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The Texas High-Precision Radial-velocity Programs

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Abstract. Several different high-precision radial-velocity programs are now underway at The University of Texas. This paper discusses the aspects of these programs that are related to the problem of detection of extrasolar planetary systems. This includes the McDonald Observatory Planetary Search program on the McDonald 2.7-m Harlan Smith Telescope, an accompanying program of high-resolution stellar line profile measurement, the European Southern Observatory planetary search program, the Keck Hyades survey, and the Hobby·Eberly Telescope planet surveys. Here, we summarize each of these programs, and present recent results from each.

1. Introduction

Since 1987 we have pursued a variety of research programs at McDonald Observatory centered around the use of high precision radial velocity measurement. We have used this powerful technique to attack two major scientific problems: the detection of planetary systems around other stars, and the study of non-radial pulsation modes in a variety of stars. The latter subject is discussed in detail by Hatzes *et al.* (1999). In this paper, we summarize the multi-faceted program of research on extra-solar planetary systems at The University of Texas.

2. The McDonald Observatory Planetary Search Program

In September 1987, we began making high-precision radial velocity observations of a group of nearby solar-type stars with the goal of detecting Jovian planets in orbit around them. This McDonald Observatory Planetary Search Program (MOPS) uses the coudé échelle spectrograph of the McDonald Observatory 2.7-m Harlan Smith Telescope. The MOPS spectrograph configuration isolates a single order of the échelle grating on a Texas Instruments 800×800 CCD. At the time the MOPS started, a cross-dispersed échelle spectrograph was not available at McDonald Observatory. The survey first used the telluric O_2 band at 6300 Å as the velocity metric, following the suggestion of Griffin and Griffin (1973). This technique gave us a routine radial velocity precision of about 15 $\mathrm{m\,s^{-1}}$ for stars down to about $V = 5$. However, the data obtained with this technique suffered from some source of long-term systematic errors, which was probably the intrinsic velocity variability of the terrestrial atmosphere, i.e. winds. In order to eliminate this systematic error and to improve our overall measurement precision, we installed a stabilized I_2 gas absorption cell as the velocity metric in October 1990. The use of this sealed stabilized I_2 cell removes potential problems with possible long-term systematic velocity errors. With the I_2 cell and the 9-Å bandpass of the single échelle order on the CCD, we are able to achieve 10–15 $m\,s^{-1}$ velocity precision.

The search strategy for this program was based on our understanding of the formation and evolution of planetary systems at the time the survey started. It was then assumed that giant planets would only form at several AU from the parent star, where the proto-planetary nebula was cool enough for water to condense. Thus, we expected to find Jovian mass objects with orbital period of 5–20 years and stellar reflex velocities of 20 $m\,s^{-1}$ or less. With 10–15 $m\,s^{-1}$ velocity precision, the best strategy for attempting to detect a signal that has an amplitude near the precision of a single measurement and a very long period is simply to take a lot of measurements. For example, a system with a K velocity equal to the σ of a single measurement can be detected with a false alarm probability of 10^{-5} by obtaining about 90 measurements spread over the orbital period (Cochran & Hatzes 1996). At that time, we had no idea that Jovian planets would be found in 4-day orbits!

The target list for the MOPS comprises 36 bright solar-type stars. The list was intentionally kept small, once again reflecting the understanding of planet formation when the program started. We elected to concentrate on intensive observations of a small group of stars, rather than sparser sampling of more stars. The MOPS was successful in being the co-discoverer of a low-mass companion in a highly eccentric orbit around the faintest star on the list, 16 Cygni B (Cochran *et al.* 1997).

Several of the stars in the observing list are mid- to late-F stars. As was pointed out by Cochran & Hatzes (1994), and then quantified by Saar *et al.* (1998), most stars earlier than about F8 or F9 show large intrinsic radial velocity scatter, associated with stellar activity. Some examples of MOPS stars showing this phenomenon are π^3 Ori (F6V), γ Ser (F6V), and α CMi A (F5IV-V).

The MOPS survey list also included some number of binary stars. Orbital stability calculations (Wiegert & Holman 1997) indicate that stable planetary orbits can exist in a wide variety of binary systems. Data on three such systems are shown in Figure 1. The orbital solution for χ^1 Ori is from Irwin *et al.* (1992) and for γ Cep from Walker *et al.* (1992). Our data on these systems will also be used to improve the binary orbit solution for these systems. The star μ Her has shown a secular deceleration over the entire span of observations, indicating a distant companion which is either a low-mass star or a brown dwarf. Hipparcos results show no indication of a companion.

