# The ESO radial velocity planet search program

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**Abstract.** We give an overview of current search programs for extra-solar planets using high precision radial velocities. Gemini's possibilities in this new field are identified. Pending instrumental developments at ESO are discussed in terms of their promise for RV measurement precision as well as important stellar line profile studies. Preliminary results are shown from the planet search program carried out at the ESO CAT+CES with data on the candidate extra-solar planets around $\iota$ Hor and $\phi^2$ Pav.

**Instrumentation.** Future fibre-fed spectrograph with $R > 120,000$; required wavelength range $5100 - 5900$ Å; $R > 200,000$; if fibre-fed: image quality not crucial, AO not required; special calibrations: iodine gas absorption cell.

## 1. Introduction

The search for extra-solar planets has become a science priority for ESO. Various techniques are being evaluated and developed, with high-precision radial velocities (RV) being the method immediately available. Identifying the reflex motion of a star around the barycenter with a planetary companion, this indirect method has recently led to the first burst of discoveries of planetary mass companions to solar-type stars. Table 1 summarizes these discoveries ordered according to orbital period $P$. Also listed are the RV semi-amplitude $K$, the minimum companion mass $m \sin i$, the orbital semi-major axis $a$ and eccentricity $e$, and the discovery and confirmation papers.

The extra-solar planet most closely resembling Jupiter in our own solar system is the companion to 47 UMa in a cicular orbit at 2.1 AU from its host star. All other long-period objects have high eccentricities, and two of them (70 Vir and HD 114762) have been named "superplanets" due to their very high mass. Especially for HD 114762 it cannot be excluded that it is a brown dwarf in a low inclination orbit.

| Host star | $P$ [day] | $K$ [m/s] | $m \sin i$ [$\mathrm{M_{Jup}}$] | $a$ [AU] | $e$ | discoverer (confirmer) |
|---|---|---|---|---|---|---|
| 47 UMa | 1088 | 45.5 | 2.3 | 2.1 | 0.08 | BM96 |
| 16 Cyg B | 801 | 43.9 | 1.5 | 1.68 | 0.67 | C97 |
| 70 Vir | 117 | 318 | 6.6 | 0.43 | 0.40 | MB96 |
| HD 114762 | 84 | 616 | 9 | 0.38 | 0.38 | L89 (C91) |
| $\rho$ CrB | 39.6 | 67 | 1.1 | 0.23 | 0.028 | N97 |
| $\rho^1$ Cnc | 14.7 | 77 | 0.84 | 0.11 | 0.05 | B97 |
| $\upsilon$ And | 4.6 | 71 | 0.68 | 0.05 | 0.11 | B97 |
| 51 Peg | 4.2 | 56 | 0.5 | 0.046 | 0.02 | MQ95 (M97) |
| $\tau$ Boo | 3.3 | 469 | 3.87 | 0.057 | 0.02 | B97 |

**Table 1: RV signals in solar-type stars and their interpretation as planets**

The discovery of the short-period Jupiter mass planets (lower half of Table 1) had not been anticipated. However, it is worth noting that RV searches are still biased towards the discovery of these objects due to the involved high radial velocity amplitudes for relatively low-mass objects as well as the possibility to find such an object in relatively short time. Not included in Table 1 are the several brown dwarf candidates found with precision radial velocities by Mayor et al. (1997).

An overview of planet search surveys via high-precision radial velocities that are currently ongoing or planned for the near future is given in Table 2. Within a few years the number of clear discoveries can be expected to become large enough to begin statistical analyses of the properties of extra-solar planets and planetary systems.

The particular scientific perspectives of the considerable efforts undertaken in this field include obtaining information on

1) the star and planet formation process,
2) the mass function from stars to brown dwarfs and further down to planets,
3) the dependence of planetary properties on stellar properties,
4) the minimum mass for hydrogen burning stars,
5) brown dwarfs as contributors to the missing mass of the galactic disk and halo.

