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# A Radial Velocity Search for Extra-Solar Planets Using an Iodine Gas Absorption Cell at the CAT + CES

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## Introduction

The origin of the solar system is a fundamental problem in astrophysics for which many basic questions remain to be answered. Is planet formation a common or rare phenomenon? Is it a natural extension of the star formation process or is a different mechanism involved? Unlike most stars, the Sun is not found in a binary system. Is its single status related to the fact that it has a planetary system? Unfortunately, the answers to these and other important questions are hampered by the fact that the only known example of a planetary system (around a non-degenerate star) is the one around the Sun. Clearly, before one can develop general theories of planet formation, one must collect a large body of astronomical data that includes the frequency of planetary systems, the planetary mass function, and the correlation of such systems with mass, age, stellar composition, etc. of the primary star.

Although a number of direct and indirect techniques have been proposed for extra-solar planet detections, radial velocity measurements are proving to be a cost effective means of using ground-based facilities to search for planets. What radial velocity precision is needed to detect Jovian-sized planets? Naturally, one uses the Jupiter-Sun system as a guide where the Sun orbits around the barycentre with an average velocity of 12 m $s^{-1}$ and a period of 12 years. Thus, an instrument capable of measuring relative stellar radial velocities to a precision better than 10 m $s^{-1}$ and with a decade-long stability should be able to detect the presence of a Jovian-massed planet orbiting 5 AU from a solar-type star. Lower mass objects can be detected in orbits with smaller semi-major axes.

## Radial Velocity Technique

Traditional radial velocity measurement techniques rarely exceed a precision of 200–500 m $s^{-1}$. The reason for this is that the wavelength reference is taken at a different time and often traverses a different light path than that of the stellar spectrum. Use of radial velocity standard stars circumvents the problem of different light paths for the reference and stellar spectra, but the standard observation is still made at a different time and there is always the danger that the standard star is a low-amplitude variable.

The instrumental errors can be minimized by superimposing the wavelength reference on top of the stellar observation. One means of accomplishing this is to pass the starlight through an absorbing gas prior to its entrance into the spectrograph. The gas produces its own set of absorption lines against which velocity shifts of the stellar spectrum are measured. Since instrumental shifts now affect both the wavelength reference and stellar spectrum equally, a high degree of precision is achieved.

Griffin and Griffin (1973) first proposed using telluric $O_2$ lines at 6300 Å as a radial velocity reference. In this

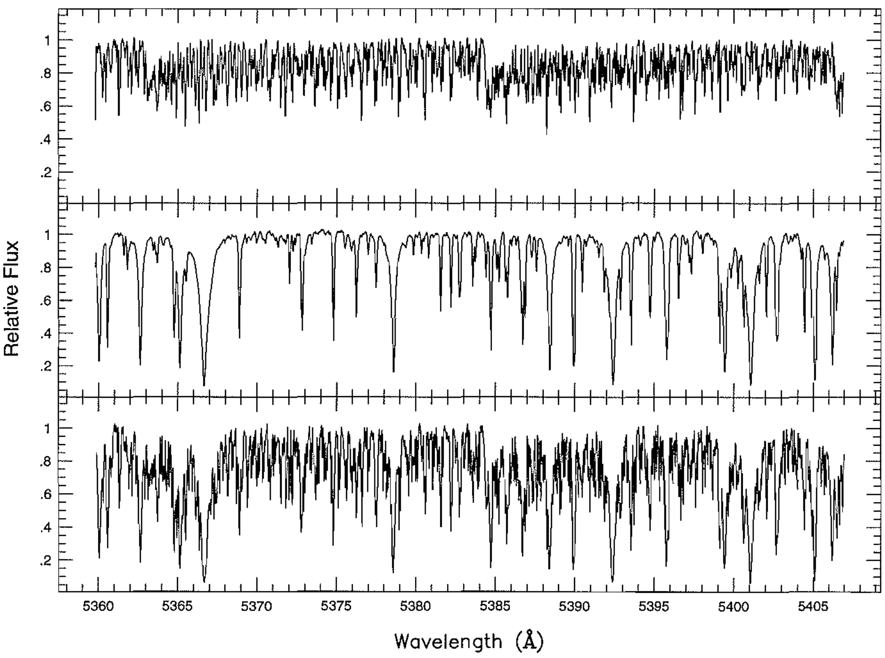

Figure 1: *(Top) Absorption spectrum of the $I_2$ cell obtained by taking a dome flatfield through the cell. (Middle) Spectrum of α Cen B without the $I_2$ cell from 5360 Å to 5407 Å. (Bottom) Spectrum of α Cen B taken with the $I_2$ cell in front of the entrance slit of the ESO CES. All spectra have been normalized to the continuum.*

