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THE FIRST HOBBY-EBERLY TELESCOPE PLANET: A COMPANION TO HD 37605[1]

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ABSTRACT

We report the first detection of a planetary-mass companion to a star using the High Resolution Spectrograph (HRS) of the Hobby-Eberly Telescope (HET). The HET HRS now gives routine radial velocity precision of 2–3 m s^{-1} for high signal-to-noise ratio observations of quiescent stars. The planetary-mass companion to the metal-rich K0 V star HD 37605 has an orbital period of 54.23 days, an orbital eccentricity of 0.737, and a minimum mass of 2.84 Jupiter masses. The queue-scheduled operation of the HET enabled us to discover this relatively short period planet with a total observation time span of just two orbital periods. The ability of queue-scheduled large-aperture telescopes to respond quickly to interesting and important results demonstrates the power of this new approach in searching for extrasolar planets, as well as in other areas of research requiring rapid response time critical observations.

Subject heading: stars: individual (HD 37605)

1. INTRODUCTION

Traditional ground-based radial velocity searches for extrasolar planetary systems have used medium- and large-sized telescopes assigned to the program for particular nights of observing. While this type of approach has been extremely successful, resulting in about 120 detections of planetary-mass companions to solar-type stars, the vagaries of the telescope scheduling process introduces certain restrictions and constraints on the optimal acquisition of time-critical observations. In radial velocity surveys, it is often the case that once a candidate planetary system has been identified and a preliminary orbit determined, additional observations must be obtained at particular orbital phases in order to place tighter constraints on particular orbital elements. Obtaining the necessary data at the optimal orbital phase may be extremely difficult if observing runs are scheduled for a few nights once per month, or even less frequently. Thus a telescope that is queue-scheduled, such as the Hobby-Eberly Telescope (HET), permits the observer to react quickly to the data and to obtain timely follow-up observations of critical targets at the orbital phases where they are needed. We report use of the HET to detect a planetary companion in a 54.23 day period orbit to the star HD 37605. The ability of the HET observing queue to accommodate our observing needs enabled us to discover the planet with a total of only 100 days (slightly less than two orbital periods) elapsing between the first and final observations. We discuss both the detection of the planetary companion itself and the special attributes of the HET that enabled the final orbital confirmation to be obtained in a very timely and expeditious manner.

[1] Based on observations obtained with the Hobby-Eberly Telescope, which is a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig Maximilians Universität München, and Georg August Universität Göttingen.

2. THE HET AND ITS HIGH RESOLUTION SPECTROGRAPH

The HET consists of an array of 91 hexagonal-shape, spherical figure mirrors, each of 1 m diameter, in a fixed truss tilted at 35° zenith distance, resulting in a maximum effective aperture of 9.2 m diameter. Declination ranges in the sky between $-11°$ and $+72°$ can be selected by rotating the telescope truss in azimuth. A star is observed by tracking an optical fiber bundle along the telescope focal plane while the telescope structure remains fixed, and feeding the light into the spectrograph. The HET design was optimized for large-scale, low sky-density spectroscopic surveys. The telescope is *not* assigned to a given program for a given night but rather is queue-scheduled, thus interleaving observations from a large number of different programs employing different instrument configurations. The HET data distribution policy is to allow the PI to gain access to the previous nights' data every morning, allowing rapid feedback to the HET astronomers. This is an ideal mode of operation for our high-precision radial velocity program.