Being an indirect method the precision radial velocity technique needs to be checked against instrinsic stellar variability as the possible cause of the apparent radial velocity modulation. To do this a time series of stellar line profiles must be studied at very high resolving power ($R > 200,000$) in order to see the variability of the line shape (or line bisector) as opposed to a pure shift of the line as a whole. While the latter is the typical effect arising from a companion to the star, the former effect cannot be caused by an orbiting low-mass object at a separation of $\approx 10$ stellar radii such as 51 Peg. Contrary to an earlier claim by Gray (1997) and Gray & Hatzes (1997)

| Observatory/instrument<br>(Investigators) | # of stars | Types (dwarfs) | Start | Accuracy |
|---|---|---|---|---|
| Keck HIRES<br>(Marcy, Butler et al.) | 400 | late F to late K | July 1996 | $\approx 2$ ms$^{-1}$ |
| Lick 3m Shane or CAT<br>+ Hamilton Echelle<br>(Marcy, Butler et al.) | 120 | late F to M | 1987 | $\geq 3$ ms$^{-1}$ |
| AAO 3.9m<br>(Butler, Marcy et al.) | 150 | late F to K | Sept. 1997 | $\geq 3$ ms$^{-1}$ |
| Keck HIRES & follow-up<br>with AFOE/CORALIE<br>(Latham et al.) | 1000 | late F to G | mid-1997 | planned precision $\approx 10$ ms$^{-1}$ |
| Haute Pr. 1.93m + ELODIE<br>(Mayor, Queloz, Sivan,<br>Mariotti, Perrier, Beuzit) | 350 | G and K | 1994 | Feb. 97 upgrade to 7 ms$^{-1}$ |
| Swiss 1.2m at La Silla<br>+ CORALIE<br>(Mayor, Queloz, Udry et al.) | 800 | late F to late K | June 1998 | expected precision 5 ms$^{-1}$ |
| Whipple 1.5m + AFOE<br>(Noyes et al.) | 100 | solar-type | mid-1996 | 10 ms$^{-1}$ |
| Hobby Ebberly Tel. + HRS<br>(Cochran, Hatzes) | 300 | mid-F to late G | Sept. 1998 | $3 - 10$ ms$^{-1}$ |
| McDonald 2.7m + Coudé<br>(Cochran, Hatzes) | 30 | late F to late K | 1987 | 20 ms$^{-1}$ |
| ESO CAT/3.6m + CES<br>(Kürster, Hatzes, Cochran,<br>Dennerl, Döbereiner, Endl) | 35 | late F to M | Nov. 1992 | $10 - 20$ ms$^{-1}$ plans for $1 - 2$ ms$^{-1}$ |

**Table 2: Planet search surveys using precision radial velocities**

that the signal in 51 Peg might be attributed to non-radial velocities, more recent measurements of the line bisectors of this star (Gray 1998; Hatzes et al. 1998) failed to confirm this finding. Another concern is stellar activity, since star spots can lead to line shape changes with the stellar rotational period, and varying granulation patterns produce line shape changes over the activity cycle. Lacking sufficient resolving power these effects could be interpreted as radial velocity shifts (Saar & Donahue 1997).

## 2. Relevance to Gemini

If it can be equipped with an iodine cell for self-calibration (see Sections 3 and 4), Gemini's high resolution optical spectrograph HROS could probably be used for a similar radial velocity search program. A concern is the usual flexure problem in Cassegrain mounted instruments. It would have to be seen whether instrumental profile modelling (Butler et al. 1996) would be sufficient to overcome this problem. With a resolving power of $R = 50,000$ HROS will not be suitable to check possible candidate objects for intrinsic stellar variability via high resolution line profile (line bisector) studies. These will require a future fibre-fed spectrograph with very high resolution (see Kurz 1997); this instrument should then be designed for $R > 200,000$.