case the absorbing medium is naturally provided by the earth's atmosphere. This technique was extensively used at McDonald Observatory as part of a planet search programme and a long-term precision of about 15–20 m $s^{-1}$ was demonstrated (Cochran and Hatzes 1990). The ultimate precision of this method is determined by pressure and temperature changes of the earth's atmosphere as well as by Doppler shifts of the $O_2$ lines due to winds. These errors can be eliminated if the observer has some control over the absorbing gas.

Modern improvements to the simple telluric technique enclose a gas in a cell that can be temperature and pressure regulated. Use of such a gaseous absorption cell was pioneered for stellar applications by Campbell and Walker (1979) who chose hydrogen fluoride (HF) as the absorbing gas. They have demonstrated in more than a decade of use that the HF cell can measure relative radial velocities with a long-term precision of about 13 m $s^{-1}$ (Campbell et al. 1988). Although the HF cell has proved capable of achieving the desired precision needed for detecting Jovian-sized planets around solar-type stars, there are a number of disadvantages to using such a device. The path length of the cell that is required to produce reasonably deep HF absorption lines is about 1 m and this could pose a problem if space in front of the spectrograph slit were limited. HF also has significant pressure shifts and must be regulated to a rather high temperature of 100°C. This is a highly reactive chemical, and prolonged exposure of the cell to HF will destroy the container walls. Consequently, the absorption cell must be made of inert material and has to be refilled for each observing run. The greatest disadvantage, however, is the hazardous nature of HF, and human exposure to this gas is fatal.

Gaseous molecular iodine ($I_2$) is a benign alternative to HF and the advantages of using this substance in an absorption cell are numerous. $I_2$ has a strong electronic band ($B^3\Pi^+_{0u} - X^1\Sigma^+_g$) in the 5000–6000 Å spectral region producing a rich spectrum of extremely narrow lines. Pressure shifts of $I_2$ are much smaller than for HF and this results in a very stable reference spectrum (Schweizer et al. 1973). The vapour pressure is high enough (about 0.5 torr) to produce significant absorption at room temperature in a cell 10–20 cm in length. Iodine gas does not react with glass so that the construction of the cell is relatively easy and can be done by any glassblower. Also, a fixed number of $I_2$ molecules are permanently sealed in the cell for its entire lifetime, so there is no need to refill it prior to each observing run. This guarantees that there is no variation in the amount of absorbing iodine from run to run. The device operates at a modest temperature of 50°C and its small mass can be temperature regulated using commercially available temperature controllers. In short, iodine absorption cells require virtually no maintenance and are easy, and above all, safe to use.