The High Resolution Spectrograph (HRS; Tull 1998) for the HET was built by a team headed by Robert Tull and Phillip MacQueen. This spectrograph was designed to be able to make stellar radial velocity variation measurements with a precision of 3 m s^{-1} or better on stars as faint as $V = 10$. The instrument is housed in an insulated enclosure in the basement of the HET building and thus is not moving with the telescope. The image scrambling provided by the 34.3 m long optical fiber feed helps ensure that the pupil seen by the spectrograph is always illuminated in a consistent manner. Only a set number of instrument configurations are available, and these are all defined by

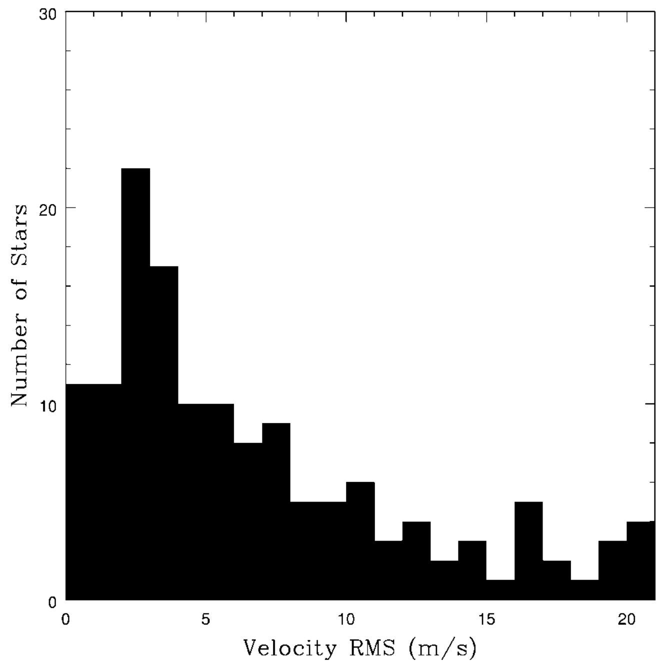

FIG. 1.—Histogram of the velocity rms of 142 stars observed in this program with the HET HRS.

kinematic mounts for the grating and cross-disperser positions. The I_2 gas cell is contained in a collimated section in front of the spectrograph slit, so refocusing of any optics is unnecessary for I_2 cell use. The detector is a mosaic of two 2048 × 4100 pixel E2V CCDs. For our high-precision radial velocity observations, we use the HRS in a mode giving resolving power of 60,000. The echelle grating was used on the center of the blaze, and the cross-disperser was positioned so that the break between the "red" and the "blue" CCD chips was at around 5940 Å. For most seeing conditions, a 2″ diameter optical fiber was used.

So far, we have observed 173 F–M dwarfs 4 or more times. The F through K stars are selected to be stars with low levels of stellar activity based on X-ray emission, photometric variability, and measured Ca II H and K emission. We intentionally do not bias the selection on stellar metallicity, but we do attempt to exclude stars with $v \sin i$ greater than about 15 km s^{-1} and known short-period binary stars. The separate M dwarf survey and its selection criteria are discussed by Endl et al. (2003). Of all of these stars, 20 show large-amplitude variations indicative of previously unknown binary star systems, and 11 additional stars show rms variations greater than 20 m s^{-1}, but probably not large enough to be due to binary stellar companions. These stars represent good candidates for short-period planetary companions. Figure 1 shows a histogram of the velocity rms about the mean of our time series measurements for the remaining 142 stars having an rms of 20 m s^{-1} or less, after any statistically significant linear velocity trends have been removed. The time span of the data for each star ranges from 1 week to greater than 3 yr. The median rms of the 123 stars in Figure 1 with rms of 13 m s^{-1} or less is 4.0 m s^{-1}. If we examine just the 112 stars with rms of 8 m s^{-1} or less (the bulk of the sample), then both the mean and the median rms of the remaining "stable" stars are just 3.6 m s^{-1}. The peak of the histogram is centered in the 2–3 m s^{-1} bin. We note that a significant contributing factor to the observed velocity rms is intrinsic to the stars themselves. We have *not* attempted to correct these rms values in any way for velocity variations induced by stellar photospheric and chromospheric activity ("jitter"). In general, the stars for which we have obtained the lowest rms are old, inactive stars with spectra of high signal-to-noise ratio (S/N). Thus, Figure 1 clearly demonstrates that we have achieved routine radial velocity precision of 3 m s^{-1} or better with the HET HRS in routine "production mode" on a large sample of a wide variety of stars over a substantial time period. Indeed, a significant fraction of our stars are showing radial velocity precision of 2 m s^{-1} or better, which is comparable to the precision achieved for high S/N observations with the ESO VLT/UVES by Kürster et al. (2003). Our 2–3 m s^{-1} precision is significantly better than that obtained with CORALIE (Naef et al. 2001) or ELODIE (Baranne et al. 1996) and is directly competitive with the 3 m s^{-1} precision that is achieved on the Keck HIRES (Vogt et al. 2000), AAT (Jones et al. 2002), or the 2 m s^{-1} demonstrated by HARPS (Pepe et al. 2004).

