efficient search for extra-solar planets. The consortium science team will use the garantied time only to search and study exoplanets. However, HARPS is a high-resolution echelle spectrometer with a broad wavelength domain perfectly suited for an unlimited range of scientific applications.

For normal spectroscopy, HARPS can be considered as complementary to UVES for stars bright enough. To acquire radial velocities of individual targets (not in dense fields for which GIRAFFE or the UVES link have to be considered) HARPS will offer extremely competitive possibilities. The broad band cross-correlation technique is able to provide rather precise radial velocities for very faint stars. For most stars velocities will be determined with a precision close to $100\,\mathrm{m\,s^{-1}}$ with signal-to-noise as small as S/N=1.

HARPS will offer unique possibilities to study:

- faint pulsating stars in the LMC, SMC and globular clusters
- faint spectroscopic binaries of special interest (eclipsing binaries in globular clusters or LMC, X-ray sources, stars at the bottom of the main sequence, etc)
- the Doppler monitoring of spectroscopic binaries to provide precise stellar masses in combination with the VLTI measurements
- study of the low-amplitude pulsating stars (e.g. γ Dor-type stars)
- radial velocities of faint halo stars to study the structure of our Galaxy
- etc.

Asterosismology

HARPS will also be a unique instrument to derive the acoustic modes of a few bright stars of the southern hemisphere.

Studies of global solar p-mode oscillations have provided novel measurements of several properties of the Sun, including the depth of the convection zone, the gradient of the molecular weight, and the internal dynamics. The success of helioseismology, particularly by using integrated sunlight in probing the deepest layers, encourages corresponding investigations of other stars and promises new test of the theory of stellar structure and evolution. So far the only observational constraints on theoretical models of stellar interiors have been comparisons between measured total luminosity, spectrum shape, stellar radii and predicted values for stars of known masses. Of special interest is then application of asterosismology to

Sun-like stars which refer to stars on or near the main sequence that have relatively shallow convection zones that might experience p-mode oscillations similar to those found in the Sun. Probing the internal structure of these stars should constrain the models of convection. Even more directly, accurate oscillation data might provide a confrontation with the theory of stellar structure; by comparing observed frequencies (and other stellar observable) with those predicted by theory, one may hope to assess the importance of phenomena that are not included in traditional treatments of stellar evolution. The application of pulsation analysis techniques to solar-like stars is difficult because of extremely small variations in intensity and velocity associated with the pulsation modes and need to have adequate temporal coverage to resolve the modes of interest.

Oscillations of stars that lie in and on the hotter side of the instability strip in the stellar color-magnitude diagram have been well studied, because the large amplitudes allow ready detection with appropriate instruments. However, for stars on the cool side of the instability strip lying near the main sequence, the oscillations are expected to have amplitudes akin to those of the Sun, namely about 0.1 - $0.3\,\mathrm{ms}^{-1}$ in disc integrated Doppler shift, and 3 - $5 \cdot 10^{-6}$ in disc-integrated relative intensity. Given the apparent faintness of star relative to the Sun, it is major technological problem to detect the small amplitude oscillations in the face of photon noise, guiding error, mechanical and other instrumental instabilities. There are principally 2 methods for detecting global stellar oscillations: one method is to measure the changes in the integrated intensity of the star resulting from oscillations using very precise relative photometry and the other technique is to detect the them by measuring the Doppler shift of spectral lines. Photometric methods must confront atmospheric fluctuations (unless conducted from space) and differential photometric methods attained almost their limit in the experience of Gilliland et al. (1993) using a network of large (4m) telescopes. Many searches for stellar oscillations have been using spectroscopic methods. But so far none of the claimed oscillation spectrum has been convincing, with the exceptions of the work of the AFOE group at CfA (Brown 1998) and the latest observations of Procyon at OHP with ELODIE spectrograph in November 98 shown on Fig. 12 (Martic et al. 1999). The wavelength reference was the channelled spectrum of white light recorded on the second fiber, simultaneously with the stellar spectrum. This technique is new and seems to offer a great potential in this field.