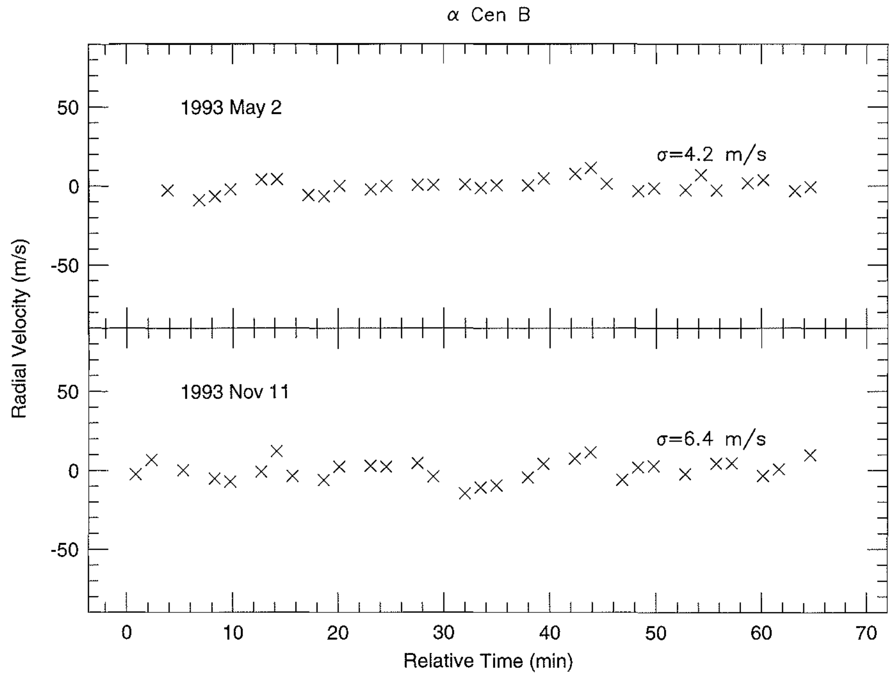

Figure 2: *The short-term radial velocity variations of α Cen B on 1993 May 2 (top) and 1993 Nov. 11 (bottom). The standard deviations of the measurements are 4.2 m $s^{-1}$ and 6.4 m $s^{-1}$, respectively.*

Use of $I_2$ as a wavelength standard has been employed by numerous investigators. Beckers (1973) used an iodine absorption cell to study material motions in sunspot umbrae. More recently, Libbrecht (1988) and Marcy and Butler (1992) have pioneered using the $I_2$ technique to measure relative stellar radial velocities. Iodine absorption cells are routinely used at McDonald Observatory as part of a planetary search programme (Cochran and Hatzes 1994) and to study low-amplitude variability in stars (Hatzes and Cochran 1993, 1994a, b). These studies have shown that, depending on the spectral resolution of the data, a long-term radial velocity precision of 7–20 m $s^{-1}$ is possible using an iodine absorption cell.

There are a number of programmes using precision radial velocity measurements to search for extra-solar planets. Campbell et al. (1988) have used their HF absorption cell at the CFHT 3.6-m telescope. Radial velocity surveys using iodine absorption cells are being conducted with the Lick 3-m telescope by Marcy and Butler (1992) and the McDonald Observatory 2.7-m telescope by Cochran and Hatzes (1994). McMillan et al. (1993) use a Fabry-Perot in transmission along with the Steward 0.9-m telescope for their planet search programme. In spite of the variety of telescopes and radial velocity techniques employed, these programmes share the common feature that they are all conducted from the northern hemisphere. There is one radial velocity survey for low-mass companions among southern hemisphere objects carried out by Murdoch et al. (1993) on a sample of 29 solar-type stars. However, the mean accuracy of their measurements, computed using digital cross-correlation techniques, is only 55 m $s^{-1}$, too large for the detection of Jovian-sized planets. In November 1992 we began a higher precision radial velocity survey of southern hemisphere stars at ESO in order to increase the statistical sample of stars being surveyed for planets.

It was realized that the many advantages of the iodine gas absorption cell made it the ideal device for use at the ESO 1.4-m Coudé Auxiliary Telescope (CAT) and Coudé Echelle Spectrograph (CES). The space in front of the entrance slit to the CES allowed for a device no more than about 10 m in length (no problem for an iodine cell), otherwise it would obscure the guide camera. A hazardous gas such as HF would not have been desirable to use since we did not wish for the ESO staff to handle potentially lethal chemicals. Finally, since all the observing was to be conducted remotely from Garching it was

Table 1: *Comparison of Radial Velocity Programmes*

| Telescope | Technique | Resolving power | $\Delta\lambda$ [Å] | $\sigma$ [m s$^{-1}$] | Reference |
|---|---|---|---|---|---|
| Mt. John 1.0-m | Digital CC | 100,000 | 45 | 55 | Murdoch et al. 1993 |
| McDonald 2.7-m | Telluric $O_2$ | 200,000 | 12 | 15–20 | Cochran & Hatzes 1990 |
| Steward 0.9-m | Fabry-Perot | 74,000 | 300 | 8–14 | McMillan et al. 1993, MS |
| CFHT 3.6-m | HF cell | 40,000 | 133 | 13 | Campbell et al. 1988 |
| Lick 0.6-m CAT | $I_2$cell | 40,000 | 200 | 20 | Marcy & Butler 1993 |
| McDonald 2.1-m | $I_2$cell | 48,000 | 24 | 20–25 | Hatzes & Cochran 1993 |
| McDonald 2.7-m | $I_2$cell | 200,000 | 9 | 10–15 | Cochran & Hatzes 1994 |
| ESO 1.4-m CAT | $I_2$cell | 100,000 | 48 | 4–7 | This work |

paramount to have a device that was not only safe, but could be used with minimal training of the personnel.