TABLE 1
STELLAR PROPERTIES FOR HD 37605

Parameter	Derived Value
T_{eff} (K)	5475 ± 50
log g	4.55 ± 0.1
ξ (km s^{-1})	0.8 ± 0.2
[Fe/H]	0.39 ± 0.07

3. THE PLANETARY COMPANION TO HD 37605

3.1. *Characteristics of the Host Star*

HD 37605 (HIP 26664, BD +05 985, SAO 113015, G99-22) is a $V = 8.69$ K0 V star. The *Hipparcos* (ESA 1997) parallax of 23.32 mas corresponds to a distance of 42.9 pc and gives an absolute magnitude of $M_V = 5.51$. The stellar parameters effective temperature, T_{eff}, surface gravity, log g, and microturbulence, ξ, listed in Table 1 were derived using MOOG (Sneden 1973) with atmospheres based on the 1995 version of the ATLAS9 code (Castelli et al. 1997) following the procedure outlined in Paulson et al. (2003) and briefly described below. Within IRAF, we fit the 20 Fe I and 12 Fe II lines listed in Table 1 of Paulson et al. (2003) with Gaussian profiles to obtain equivalent widths. The T_{eff} was derived by requiring that individual line abundances be independent of excitation potential. Likewise, ξ was derived by requiring that individual line abundances be independent of line strength. The log g was determined by forcing ionization equilibrium between neutral and singly ionized Fe. We adopted solar log ϵ(Fe) of 7.52 from Anders & Grevesse (1989), which yields an [Fe/H] for HD 37605 of 0.39 ± 0.06.

3.2. *HET Radial Velocity Observations*

Our typical HET observing technique is to obtain about 4–5 initial radial velocity measurements over the course of 1–2 weeks, in order to search for short-period "hot Jupiter" radial velocity variability. If a star appears stable on short timescales, it is then scheduled for less frequent observations in order to search for longer period orbits. For HD 37605 ($V = 8.7$), exposure times were 900 s, giving a typical S/N of about 250 per resolution element. The initial set of observations of HD 37605 were constant to within the observational error, but the next observation taken about 1 month later showed a decrease of about 200 m s^{-1}. We then took advantage of the queue-scheduled operations of the HET to put the star back into the

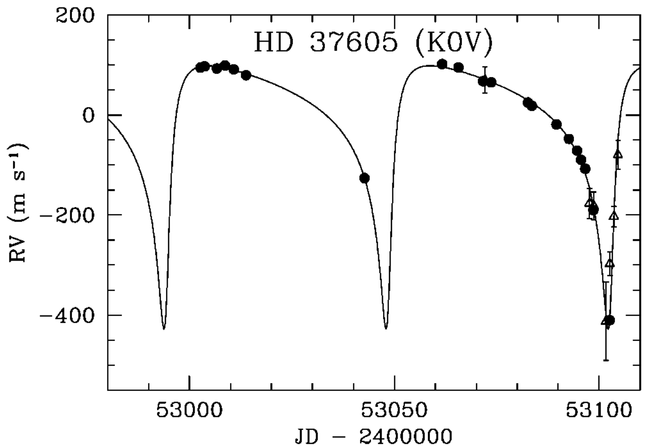

Fig. 2.—Radial velocity data for HD 37605 from the HET HRS (*filled circles*) and from the McDonald Observatory 2.1 m Sandiford Cassegrain echelle (*open triangles*). The size of most of the HET error bars is smaller than the size of the data points. The best-fit combined Keplerian orbital solution is plotted as a solid line. The rms residual of the HET/HRS data from the orbital solution is 4.7 m s^{-1}.