Using a large number of lines observable with traditional echelle spectrograph like HARPS will allow for very precise overall measurements. One is however dependent on the mechanical and thermal stability of the spectrograph at least for times comparable to the oscillation period of the star under observation. The photon noise-limited Doppler sensitivity attainable from a stellar spectrum is proportional to the number, optical depth and narrowness of its absorption lines. This favors later stars, as the number of deep lines decreases rapidly with spectral type for star hotter than the Sun; It also rules out rapid rotators since excessive

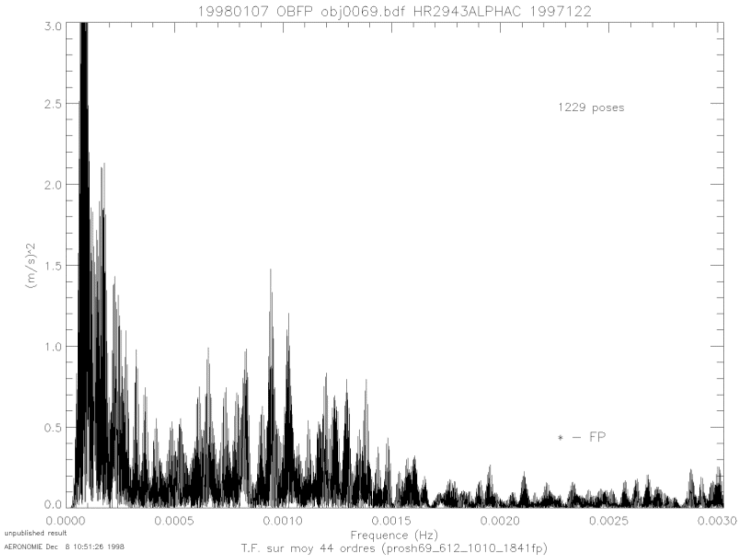


Figure 12: Oscillation spectrum of Procyon as observed at OHP with the ELODIE spectrograph in November 1998

rotational broadening smears out the absorption lines and diminish utility for Doppler measurements. A time series of spectroscopic Doppler Observations with good signal-to-noise, high spectral resolution and broad wavelength coverage should be provided with HARPS echelle spectroscopy.

Requirements of asterosismology with HARPS include the capability to make a long series of spectra for several consecutive nights, with a short time interval between exposures (less than one minute). Though these requirements were not taken as design drivers in our HARPS study, we made sure that HARPS can indeed make exposures as short as 15 s, with a CCD readout time of 5 s and the possibility to make a long series of exposures without any interruption.

Two aspects may be emphasized here:

- there is a considerable improvement of asterosismology measurements when several telescopes at various longitudes may look at the same star in a network fashion. Though in the Southern Hemisphere, there is a significant band of latitude that can be observed by both La Silla and OHP (which includes Procyon). Therefore, stars could be observed in conjunction with HARPS at other locations, in particular with ELODIE or EMILIE at OHP for a more extended period of time.

- CNES is preparing the COROT space mission (to be launched in 2002), which will monitor the intensity oscillations of many stars for several months continuously. Therefore, some of the stars that have been detected to produce oscillations in intensity could also be observed in radial velocities for a complementary set of physical constraints.

8 Operations

8.1 The Scientific Team

A scientific team (ST) of about a dozen astronomers is foreseen to take the full responsibility of the HARPS survey. This survey will be conducted as one single programme by the whole team and not as the addition of a few distinct programmes. The ST will have the responsibility for:

- The maintenance of the spectrograph itself.
- The maintenance of the control and reduction software.
- The preparation and update of the input list of targets.
- The observations with HARPS.
- The complementary observations if needed (photometric. monitoring, adaptive optics imagery, interferometric astrometry, etc).
- The full reduction and archiving of the observations as well as their quality control.
- The distribution to the astronomical community, upon request, of the high-resolution spectra measured during the survey.
- The analysis and interpretation of the measurements
- The update of the scientific goals of the survey depending on the progresses expected in the field of the formation and physics of giant planets.

Our past experience with ELODIE (25 % of observing time of the OHP 1.93-cm telescope) and more recently with CORALIE ($\sim$ 50 % of the nights of the L. EULER Swiss telescope at La Silla) has shown that a limited team, with members devoting a large fraction of their time to a single programme, can easily and efficiently handle a large observing survey.

8.2 Data Archiving and Access Policy

The complete raw data will be archived: calibration as well as scientific frames. The spectra (S2D) will also be archived. At the end of the observing nights, the local database (in the dome) will be updated as well as the automatic level of priority given to all the stars of the programme.

As the scientific goals of the core-survey imply a monitoring of several years, we do not foresee a public access to the obtained velocities during the span of the programme. However, it is also true that this huge set of high S/N spectra could be of interest for many scientific goals not related to the search and study of extra-solar planets. One year after the measurements we would be glad to give free access, upon request, to these spectra.