3. High Resolution Line Profile Measurements

High spectral resolution stellar line profile measurements nicely complement precise radial velocity measurements by giving clues as to the astrophysical origin of any observed radial velocity measurements. Such observations were the root of the controversy prompted by Gray's (1997) claim that there was a 4.23-day periodicity in the spectral line bisectors of 51 Peg. At McDonald Observatory, the high-resolution mode of the 2.7-m 2d-coudé spectrograph (Tull *et al.* 1995)

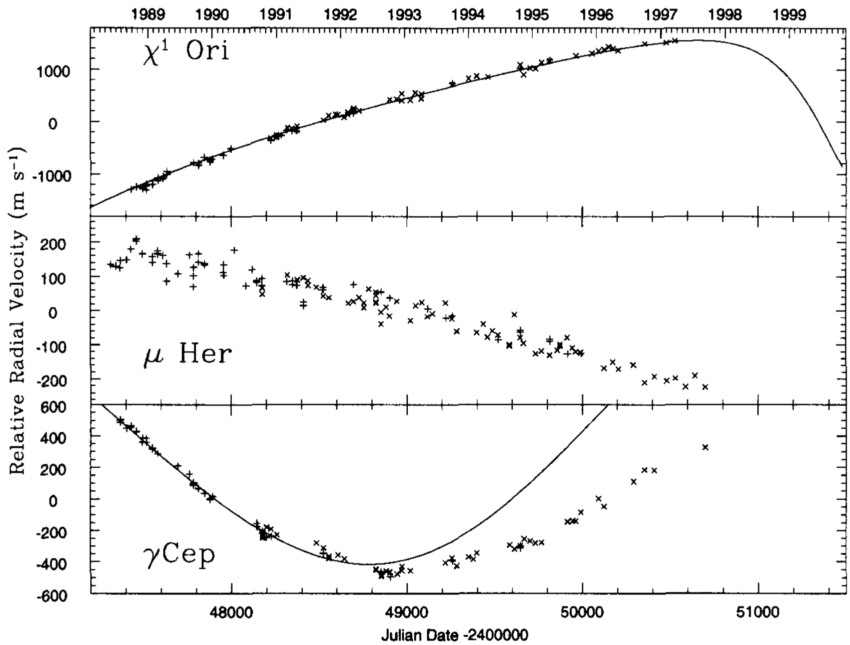

Figure 1. MOPS high precision radial velocity data on three binary stars. The solid lines are published orbital solutions for two of these stars.

can give $R = 240\,000$, enabling stellar line profiles to be fully resolved. We used the 2d-coudé to obtain over 120 high-resolution spectra of 51 Peg over 18 nights spanning the time period of July–September 1997. Our data included the Fe I 6253Å line used by Gray, as well as a number of other strong, isolated stellar lines. Preliminary results of our analysis of the line bisectors were given in Hatzes, Cochran & Bakker (1998a), and a more detailed analysis including additional spectral line bisectors, as well as an analysis of line depth ratios indicative of effective temperature changes was given in Hatzes, Cochran & Bakker (1998b). Figure 2 shows the weighted average of our 51 Peg velocity span and curvature measurements for seven different spectral lines. The rms scatter of the phase-binned span measurements is about $1.3\,\mathrm{m\,s^{-1}}$ and $4.0\,\mathrm{m\,s^{-1}}$ for the curvature measurements. We have also computed the ratio of the depths of the V I 6251.83 Å and the Fe I line at 6252.57 Å. Gray & Johanson (1991) have shown that this ratio provides a very sensitive measurement of changes to the effective temperature of solar-type stars. The rms scatter of the phase-binned line depth ratios is about 0.0015 which results in a peak-to-peak disk-integrated temperature variation of 6.6 K. A least squares sine fit (period = 4.23 d) to the phase binned data yields an amplitude of 0.00038 which gives a peak-to-peak $\Delta T = 1.7$ K. These data demonstrate definitively and unequivocally that 51 Peg exhibits *no* spectral variability with the 4.23 day orbital period of the planet

