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Final Performance Report:

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Radial Velocity Detection of Extra-Solar Planetary Systems

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1 The McDonald Observatory Planetary Search

This grant funded the operation of the McDonald Observatory Planetary Search Program (MOPS) from 1 March 1994 through 28 February 1997, with a 12 month no-cost extension to 28 February 1998. Support of the science has been continued under NASA Grant NAG5-4384. The MOPS was designed to search for Jovian-mass planets in orbit around solar-type stars by making high-precision measurements of the radial velocity (RV) of a star, to attempt to detect the reflex orbital motion of the star around the star-planet barycenter. In our solar system, the velocity of the Sun around the Sun-Jupiter barycenter averages $12.3\,\mathrm{m\,s^{-1}}$. The MOPS survey started operation in September 1987, and searches 36 bright, nearby, solar-type dwarfs to $10\,\mathrm{m\,s^{-1}}$ precision. The survey was started using telluric O_2 absorption lines as the velocity reference metric (Griffin & Griffin 1973). Observations use the McDonald Observatory 2.7-m Harlan Smith Telescope coudé spectrograph with the six-foot camera. This spectrograph configuration isolates a single order of the echelle grating on a Texas Instruments 800×800 CCD. The telluric line method gave us a routine radial velocity precision of about $15\,\mathrm{m\,s^{-1}}$ for stars down to about 5^{th} magnitude. 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 for the MOPS in October 1990. In use at the telescope, the cell is placed directly in front of the spectrograph entrance slit, with starlight passing through the cell. The use of this sealed stabilized I_2 cell removes potential problems with possible long-term drifts in the velocity metric. The survey now includes a sample of 36 nearby F, G, and K type stars of luminosity class V or IV-V.

2 Measurement Precision

One excellent indicator of both the random and systematic measurement errors is the results of observations of an object thought to be constant in radial velocity – our sun (McMillan *et al.* 1993). In order to monitor overall system performance as a regular part of the MOPS, we have obtained observations of a standard spot on the lunar surface. This gives us a measurement of disk-integrated sunlight in a manner approximating as closely as possible the observation of a star. The observed velocities are reduced to heliocentric velocities (as opposed to barycentric velocities in the case of stellar observations) using the

JPL DE200 planetary ephemeris. Our lunar observations using the telluric O_2 method gave an rms scatter of the individual data points about the mean of $12.0\,\mathrm{m\,s^{-1}}$. Data taken with the stabilized I_2 cell show an rms scatter of $8.1\,\mathrm{m\,s^{-1}}$. This improved level of precision with the I_2 cell and lack of obvious systematic error at this measurement level demonstrates that we have indeed succeeded in controlling the major source of long-term systematic errors, and that we have met our original design goal in radial velocity precision achieved in long term operation of the MOPS program. However, we were not yet fully satisfied with the precision we had achieved. Valenti *et al.* (1995) developed a technique for determining temporal and spatial changes in a spectrometer instrumental point-spread-function (PSF), using the observed spectrum of a reference source such as an I_2 absorption cell. Butler *et al.* (1996) then showed how this technique can be used to achieve significant improvement in the precision of Doppler measurements. To improve our measurement precision, we have implemented this PSF modeling procedure in our data reductions. This has improved our measurement precision for high S/N data to about $6\,\mathrm{m\,s^{-1}}$.

3 A Planetary Companion to 16 Cygni B

The faintest star on the MOPS survey list is 16 Cygni B, the secondary star in a system comprising a pair of G dwarfs in a wide visual binary, and a distant M dwarf. Both of the G dwarf stars in the 16 Cygni system have effective temperatures, masses, surface gravities, and heavy element abundances very close to the solar value, making 16 Cyg B one of the stars whose physical parameters are most similar to those of the Sun. During 1996, both our group at McDonald and the Lick (Marcy and Butler) groups each separately became convinced that they were seeing periodic radial velocity variations in 16 Cyg B, and were able to obtain totally independent orbital solutions. We became aware of each others' work on this star, and found that these separate orbital solutions agreed to within the uncertainties. We then decided to combine all of the data into a joint solution. The weighted orbital solution for the combined Lick and McDonald data is given below. This solution agrees