8.3 Maintenance

Due to the extreme stability expected over 5 years or more for HARPS – a mandatory condition for the success of the survey – we suggest that the maintenance of the spectrograph, detector, cryogeny and vacuum system be on the full responsibility of the scientific team. ESO technical staff should only act for maintaining operation on the different elements after explicit and written agreement by the person of the ST in charge of the maintenance.

Every time a major technical problem appears on the system, the consortium has to send at La Silla the competent people to fix the problem. For all operations related to the bonnette, special protection and care should be brought to the optical fibres.

8.4 Report to ESO executives and OPC

We propose that progresses of the commissioning phase and scientific programme be reported to ESO executives and OPC:

- one report at the end of the commissioning phase
- one report every year during the 5-year span of the observing phase.

All these reports have to be delivered on written form to ESO and, upon request, also through an annual oral presentation to the OPC.

9 References

Adams, F.C., Ruden, S.P., & Shu, F.H., 1989, ApJ 347, 959

Baliunas, S., Horne, J., Porter, A., *et al.* , 1985, ApJ 294, 310

Baranne, A., Queloz, D., Mayor, M., *et al.* , 1996, A&A Suppl. Series 119, 373

Beckwith, S., & Sargent, A., 1996, Nature 383, 139

Benz, W., Bowers, R.L., Cameron, A.G.W., & Press, W.H., 1990, ApJ 348, 647

Boss, A., 1995a, Nature 375, 13

Boss, A., 1995b, Nature 377, 578

Boss, A., 1997, Science 276, 1836

Brown, T., 1998 in 10^{th} Cambridge Workshop on "Cool stars, stellar systems and the sun", Ed. R. Donahue, J. Bookbinder, ASP Conf. Series, p.289

Butler, R.P., & Marcy, G., 1996, ApJ 464, L153

Butler, R. P., Marcy, G. W., Williams, E., et al., 1996, PASP 108, 500

Butler, P., Marcy, G., Vogt, S., Apps, K., 1999, PASP Research Note, submitted

Cameron, A.G.W., & Iben, I.Jr., 1986, ApJ 305, 228

Chabrier, G., Saumon, D., Hubbard, W.B., & Lunine, J.I., 1992, ApJ 391, 817

Delfosse, X., Forveille, T., Mayor, M., Perrier, C., Naef, D., & Queloz D., 1998a, A&A 338, L67

Delfosse, X., Forveille, T., Beuzit, J.-L., Udry, S., Mayor, M. & Perrier, C., 1998b, in *Precise stellar radial velocities*, IAU 170, ASP Conf. Ser., Eds. Hearnshaw J. & Scarfe C.

Delfosse, X., Forveille, T., Beuzit, J.-L., Udry, S., Mayor, M. & Perrier, C., 1999, A&A in press

ESO, 1997, Final Report on the ESO WG on the Detection of Extrasolar Planets, Doc. No.: SPG-VLTI-97/002

ESO, 1998a, Announcement of Opportunity for HARPS, Garching May 20, 1998

ESO, 1998b, Press Release, November 24, 1998

Fischer, D., Marcy, G., Butler, P., Vogt, S., Apps. K., 1999, PASP, in press

Goldreich, P., & Tremaine, S., 1980, ApJ 241, 425

Goldreich, P., & Soter, S., 1966, Icarus 5, 375

Gonzales, G., 1998, A&A 334, 221

Guillot, T., Burrows, A., Hubbard, W.B., Lunine, J.L., Saumon, D., 1996, ApJ 459, L35

Hartmann, L., Calvet, N., Gullbring, E. & D'Allessio, P., 1998, ApJ 495, 385

Hayashi, C., 1981, Prog. Theor. Phys. Suppl. 70, 35

Lin, D.N.C., & Papaloizou, J., 1986, ApJ 309, 846

Lin, D.N.C., & Papaloizou, J., 1993, in *Protostar & Planets III*, eds. E. Levy & J.I. Lunine (Tucson: University of Arizona Press)

Lin, D.N.C., Bodenheimer, P., & Richardson, D.C., 1996, Nature 380, 606

Lubow, S.H., Tout, C.A., & Livio, M., 1996, ApJ 484, 866

Marcy, G., & Butler, R.P., 1996, ApJ 464, L151

Marcy, G., & Butler, R.P., 1998, ARAA 36, 56

Marcy, G., Butler, R.P., Vogt, S., Fischer, D., & Lissauer, J., 1998, ApJ 505, L147