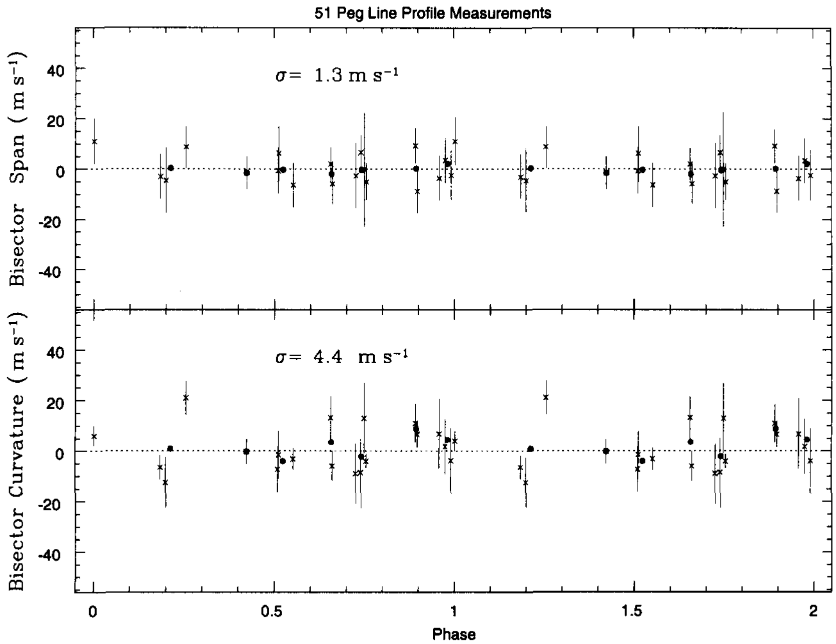

Figure 2. (Top) The mean bisector velocity span measurements (crosses) for 51 Pegasi, averaged over all spectral lines as a function of phase. (Bottom) The mean bisector curvature measurements (crosses) averaged over all spectral lines as a function of phase. The solid points in both panels represent phase-binned values.

discovered by Mayor & Queloz (1995). The upper limits we place on the 51 Peg photospheric line bisector variations are more than an order of magnitude smaller than the bisector variations reported by Gray (1997). Additional observations of 51 Peg by Gray (1998) confirm the lack of line profile variability shown in Fig 2.

Similar high spectral resolution observations of photospheric line profile bisectors in τ Boo, υ And and 55 Cnc show no evidence of stellar oscillations (Hatzes & Cochran 1998).

4. The ESO Planet Survey

The Texas group has been collaborating with M. Kürster, K. Dennerl, and S. Döbereiner to use the ESO 1.4-m Coudé Auxiliary Telescope (CAT) and Coudé Echelle Spectrograph (CES) to operate a southern hemisphere high precision radial velocity program. This survey, started in 1992, follows the pioneering survey of Murdoch *et al.* (1993) at improved velocity precision. Details of the ESO program are given by Hatzes *et al.* (1996) and by Kürster *et al.* (1999), and will not be repeated here. In Figure 3 we show our radial velocity measurements of α Cen A, B and C. The solid curve gives the orbital solution for A and B from Heintz (1982). Clearly, our data can significantly improve this orbit determination.

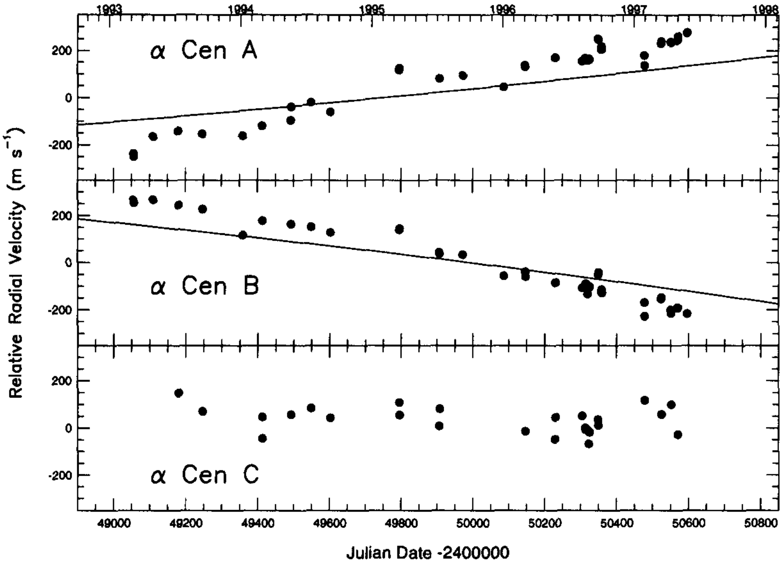

Figure 3. ESO radial velocity measurements of *alpha* Centauri A (top), B (center), and C (bottom). The solid line in A and B is the orbital solution from Heintz (1982).