## Construction and Use of the Iodine Cell

The ESO iodine absorption cell was constructed at the University of Texas and shipped to La Silla in August 1992. The construction of the cell was very straightforward. A glassblower first attached two optical quartz windows, 0.63 cm thick and 5 cm in diameter, to the ends of a quartz tube 10 cm in length. A feed-through tube 1 cm in diameter was then fused through the cylindrical walls near the centre of the cell and the free end of this tube was attached to a glass manifold. At one end of the manifold was a sample tube containing solid iodine and at the other end was a valve with an exit tube that first passed through a liquid nitrogen trap on its way to a vacuum pump. The cold trap prevented iodine from entering and damaging the pump. After air was evacuated from the manifold, the valve was sealed so as to allow gaseous $I_2$ (which had sublimated from the solid $I_2$) to fill the entire chamber (manifold + the cell). The glassblower then detached the cell by applying a torch to the feed-through tube. Since this tube was now under vacuum, as the glass became molten the tube collapsed on itself and permanently sealed gaseous iodine in the cell.

Surrounding the cell is heating foil and a 0.65 cm thick layer of insulation. The cell is regulated by a commercial temperature controller which measures the temperature of the cell and provides power to the heater foil as needed. The cell is regulated at a temperature of 50°C. Our experience indicates that temperatures below this may result in iodine condensing out of the gaseous phase within the cell; regulating the cell at higher temperatures may create unnecessary heat dissipation that could create air currents in the slit room that may affect the seeing conditions.

The decision whether the iodine cell should be used with the short camera (R=50,000) or the long camera (R=100,000) of the CES depends on the desired radial velocity accuracy and the magnitudes of the objects studied. The radial velocity precision is proportional to $R^{-3/2}(S/N)^{-1}$ where R is the resolving power and S/N is the signal-to-noise ratio (Hatzes and Cochran 1992). For the planet detection programme the highest precision possible was desired and since most of the programme objects are bright, the lower photon count rate of the long camera/CCD#30 setup did not present a problem. Furthermore, higher resolution data are less sensitive to changes in the instrumental profile of the spectrograph (Hatzes and Cochran 1992). For radial velocity work on faint objects the increased speed of the short camera may outweigh its lower velocity resolution (dispersion) and a higher radial velocity precision may result.

The ESO iodine cell has been used successfully on nine observing runs with the 1.4-m CAT and the long camera of the CES spanning November 1992 to March 1994. All observing runs, including the inaugural run, were smoothly conducted remotely from Garching. This is a testament to the ease of using such a device. At first the ESO staff installed the cell and temperature controller prior to each run; now they permanently reside in the slit room. During the course of observing the night assistant is requested to move the cell in or out of the light path as needed.

Although the iodine cell can be used anywhere in the wavelength region 5000–6000 Å, for the planetary search programme a region centred on 5385 Å was chosen. Solar-type stars (the predominant objects of our survey) have a high density of spectral lines in this wavelength region and this wavelength also corresponds to the blaze peak of the echelle grating of the CES. The detector was CCD#30 which has 2048×2048 pixels. The spectra had a wavelength range of 48 Å at a spectral resolution of 0.054 Å (dispersion = 0.024 Å pixel$^{-1}$).

In order to compute radial velocities with an iodine absorption cell one requires a spectrum of pure iodine, a spectrum of the programme star, and a spectrum of the star taken through the iodine cell. Figure 1 shows typical radial velocity data taken with the $I_2$ cell at the 1.4-m CAT/CES. The top panel shows a spectrum of molecular iodine produced by observing a continuum calibration lamp (dome flatfield) with the cell in place. The central panel shows an ob-