queue at high priority for frequent observations. Following our request for frequent coverage, the HET Resident Astronomers then obtained spectra every 3–4 days during the decrease in radial velocity. Data from each night's observations were reduced and velocities computed the following morning. We were easily able to fit a new orbital solution as the data from each night became available. It quickly became obvious that the radial velocity minimum and periastron passage would occur just as the star was being lost from the HET observability window; the last HET data points would be obtained during evening twilight. It was critical to attempt to obtain nightly HET velocity measurements during this orbital phase, as the depth of the velocity minimum would constrain the orbital eccentricity and the K velocity (and hence the companion minimum mass). Since these were going to be difficult HET observations, and it was quite possible that the HET would no longer be able to observe the star before the periastron passage was complete, we arranged for the McDonald Observatory 2.1 m telescope observer to obtain radial velocity measurements with the Sandiford Cassegrain Echelle spectrograph (McCarthy et al. 1993) and its I_2 cell during this interval. This instrument records the 5000–6000 Å region at resolving power of 60,000. These 2.1 m data would be of significantly lower velocity precision as a result of the much lower S/N and the inherent mechanical and thermal instability of a large heavy Cassegrain spectrograph, but they would certainly be adequate to cover this crucial interval when the HET might not be able to observe the star. The HET data for HD 37605 are shown as filled dots in Figure 2, and the 2.1 m Sandiford echelle data are shown as open triangles. The observed velocities from both telescopes are given in Table 2. The velocities in this table have been corrected for the different (and arbitrary) velocity zero points of the two instruments used. The simultaneous orbital solution to both data sets is also shown in Figure 2. The rms residual of the HET/HRS data from this orbital solution is 4.7 m s^{-1}. The rms residual of the 2.1 m Sandiford echelle data from the solution is 44.2 m s^{-1}.

TABLE 2
Differential Radial Velocities for HD 37605

JD−2,400,000	Velocity (m s^{-1})	Uncertainty (m s^{-1})	Instrument
53,002.6715 ……	94.7	8.4	HET HRS
53,003.6853 ……	97.1	7.8	HET HRS
53,006.6620 ……	92.8	7.0	HET HRS
53,008.6641 ……	98.6	6.2	HET HRS
53,010.8048 ……	90.8	6.2	HET HRS
53,013.7940 ……	79.3	6.6	HET HRS
53,042.7280 ……	−126.4	7.0	HET HRS
53,061.6676 ……	101.7	4.2	HET HRS
53,065.6468 ……	94.8	4.8	HET HRS
53,071.6438 ……	67.5	4.6	HET HRS
53,073.6382 ……	64.9	4.2	HET HRS
53,082.6237 ……	24.6	4.1	HET HRS
53,083.5954 ……	18.2	5.6	HET HRS
53,089.5958 ……	−19.0	4.0	HET HRS
53,092.5980 ……	−47.9	4.1	HET HRS
53,094.5866 ……	−71.2	3.3	HET HRS
53,095.5864 ……	−89.6	3.5	HET HRS
53,096.5874 ……	−107.7	6.7	HET HRS
53,098.5763 ……	−190.0	4.2	HET HRS
53,102.5727 ……	−409.9	5.5	HET HRS
53,072.1363 ……	69.5	25.99	2.1 m
53,097.6345 ……	−177.0	30.24	2.1 m
53,098.6555 ……	−181.7	27.91	2.1 m
53,101.6647 ……	−412.1	78.12	2.1 m
53,102.6034 ……	−297.5	23.58	2.1 m
53,103.5928 ……	−203.0	20.37	2.1 m
53,104.5972 ……	−79.7	29.20	2.1 m