5. The Keck Hyades Survey

The NASA partnership in the Keck Observatory offers a wonderful opportunity to pursue radial velocity projects that simply can not be done on 2.4-m size telescopes. Instead of simply trying to discover planets around random bright nearby stars, Keck can be used to begin to explore the *physics* of planetary system formation. One would expect the mass of a star to depend in some way on the physical properties (such as the mass or the density) of the proto-stellar cloud fragment from which it formed. These same cloud fragment properties should also influence the efficiency or rate of planet formation in the proto-stellar nebula. Do massive stars form massive planets, or does tidal truncation limit the size to which a planet can grow? Would we then expect massive stars to have a substantial system of giant planets of similar mass resembling the Galilean satellites of Jupiter? The Hyades star cluster is an excellent place to seek answers to these questions. The Hyades is the nearest star cluster to the Sun, and represents a sample of stars formed at the same epoch ($\sim$ 800 My age) with the same heavy element abundance ([Fe/H] = 0.18). There is no convincing evidence for an internal spread in either age or metallicity, indicating that the Hyades dwarfs are indeed a homogeneous sample of stars.

We have started a study of the dependence of planet formation on stellar mass by searching for low-amplitude radial-velocity (RV) variations indicative of Jupiter- or Saturn-mass planets in a carefully selected sample of main-sequence Hyades cluster stars. Thus, the dominant independent variable in the survey is the mass of the star. Hyades dwarfs range in brightness from about V magnitude of 6.5 for a mid-F star, through 9–11 for K stars. A large number of Hyades M dwarfs have been identified extending through fainter magnitudes. For this study, we use the Keck 1 HIRES spectrograph with its sealed, temperature-stabilized, I_2 absorption cell. We aim for a routine RV precision of 3 $m\,s^{-1}$ for most of the stars in the sample, with somewhat lower precision for the faintest stars. The large aperture of the Keck Telescope is essential for this survey in order to reach the fainter members of the Hyades main-sequence. We attempt to obtain at least two good RV observations of each program object per year, with the observations spread in time over the interval in which the Hyades are observable. Our results so far demonstrate that we have been able to achieve a long-term (year-to-year) radial velocity precision of 4–5 $m\,s^{-1}$ with the Keck HIRES I_2 cell. We are confident that we will be able to improve this precision to our goal of 3 $m\,s^{-1}$.

6. The Hobby·Eberly Telescope Surveys of Nearby Stars

The Hobby·Eberly Telescope (HET) was dedicated on 1997 October 8. Scientific commissioning of the telescope is now underway. The high resolution spectrograph is on schedule for installation in late 1998, and will be available for routine scientific use in early 1999. With its large aperture, queue scheduled operations, and high-resolution spectrograph designed to give excellent radial-velocity precision and long-term stability, the HET is an *ideal* facility for expanded RV surveys for low-mass companions. The queue-scheduled mode of the HET allows us to observe objects distributed throughout the sky in a highly efficient manner. The sampling of our synoptic RV observations can be optimized to be sensitive to a wide range of possible orbital periods with minimal aliasing.

We plan to begin two major new RV surveys with the HET. The first of the surveys will be our "Survey of the Solar Neighborhood", in which we will obtain high precision radial velocity measurements on all available nearby stars at $\delta \geq 30°$. This survey will complement the survey of nearby stars undertaken by the SFSU/UCB group on Keck, which concentrates on stars at $\delta \leq 30°$. The purpose of these this survey is to obtain as complete an inventory as possible of the nearest planetary systems to our Sun.

The second survey will be the "Metallicity Survey", in which we will explore the dependence of planet formation on the heavy element abundance of the star. We will survey a large number of stars with [Fe/H] spanning the range from about -1.5 to $+0.5$, thus sampling two orders of magnitude of metallicity.

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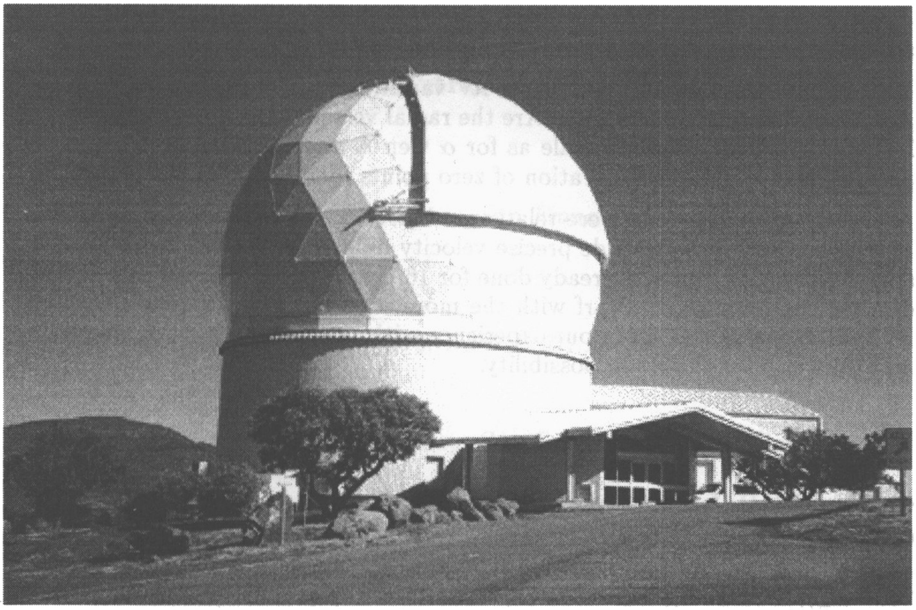