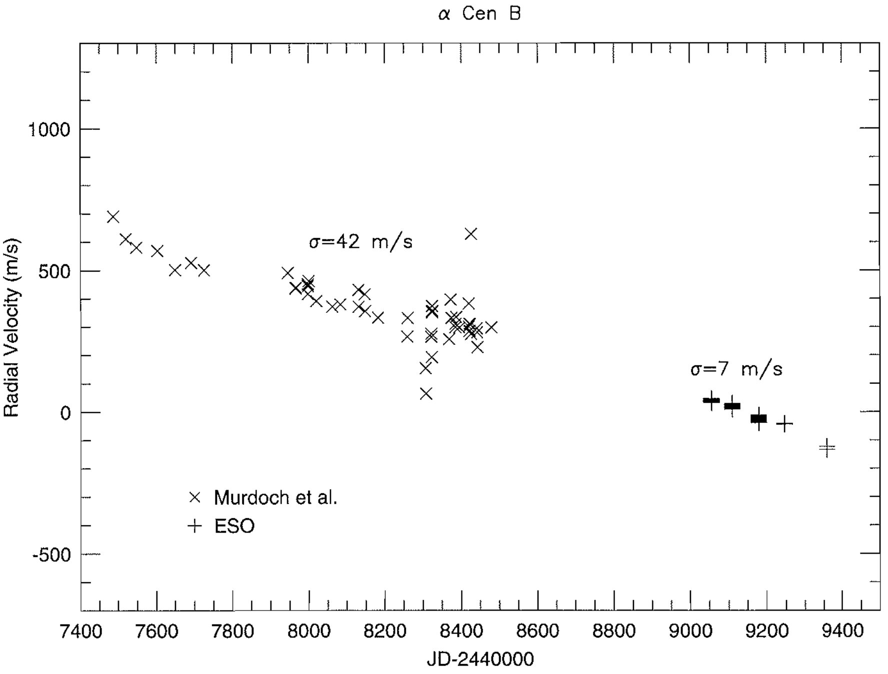

Figure 3: *The radial velocity variations of* α *Cen B. Data from Murdoch et al. (1993) are indicated by '×' and the ESO* $I_2$ *cell measurements are depicted by '+'. The long-term trend is due to the orbit around* α Cen A.

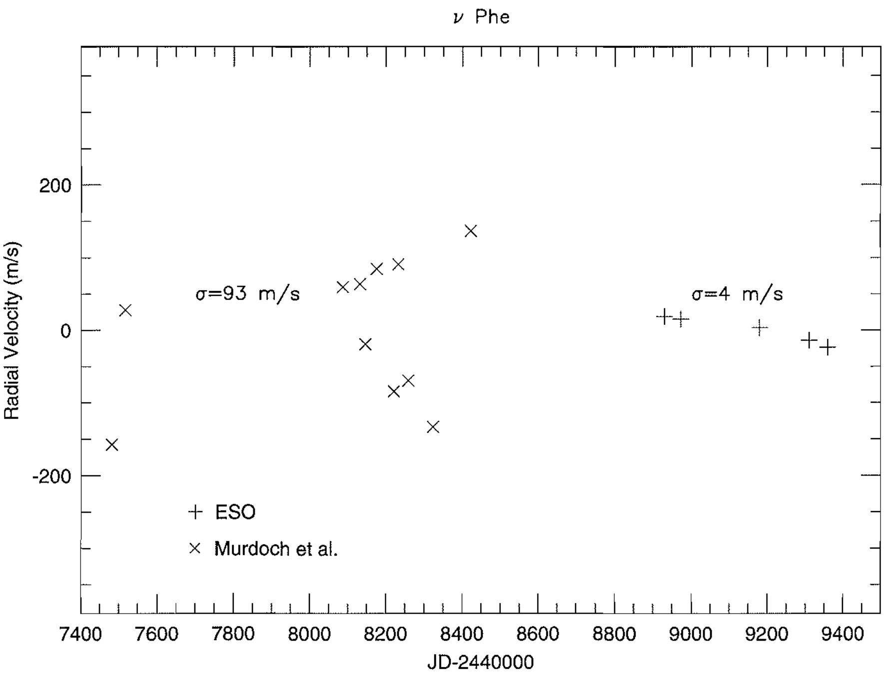

Figure 4: *The relative radial velocity of ν Phe. Once again the '+'s represent data from Murdoch et al. 1993 and 'x's indicate the ESO measurements.*

servation of one of the planet search programme stars, the K1V star α Cen B, taken without the iodine cell. The bottom panel shows an observation of α Cen B taken with the iodine cell in front of the entrance slit of the spectrograph.