Table 1: Combined weighted Orbital Solution for 16 Cygni B

Parameter	Value	Uncertainty
Orbital Period P (days)	800.8	11.7
Velocity Semi-amplitude K ($\mathrm{m\,s^{-1}}$)	43.9	6.9
Eccentricity e	0.634	0.082
Longitude of Periastron ω (degrees)	83.2	12.7
Periastron Date T_0 (Julian Date)	2448935.3	12.0

very well with the orbital solutions derived separately from each independent data set. If we adopt a mass for 16 Cyg B of $1.0\mathrm{M}_\odot$, this solution gives a planetary orbital semi-major axis of 1.6 AU, and $M_P \sin i = 1.5 M_J$. The long period, the large amplitude, and the shape of the radial velocity curve of 16 Cygni B all argue strongly for orbital motion as the cause of the observed velocity variations. The companion object to 16 Cygni B is unique in its combination of low mass and very large orbital eccentricity. We now feel that the highly eccentric orbit of the companion to 16 Cyg B is the result of the formation of this planet in a binary star system. According to the classical analytical studies of the orbital stability of planets in binary star systems, the planet around 16 Cyg B should be stable against perturbations by the other star in the binary, 16 Cyg A, as long as the stellar semi-major axis is greater than about 10 AU. Even if the planetary orbit is "stable", it is still quite possible for the stellar companion to strongly influence the evolution of the planetary orbit. In cases where there is an inclination between then stellar and planetary orbital planes, the planetary orbit will suffer an exchange of energy between inclination and eccentricity, with the semi-major axis remaining approximately constant, an effect first discussed by Kozai in 1962. This mechanism has been explored in detail by Holman *et al.* (1997) and by Mazeh *et al.* (1997). If the planetary companion to 16 Cyg B were formed in an initially circular orbit in a plane inclined to the plane of the stellar binary by at least 40°, then the eccentricity of the planet will oscillate between high- and low-eccentricity states, on a 10^7–10^9 year timescale. The planet would spend about 40% of the time at $e > 0.6$.

4 High-Resolution Spectroscopy of Planetary System Candidate Stars

The recently commissioned 2dcoudé spectrograph (Tull *et al.* 1995) on the McDonald Observatory 2.7m Harlan Smith Telescope provided us with an extremely powerful new instrument to use for investigating the central stars of candidate planetary systems. The high-resolution $R = 230,000$ F1 mode of 2dcoudé allows us to fully resolve virtually all stellar photospheric absorption line profiles,. This is simply not possible with $R = 60,000-100,000$ spectrographs commonly found on medium to large telescopes. We have used 2dcoudé in its high-resolution mode to investigate the central stars of candidate planetary systems. The first target for this study was 51 Peg (Hatzes *et al.* 1997). After Mayor and Queloz (1995) announced the detection of radial velocity variations in 51 Peg, and these variations were independently confirmed (IAU Circular 6251, 1995), we had no doubt of the reality of the velocity data. We did have some concerns, however, about the interpretation of the observed radial velocity variations as being the result of the reflex motion due to a low mass companion object. We felt that the possibility of intrinsic stellar origins of the observed RV variations needed to be investigated in greater detail. In November 1995 we obtained a series of 2dcoudé F1 high resolution spectra of 51 Peg with $S/N > 500$ covering a full RV period. Analysis of these data showed no detectable line profile variations indicative of stellar pulsations at the 4σ level. As part of our work in this area, Hatzes (1996) developed a kinematic model of the RV and spectral line profile variations expected for nonradial sectoral ($\ell = m$) modes. Our results, analyzed using our kinematic model, were published in The Astrophysical Journal (Hatzes *et al.* 1997). Gray (1997) subsequently has published a claim of detection of stellar photospheric line profile variations in phase with the observed radial velocity period of 51 Peg. This result by Gray cast serious doubt on the planet interpretation of the RV data for 51 Peg as well as three other stars with similar RV variations (τ Boo, υ And and ρ^1 CNC), and ignited in a heated controversy. We then obtained over 100 additional spectra of 51 Pegasi, in an attempt to achieve a definitive resolution of the dispute. The new data, published in *Nature* (Hatzes *et al.* 1998) also showed no variations in spectral line profiles at a level less than 20% of that claimed to have been detected by Gray(1997). These data succeeded in convincing the scientific community that 51 Peg indeed had a planetary companion. Gray (1998) then conceded that his 1997 claim was not correct. Additional data were obtained on another 51 Peg type star, τ Boo. This star also shows no detectable line profile variations that might indicate pulsational variability as the cause of the observed radial velocity variations. Our results demonstrate conclusively and convincingly that all of these 51 Peg type systems have Jovian mass companions in short-period orbits.