Figure 4. The Hobby·Eberly Telescope on Mt. Fowlkes at McDonald Observatory near Ft. Davis Texas.

Discussion

Brown: Has any new correction been made to the calculations of line bisector shifts due to possible pulsations in τ Boö? The codes used by Gray and Hatzes to calculate these variations seemed to be in error, based on comparisons with Brown et al. (1998).

Cochran: The disagreement between the techniques of Brown et al. and of Hatzes has not been resolved. We don't know which one is in error. However, none of us detect any variations in line profile shapes in any of the short period planetary candidates.

Fekel: In the Keck Hyades survey, what mass range are you sampling? How does this mass range compare with the ranges of the samples of the Mayor et al. and the Marcy et al. groups?

Cochran: The Hyades target stars range in spectral type from about F8 through to M3. The upper mass limit is set by stellar rotation and intrinsic stellar variability. The lower limit is set by the apparent magnitude.

Skuljan: You said you were able to repeat the beautiful precision of a few m/s over a long period of time. As a proof of this we saw a plot for one star having three measurements in one year and one measurement the next year. Have you used more observations in fact?

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Cochran: Yes, indeed, we have many observations of many stars clearly demonstrating the level of precision we are now able to achieve.

Soderblom: You showed us a plot of RV variations of α Cen and Proxima Cen. Are these just relative changes? Are the radial velocities for the M dwarf (Proxima) on the same absolute scale as for α Cen A and B? Perhaps your Hyades program can provide a calibration of zero points for spectral types F to M.

Cochran: All of the data were relative radial velocities, not absolute velocities. It is quite possible to provide precise velocity differences for two stars of similar spectral type, as we have already done for 16 Cyg A and B. However, we cannot directly compare an M dwarf with the more solar-like spectra of α Cen A and B. Your suggestion of using our experience with the Hyades is quite interesting, and we will investigate the possibility.

References

Cochran, W. D. & Hatzes, A. P. 1994, BAAS, 26, 868.

Cochran, W. D. & Hatzes, A. P. 1996, Ap&SS, 241, 43.

Cochran, W. D., Hatzes, A. P., Butler, R. P. & Marcy, G. W. 1997, ApJ, 483, 457.

Gray, D. F. 1997, Nature, 385, 795.

Gray, D. F. 1998, Nature, 391, 153.

Gray, D. F. & Johanson, H. L. 1991, PASP, 103, 439.

Griffin, R. & Griffin, R. 1973, MNRAS, 162, 243.

Hatzes, A. P., Kürster, M., Cochran, W. D., Dennerl, K. & Döbereiner, S., 1996, JGR, 101, 9285.

Hatzes, A. P. & Cochran, W. D. 1998, ApJ, 502, 944.

Hatzes, A. P., Cochran, W. D. & Bakker, E. J. 1998a, Nature, 391, 154.

Hatzes, A. P., Cochran, W. D. & Bakker, E. J. 1998b, ApJ, in press.

Hatzes, A. P., Kanaan, A. & Mkrtichian, D. 1999, this volume.

Heintz, W. D. 1982, The Observatory, 102, 42.

Irwin, A. W., Yang, S. & Walker, G. A. H. 1992, PASP, 104, 101.

Kürster, M., Hatzes, A. P., Cochran, W. D., Dennerl, K., Döbereiner, S., & Endl, M. 1999, this volume.

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

Murdoch, K. A., Hearnshaw, J. B. & Clark, M. 1993, ApJ, 413, 349.

Saar, S. H, Butler, R. P. & Marcy, G. W. 1998, ApJ, 498 L153.

Tull, R. G., MacQueen, P. J., Sneden , C. & Lambert, D. L. 1995, PASP, 107, 251.

Walker, G. A. H., Bohlender, D. A., Walker, A. R., Irwin, A. W., Yang, S. L. S. & Larson, A. 1992, ApJ, 396, L91.

Wiegert, P. A. & Holman, M. J. 1997, AJ, 113, 1445.