## 3. ESO's resources for high precision radial velocities

The working ESO instrument for high-precision radial velocities is the CES at La Silla, an Echelle spectrograph fed from the Nasmyth focus of the 1.4m ESO CAT telescope. A prismatic pre-disperser currently allows only part of one single Echelle order to be recorded. The current f/4.7 Long Camera provides $R = 100,000$. Self-calibration with an iodine gas absorption cell and subsequent modelling of the combined star+iodine spectrum currently yields a working long-term RV measurement precision of $\approx 20$ ms$^{-1}$ for a 30 min exposure of a 5.5 mag solar-type star. We are presently improving our modelling procedure by including the modelling of the instrumental profile aiming at a gain in accuracy by a factor of $2-3$ (see Butler et al. 1996).

In May 1997 a fibre-link from the CES to the ESO 3.6m will become available as well as the new f/12.5 Very Long Camera to achieve $R = 220,000$. With the future possibility to use a more sensitive and larger CCD we estimate that the above value of the radial velocity measurement precision can be improved down to $\approx 3$ ms$^{-1}$. The feasibility to cross-disperse the CES is currently studied in an attempt to obtain a working precision in the $1-2$ ms$^{-1}$ regime. Alternatively, the construction of a new stabilized spectrograph for the ESO 3.6m is discussed that would be designed for the goal to achieve this measurement precision.

Further resources that we will have at ESO for precision RV surveys include the new fibre-fed and stabilized Echelle spectrograph FEROS ($R = 48,000$) to be installed at the ESO 1.5m near the end of this year (Kauffer 1997), the Echelle spectrograph UVES ($R \leq 100,000$) for unit telescope 2 of the Very Large Telescope (VLT) at Paranal (Dekker & d'Odorico 1995), and the cryogenic infrared Echelle spectrograph CRIRES ($R = 100,000$) for the VLT that has just been given high priority. CRIRES holds the promise to discover direct signatures of planetary spectra (Wiedemann 1996). All these instruments, with the possible exception of the stabilized spectrograph FEROS, will require the use of a gas absorption cell for self calibration.

| Star | V [mag] | Type | Star | V [mag] | Type |
|---|---|---|---|---|---|
| $\zeta$ Tuc | 4.23 | F9V | $\beta$ Hyi | 2.80 | G2IV |
| HR 209 | 5.80 | G1V | $\nu$ Phe | 4.96 | F8V |
| HR 448 | 5.76 | G2IV | HR 506 | 5.52 | F9V |
| HR 753 | 5.82 | K3V | $\tau$ Cet | 3.50 | G8V |
| $\kappa$ For | 5.20 | G0Va | $\iota$ Hor | 5.41 | G0V |
| $\alpha$ For | 3.87 | F8V | $\zeta^1$ Ret | 5.54 | G3-5V |
| $\zeta^2$ Ret | 5.24 | G1V | $\epsilon$ Eri | 3.73 | K2V |
| $\delta$ Eri | 3.54 | K0+IV | $\alpha$ Men | 5.09 | G6V |
| HR 2400 | 5.60 | F8V | HR 2667 | 5.54 | G3V |
| HR 3259 | 5.98 | G7.5V | HR 3677 | 5.86 | G0V |
| GJ 433 | 9.79 | M2V | HR 4523 | 4.91 | G3V |
| HR 4979 | 4.85 | G3V | Prox Cen | 11.05 | dM6e |
| $\alpha$ Cen A | -0.01 | G2V | $\alpha$ Cen B | 1.33 | K1V |
| HR 5568 | 5.74 | K4V | HR 6416 | 5.48 | G8–K0V |
| Barnard | 9.54 | dM5 | HR 6998 | 5.86 | G4V |
| HR 7373 | 5.16 | G8IV | HR 7703 | 5.32 | K3V |
| $\phi^2$ Pav | 5.12 | F8V | HR 8323 | 5.58 | G0V |
| $\epsilon$ Ind | 4.69 | K4–5V | HR 8501 | 5.37 | G3V |
| HR 8883 | 5.64 | G4V | | | |