Marcy, G., Butler, P., Vogt, S., Fischer, D., Liu, M., 1999, ApJ, submitted

Martic, M., Schmitt, J., Lebrun, J.C., Barban, C., Connes, P., Michel, E., Baglin, A., Bertaux, J.L., 1999, A&A, to be submitted

Mayor, M., Queloz, D., 1995, Nature 378, 355

Mayor, M., Queloz, D., Udry, S., 1996, in *Astronomical and biochemical origins and the search for life in the universe*, IAU coll. 161. Eds. C. Cosmovici, S. Bowyer and D. Werthimer

Mayor, M., Udry, S., Queloz, D., 1998a, in 10^{th} Cambridge Workshop on "Cool stars, stellar systems and the sun", Ed. R. Donahue, J. Bookbinder, ASP Conf. Series, p.77

Mayor, M., Queloz, D., Udry, S., 1998b, in "Brown Dwarfs and extra-solar Planets", Tenerife, ASP Conf. serie, Eds. R. Rebolo, E.L. Martin, M.R. Zapatero Osorio

Mayor, M., *et al.* , 1998c, in "Protostars and Planets IV", Santa Barbara, Oral presentation

Mayor, M., *et al.* , 1998d, in "Extrasolar Planets. Formation, Detection and Modelling", Lisbonne. Eds. R. Agostinho and F. Santos

Mayor, M. *et al.* , 1999, in *Precise stellar radial velocities*, IAU 170, ASP Conf. Ser., Eds. Hearnshaw J. & Scarfe C.

Nakajima, T., Oppenheimer, B.R., Kulkarni, S.R., Golimowski, D.A., Matthews, K., & Durrance, S.T., 1995, Nature 378, 463

Nelson, A., Benz, W., Adams, F., & Arnett, D., 1998, ApJ 502, 342

Nelson A.F. & Angel, J.R.P., 1998, ApJ, 500, 940

Nelson, A., Benz, W., & Ruzmaikina, T., 1999, ApJ, submitted

Noyes, R., Hartmann, L., Baliunas, S., *et al.* , 1984, ApJ 279, 763

Oppenheimer, B.R., Kulkarni, S.R., Matthews, K., & Nakajima, T., 1995, Science 270, 1478

Pollack, J.B., Hubickyj, O., Bodenheimer, P., Lissauer, J.J., Podolak, M., & Greenzweig, Y., 1996, Icarus 124, 62

Queloz, D., 1998, in "Planets outside the Solar System", NATO ASIS, Cargèse. Eds. J.-M. Mariotti & D. Alloin

Rasio, F.A., & Ford, E.B., 1996, Science 274, 954

Rasio, F.A., Tout, C.A., Lubow, S.H., & Livio, M., 1996, ApJ 470, 1187

Rhie, S.H., *et al.* , 1999, AAS Meeting 193, Austin, Texas

Ruzmaikina, T., 1998, Lunar and Planetary Sciences XXIX, 1873

Saar, S., Butler, P., Marcy, G., 1998, ApJ 498, L153

Shu, F., Adams, F.C., & Lizano, S., 1987, ARAA 25, 23

Shu, F., Tremaine, S., Adams, F.C., & Ruden, S.P., 1990, ApJ 358, 495

Shu, F.H., Najita, J., Ruden, S.P., & Lizano, S., 1994, ApJ 429, 797

Strom, S., 1994, in *Cool Stars, Stellar Systems and the Sun*, 8th Cambridge Workshop, p. 211 (San Francisco: Astronomical Soc. Pacific)

Trilling, D., Benz, W., Guillot, T., Lunine, J.I., Hubbard, W.B., Burrows, A., 1998, ApJ 500, 428

Walker, G.A.H., Walker, A.R., Irwin, A.W., Larson, A.M., Yang, S.L.S., & Richardson, D.C., 1995, Icarus 116, 359

Ward, W.R., & Hourigan, 1989, ApJ 347, 490

Ward, W., 1997, ApJ 482, L211

Weidenschilling, S., & Marzari, F., 1996, Nature 384, 619

Wildi, F., 1998, Technical report No. OBSGE-ELOD-FPM-001, Observatoire de Genève

Wuchterl, G., 1993, Icarus 106, 323

Wuchterl, G., 1996, BAAS 28, 1108

Zuckerman, B., Forveille, T., & Kastner, J.H., 1995, Nature 373, 494