## Performance of the Iodine Cell

The ESO iodine cell has been in use long enough so that both the long- and short-term radial velocity precision can be quantified. Short-term precision is defined to be the radial velocity accuracy achievable on a given night whereas the long-term precision is determined by the month-to-month scatter of the radial velocity measurements. The short-term precision is expected to be higher than the long-term one since the instrumental profile of the spectrograph is not expected to change in the course of several hours. On the other hand, degradation of the long-term precision can result from a variety of sources. A slightly different spectrograph focus from run to run, different CCD noise, of different temperature of the spectrograph optics can all affect the instrumental response of the spectrograph and this can result in systematic radial velocity errors.

Central to quantifying the precision of any radial velocity technique is the problem of finding a radial velocity "standard", particularly when determining the long-term precision. One can always look at an object of known radial velocity such as the moon, but this is an extended source that uniformly fills the spectrograph entrance slit thereby minimizing possible errors related to variable seeing, telescope focus, or guiding. Instead we chose to quantify the radial velocity precision by using actual observations of our programme stars. The radial velocity precision thus represents an upper limit as some scatter may be due to intrinsic stellar variability of unknown nature rather than to instrumental effects.

Radial velocities were computed using a stellar spectrum taken with and without the cell and a pure molecular $I_2$ spectrum. A "model" spectrum was produced by shifting and combining the stellar and iodine spectra and comparing it to the data. The relative shift between the stellar and $I_2$ spectra as well as all coefficients of the dispersion function were varied until the rms difference between the model and data (star+iodine as in the lower panel of Fig. 1) were minimized. A more refined calculation can take into account the instrumental response or point spread function (PSF) of the spectrograph. Changes in PSF from run to run can cause significant radial velocity errors at this level of precision. Marcy and Butler (1992) have pioneered a technique for modelling the PSF using the iodine absorption lines. The radial velocity data presented here do not include PSF modelling and thus provide a better gauge of spectrograph stability.

All radial velocities were corrected for the earth's motion using the JPL DE200 Planetary Ephemeris.

### *(a) Short-term precision*

The short-term precision of the iodine cell + CES was determined by taking a series of observations on α Cen B covering approximately 1 hour on each of two nights. The exposure time for each observation was 45 s. Figure 2 shows the resulting radial velocities on 2 May 1993 and 11 November 1993. The rms scatter of the velocities on the first night was 4.2 m s$^{-1}$ and 6.4 m s$^{-1}$ on the second.

### *(b) Long-term precision*

The '+' symbols in Figure 3 show the ESO long-term relative radial velocity measurements of α Cen B using the iodine absorption cell. Also shown (as '×') are the radial velocity measurements of Murdoch et al. (1993). Since both data sets represent relative radial velocities, they each have their own zero-point velocity. Therefore, an offset was applied to the Murdoch et al. data so as to align the two data sets. The long-term trends evident in both data sets are due to the long-period orbit of the α Cen AB binary system. The rms scatter about a straight line fit to the ESO measurements result in a standard deviation of 7 m s$^{-1}$, considerably smaller than the 42 m s$^{-1}$ (also about a straight line fit) for the Murdoch et al. measurements.

Figure 4 shows the ESO and Murdoch et al. radial velocity measurements for the F8V star ν Phe after aligning the mean values of both data sets. Again, there is a greatly improved precision in the ESO data which has a standard deviation of 4 m s$^{-1}$ compared to the 93 m s$^{-1}$ of the Murdoch et al. measurements. There is a slight downward trend in the ESO data, possibly indicating the presence of a low-mass companion, but more measurements are needed to confirm this.

The ESO radial velocity measurements for the G8V star τ Cet are shown as filled circles in Figure 5. The standard deviation of these measurements is 19 m s$^{-1}$. Also shown (as '×') are the radial velocity measurements taken at McDonald Observatory using an iodine absorption cell and the coudé spectrograph of the 2.7-m telescope. Note how well the ESO data track the McDonald data. In particular, the large decrease in the radial velocity (by about 50 m s$^{-1}$) between about Julian day 2449300 and 2449350 is present in both data sets. A similar amplitude in the scatter was also evident in the radial velocity measurements of this star made by Campbell et al. (1988). This strongly suggests that the rather high scatter seen in the radial velocity measurements of τ Cet (compared to ν Phe and α Cen B) may actually be intrinsic to the star.