**Table 3: Program stars in the precision RV program at the ESO CES**

## 4. Preliminary results from the ESO planet search program at the CES

Our precision radial velocity program was begun in November 1992 at the ESO 1.4m CAT and the CES spectrograph (at $R = 100,000$) used with a temperature stabilized (at 50° C) low-pressure iodine gas absorption cell (Kürster et al. 1994). Recording $\approx 48$ Å at a central wavelength of 5389 Å we routinely achieve a long-term precision of $20 - 25$ ms$^{-1}$ for stars brighter than 6 mag. Our best case long-term precision is up to 10 ms$^{-1}$ for brighter stars.

A histogram of the absolute scatters of our differential radial velocities is shown in Figure 1 for data from the first four years of our 20 best observed stars. This histogram has not been corrected for observing conditions and includes data with varying signal-to-noise ratio. It thus reflects the "working conditions" in our survey work rather than our best case precision. Should there be genuine radial velocity variability in some stars an attempt to determine the measurement precision from this histogram alone would err on the side of overestimating the errors.

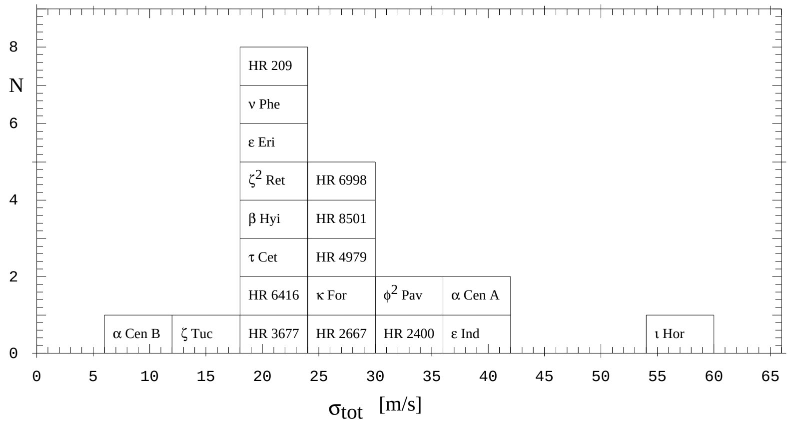

**Figure 1.** Histogram of absolute RV scatter for our 20 best observed stars

As we have shown elsewhere (Hatzes et al. 1996) three of our stars, HR 2400, HR 3677, and $\kappa$ For, exhibit strong long-term variability in the form of linear trends for HR 2400 and HR 3677 and a slightly curved trend for $\kappa$ For. With out four year data set we can exclude substellar companions as the cause of this variation due to the large observed radial velocity range ($K >> 500$, 950, and 2600 $\mathrm{ms}^{-1}$ for HR 2400, HR 3677 and $\kappa$ For, respectively) and the high lower limit to the period ($P >> 4$ yr). We most likely have discovered three previously unknown M dwarfs. Before including these three stars in the histogram (Figure 1) we subtracted the long-term trends.

The G0V star $\iota$ Hor (=HR 810) turns out to be a highly significant variable when compared with the sample (Figure 1) via an F-test. However, period analysis using the Lomb-Scargle algorithm (Scargle 1982) does not reveal a very significant period. The best period is near 600 d, but its false alarm probability is still $> 10\%$ (estimated using a bootstrap randomization scheme following Murdoch et al. 1993; see also Kürster et al. 1997). Our formal best-fit orbit for $\iota$ Hor yields $P = 599$ d, $K = 52.1$ m/s, $e = 0.49$, $m \sin i = 2.0$ $\mathrm{M_{Jupiter}}$. Figure 2 (left panel) shows our RV data folded with this period and the orbital fit. The residuals from this orbit are rather high, the r.m.s. scatter being $\sigma = 42.3$ m/s, which may indicate either a second signal in the data or a different nature of the variability.