5 Publications Resulting From this Grant

- "A High Precision Radial-Velocity Survey for Other Planetary Systems" (W. D. Cochran and A. P. Hatzes) *Astrophys. and Space Science* **212**, 281–291, 1994.

- "A Radial Velocity Search for Extra-Solar Planets Using an Iodine Gas Absorption Cell at the CAT+CES" (M. Kürster, A. P. Hatzes, W. D. Cochran, C. E. Pulliam, K. Dennerl, and S. Döbereiner) *ESO Messenger* **76**, 51–55, 1994.

- "The Symbiosis of Photometry and Radial Velocity Measurements" (W. D. Cochran) in NASA Conference Publication 10148 *Astrophysical Science with a Spaceborne Photometric Telescope* (A. F. Granados and W. F. Borucki Eds.) 45–49, 1994.

- "Looking Beyond – The Search for Other Planetary Systems" (W. D. Cochran) in *Completing The Inventory Of The Solar System* (T. W. Rettig and J. M. Hahn, Eds.) 377–390, 1996.

- "The European Southern Observatory planetary search program: Preliminary results" (A. P. Hatzes, M. Kürster, W. D. Cochran, K. Dennerl, and S. Döbereiner) *J. Geophys. Res.* **101**, 9285, 1996.

- "Radial Velocity Searches for Other Planetary Systems: Current Status and Future Prospects" (W. D. Cochran and A. P. Hatzes) *Astrophysics and Space Science* **241**, 43–60, 1996.

- "FRESIP: A Mission to Determine the Character and Frequency of Extra-Solar Planets Around Solar-like Stars" (W. J. Borucki, D. K. Cullers, E. W. Dunham, D. G. Koch, W. D. Cochran, J. A. Rose, A. Granados, and J. M. Jenkins) *Astrophysics and Space Science* **241**, 111-134, 1996.

- "Testing the Planet Hypotheses: A Search for Variability in the Spectral-Line Shapes of 51 Pegasi" (A. P. Hatzes, W. D. Cochran, and C. M. Johns-Krull) *Ap. J.* **478**, 374–380, 1997.

- "The Discovery of a Planetary Companion to 16 Cygni B" (W. D. Cochran, A. P. Hatzes, R. P. Butler, and G. W. Marcy) *Ap. J.* **483**, 457–463, 1997.

- "Confirming Planet Discoveries with Line Bisectors: Do Aldebaran and β Gem Have Planetary Companions?" (A. P. Hatzes and W. D. Cochran) to appear in *Brown Dwarfs and Extrasolar Planets* 1997.
- "Searching for Extra-solar Planets from McDonald Observatory" (A. P. Hatzes and W. D. Cochran) to appear in *Brown Dwarfs and Extrasolar Planets* 1997.
- "Extrasolar Planets" (W. D. Cochran), *Physics World*, **10**, No. 7, 31–36, 1997.
- "On the Nature of the Radial Velocity Variability of Aldebaran: A Search for Spectral Line Bisector Variations" (A. P. Hatzes and W. D. Cochran), *M.N.R.A.S.*, **293**, 469–478, 1998.
- "A Search for Variability in the Spectral Line Shapes of τ Bootis: Does this Star Really Have a Planet?" (A. P. Hatzes and W. D. Cochran), *Ap. J.* in press, 1998.
- "Further evidence for the planet around 51 Pegasi" (A. P. Hatzes, W. D. Cochran, and E. J. Bakker), *Nature*, **391**, 154–155, 1998.

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