3.3. *Orbital Solution*

We performed a simultaneous fit of the HET HRS and 2.1 m Sandiford echelle velocity data using the *Gaussfit* (McArthur et al. 1994) software, which uses a robust estimation method to find the combined orbital solution, where the arbitrary velocity zero points of both data sets are included as fit parameters. The combined orbital solution is given in Table 3 and is shown as the solid line in Figure 2. The planet is in a highly eccentric orbit. Its eccentricity of 0.737 is exceeded only by HD 80606b ($e = 0.93$) and HD 222582b ($e = 0.76$). The periastron distance of 0.070 AU is large enough for the planet to have easily avoided tidal circularization over the lifetime of the system.

The shape of the observed radial velocity curve is very difficult to explain by any mechanism other than orbital motion. Nevertheless, we have examined the available data to ensure that our interpretation of the observed velocity variations as resulting from orbital motion is indeed correct. The *Hipparcos* photometry of HD 37605 shows an rms variation of only 0.0020 mag, which is comparable to the *Hipparcos* photometric precision. Thus, the observed radial velocity variations cannot be linked to any photometric variability of the primary star. We have also searched for evidence of chromospheric variability of HD 37605. Normally, we would prefer to measure the Ca II *S* index from the Ca II H and K lines, but the HET primary mirror coatings and the HET optical fibers result in a short-wavelength cutoff of the HET HRS at around 4200 Å. We do have one spectrum of HD 37605 obtained with the McDonald

TABLE 3
Orbital Parameters for the Companion to HD 37605

Parameter	Derived Value
P (days) ………	54.23 ± 0.23
T (JD) ………..	2,452,994.27 ± 0.45
K (m s^{-1}) ……..	262.9 ± 5.5
e …………….	0.737 ± 0.010
ω (deg) ……….	211.6 ± 1.7
$f(m)$ ($M_\odot$) …….	$(3.13 \times 10^{-8}) \pm (5.9 \times 10^{-10})$
$m \sin i$ (M_J) ……	2.84 ± 0.26
a (AU) ……….	0.26 ± 0.01

Observatory 2.7 m telescope 2d coudé spectrometer, which includes the Ca II H and K lines. From this spectrum we measure a McDonald S index (Paulson et al. 2002) of 0.158 ± 0.022. This $S_{\rm McD}$ is comparable to the value found in the old, inactive star τ Ceti ($S_{\rm McD} = 0.166 \pm 0.008$), thus indicating a low level of chromospheric activity for HD 37605. We have also examined the profiles of the Hα absorption line for any possible variability that might be related to stellar activity. A careful alignment and normalization of the Hα line profile from all of our regular program spectra of HD 37605 shows no variations beyond what is expected from photon noise. Thus we conclude that the observed radial velocity variations are indeed due to a planetary-mass companion moving in a highly eccentric orbit.

4. CONCLUSIONS

We report the first discovery of an extrasolar planet using the Hobby-Eberly Telescope and its High Resolution Spectrograph. The planetary-mass companion to the metal-rich star HD 37605 is in a highly eccentric orbit. We have demonstrated that the HET HRS can produce a long-term velocity precision of 3 m s^{-1} or better over a multiyear time span. The queue-scheduled operation of the HET made the detection and characterization of the orbit far simpler than it would have been with a conventionally scheduled telescope. Once the possible orbital motion was detected, we were able to obtain immediate follow-up observations at the particular orbital phases that were crucial for the orbit determination. This highly flexible mode of telescope operation, coupled with the large telescope aperture and the extremely stable HRS, makes the HET HRS an ideal and extremely efficient and flexible facility for large surveys for extrasolar planetary systems.

The Hobby-Eberly Telescope is a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig Maximillians Universität München, and Georg August Universität Göttingen. The HET is named in honor of its principal benefactors, William P. Hobby and Robert E. Eberly. This material is based on work supported by the National Aeronautics and Space Administration under grant NAG5-13206. The authors are grateful to the University of Texas Hobby-Eberly Telescope Time Allocation Committee for their generous allotment of observing time for this program.

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