### (c) Comparison to other high precision radial velocity programmes

Table 1 compares the radial velocity precision of the ESO $I_2$ cell + CES to other high-precision radial velocity programmes. The columns list the telescope used for the programme, the radial velocity technique, the resolving power, the approximate wavelength coverage, the long-term radial velocity precision, and the reference for the work. The radial velocity precision quoted for these techniques should not be taken as the ultimate precision that can be achieved. In particular, all radial velocity measurements made with iodine cells did not take into account modelling of the point spread function. Such PSF modelling may remove any systematic errors introduced by changes in the instrumental profile and thus improve the radial velocity precision. Clearly, the ESO 1.4-m CAT + CES + iodine cell together with a simple data reduction procedure can produce a long-term precision that is at least as good, if not better, than any other high-precision radial velocity programme. This is a testament not only to the radial velocity measurement technique, but to the overall stability of the CES.

## Other Applications

Although the ESO $I_2$ cell was installed as part of a programme to search for extra-solar planets, it is also an excellent means of studying low-amplitude radial velocity variability in stars. Iodine cells have been used to study the variability of K giants (Hatzes & Cochran 1993, 1994a, b), to measure the radial velocity amplitude of rapidly oscillating Ap stars (Libbrecht 1988; Hatzes & Kürster 1994), and to search for variability among the non-Cepheid stars in the instability strip Butler (1992).

## Summary

We have started a programme of using precise radial velocity measurements to search for extra-solar planets with the ESO 1.4-m CAT + CES. The technique uses an iodine gas absorption cell placed before the entrance slit of the spectrograph. The iodine absorption spectrum that is superimposed on the stellar spectrum provides a stable reference for measuring relative stellar radial velocities. Preliminary measurements indicate that the $I_2$ cell + CAT + CES is capable of achieving a long-term radial velocity precision of 4–7 m $s^{-1}$ on bright, solar-type stars. This precision is comparable, if not better, to that of other precise radial velocity surveys currently in place. Continued observations of the programme stars should be able to detect planets with Jovian masses if they are indeed present around these stars.

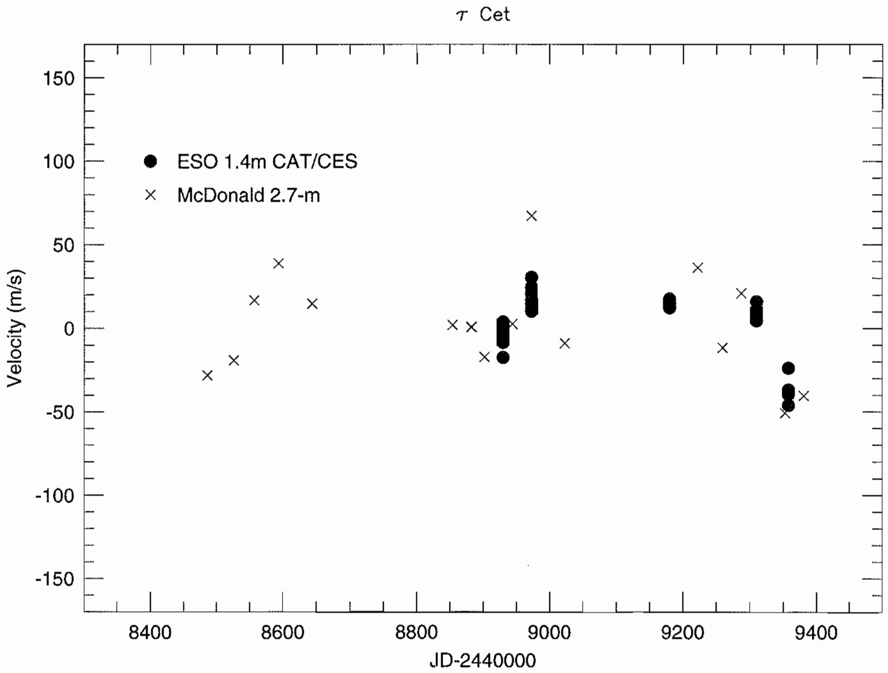

Figure 5: *(Top) The relative radial velocity measurements of τ Cet. The '×' symbols represent data taken with the McDonald Observatory 2.7-m telescope and an iodine absorption cell. The solid circles represent the ESO measurements which consist of 5–11 individual measurements per observing run.*

### Acknowledgements

This project could not have been started without the assistance of the ESO staff. We especially thank Luca Pasquini and Alain Gilliotte for installing the iodine cell at the CES.

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