The rotation period of $\iota$ Hor was estimated from CaII data to be 7.9 d by Saar & Osten (1997) and 8.6 d by Saar et al. (1997). This makes $\iota$ Hor quite an active star. It is possible that the high scatter is largely due to star spot induced line profile deformations (see Saar & Donahue 1997). We will test this hypothesis with the new $R = 220,000$ camera of the CES. Should the planetary signal be real but seen through activity induced scatter, several more of the 600 d cycles must be observed for a significant discovery.

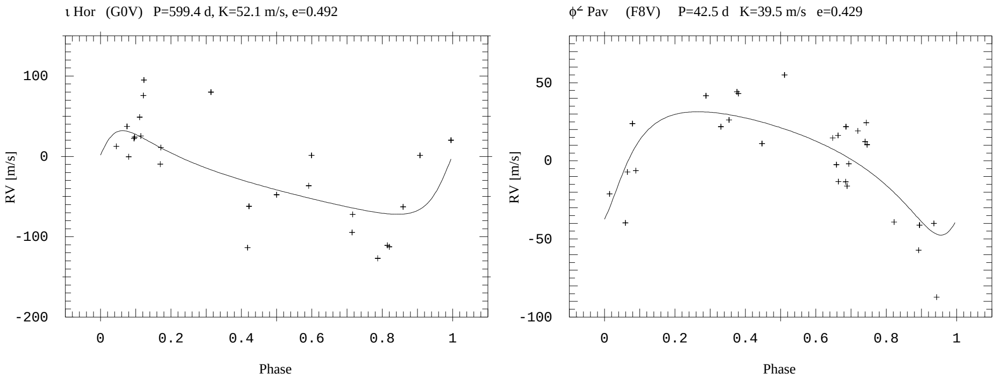

**Figure 2.** RV measurements for $\iota$ Hor (left) and $\phi^2$ Pav (right) folded with the respective best period

Our best candidate so far for having an orbiting planet is the F8V star $\phi^2$ Pav (=HR 7875). Period analysis yields a best period of 42.46 $\pm 0.10$ d with a false alarm probability of 4 permille (or '2.9$\sigma$'). The best-fit orbit is shown in Figure 2 (right panel) together with our RV measurements for $\phi^2$ Pav. The residuals from this fit scatter by 20.4 ms$^{-1}$. The corresponding orbital parameters $K = 39.5 \pm 6.0$ ms$^{-1}$ and $e = 0.43 \pm 0.18$ imply a minimun companion mass of $m \sin i = 0.69^{+0.11}_{-0.15}$ M$_{\rm Jupiter}$ assuming a mass of 1.2 M$_\odot$ for a main-sequence F8 star. The semi-major axis of this possible companion is $0.286 \pm 0.054$ AU which would thus orbit $\phi^2$ Pav at about 3/4 of the Sun-Mercury separation (0.387 AU).

In case the signal for $\phi^2$ Pav is real we should be able to announce a significant discovery with some further measurements. Should we manage to obtain the desired factor $2-3$ in improvement of the measurement precision via instrumental profile modelling (Section 3) the significance of any real signal will be substantially increased.

## 5. Conclusions

1) High-precision radial velocities have so far been the most successful method to search for extra-solar planets.
2) A total of $> 2000$ solar-type stars will soon be monitored enabling future statistical studies of the properties of extra-solar planets and planetary systems.
3) If equipped with an iodine cell, an RV survey with Gemini HROS seems possible.
4) As an indirect method, precision RVs must be confirmed by ancilliary data at very high resolving power or by independent methods.
5) Such ancilliary data can only be obtained with Gemini, if a future fibre-fed spectrograph with very high resolving power becomes available.
6) The ESO search program has produced two extra-solar planet candidates.
7) First definite results from this program are expected within this year.

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