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TWO NEW PLANETS FROM THE ANGLO-AUSTRALIAN PLANET SEARCH[1]

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ABSTRACT

Precise Doppler measurements from the Anglo-Australian Telescope (AAT) UCLES spectrometer reveal periodic Keplerian velocity variations in the stars HD 160691 and HD 27442. HD 160691 has a period of 743 days, a semiamplitude of 54 m s^{-1}, and a high eccentricity, $e = 0.62$, typical of extrasolar planets orbiting beyond 0.2 AU. The minimum ($M \sin i$) mass of the companion is 1.97 M_J, and the semimajor axis is 1.65 AU. HD 27442 has a 415 day period, a semiamplitude of 32 m s^{-1}, and an eccentricity of 0.058. The minimum mass is 1.43 M_J, and the semimajor axis is 1.18 AU. This is the first extrasolar planet orbiting beyond 0.2 AU that is in a circular orbit similar to solar system planets. The photon-limited precision of AAT/UCLES measurements is 3 m s^{-1} as demonstrated by stable stars and Keplerian fits to planet-bearing stars. In addition, we present confirmation of four previously announced planets.

Subject headings: planetary systems — stars: individual (HD 160691, HD 27442)

1. INTRODUCTION

All ~50 extrasolar planets discovered over the last 5 yr have come from precision Doppler surveys of nearby dwarf stars ranging in spectral type from late F through M4 (Mayor & Queloz 1995; Marcy & Butler 1998, 2000; Noyes et al. 1997; Cochran et al. 1997; Vogt et al. 2000; Kurster et al. 2000; Udry et al. 2000; Fischer et al. 2001). With one exception (Marcy, Butler, & Vogt 2000), all the published planets have Doppler velocity amplitudes greater than 30 m s^{-1}. With a measurement error of ~10 m s^{-1}, Doppler velocity amplitudes of 30 m s^{-1} are the smallest that can be easily detected. Detection of planets with smaller amplitudes, such as solar system analogs and Neptune-to-Saturn mass planets in short period orbits, requires measurement precision of 3 m s^{-1} or better (Butler & Marcy 1997; Butler et al. 2001).

For the case of massive planets orbiting within 3 AU, the ~50 known planets constitute a useful statistical sample. The substellar companion mass function abruptly rises at 5 M_J and continues to rise down to the detection limit near 1 M_J. About 7% of nearby stars have massive planets with orbital periods less than 5 yr, including ~0.75% with "51 Peg–like" planets in 3–5 day circular orbits (Cumming, Marcy, & Butler 1999; Butler et al. 2001). Although existing planet hunting techniques are still in their infancy, two primary results have emerged over the last 5 yr. Extrasolar planets are common, and the architecture of planetary systems is richer and more complicated than previously imagined.

Future breakthroughs will require greater measurement sensitivity. In particular, the most pressing questions at the moment are does the planet mass function continue to rise through the Jupiter to the Neptune-mass range, and what fraction of stars have "solar system–like" planets, i.e., Jupiter and Saturn analogs in circular orbits beyond 4 AU? Doppler precision of 3 m s^{-1} or better is required to address these questions.

The Anglo-Australian Planet Search, therefore, has the specific goal of achieving a long-term precision of 3 m s^{-1}. In § 2 we show that this goal has been reached. Section 3 reports the stellar characteristics and Doppler velocities of the host stars for two giant planets that have emerged from this survey. Section 4 presents velocities and orbital solutions from the Anglo-Australian Telescope (AAT) data for four planets previously announced from the Keck, CORALIE, and ESO planet surveys and is followed by a discussion of our results.

2. THE ANGLO-AUSTRALIAN DOPPLER SURVEY

The Anglo-Australian Planet Search began observations in 1998 January and is currently surveying 200 stars. Initial results from this work have been published by Tinney et al. (2001).

The AAT program stars have been chosen to be among the brightest, chromospherically inactive dwarf and subgiant stars ranging in spectral type from late F through early M. Most of the stars are south of declination $-20°$ to prevent overlap with the Keck planet survey (Vogt et al. 2000), and most of the stars are brighter than $V = 7.5$, consistent with achieving signal-to-noise ratio (S/N) $\gtrsim$ 200 with exposure times of 10 minutes or less. This S/N is required to achieve photon-limited precision of 3 m s^{-1} (Butler et al. 1996).

High-resolution spectra, $R \sim 45{,}000$, are taken with the UCLES echelle spectrometer (Diego et al. 1990) on the 3.9 m AAT. These spectra span the wavelength range from 4820 to 8550 Å. An iodine absorption cell (Marcy & Butler 1992) provides wavelength calibration from 5000 to 6000 Å. The spectrometer point-spread function is derived from the

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detailed shapes of the embedded iodine lines (Valenti, Butler, & Marcy 1995; Butler et al. 1996). Similar systems on the Lick 3 m and the Keck 10 m telescopes currently provide photon-limited precision of 3 m s^{-1} (Butler et al. 1996; Butler & Marcy 1997; Vogt et al. 2000). No nightly corrections (Walker et al. 1995) are applied to the Lick, Keck, or AAT systems.

Figure 1 shows AAT velocities of four stable dwarf stars with spectral types ranging from late F to early G. The rms of the measured velocities for these stars range from 3.8 to 4.9 m s^{-1}, consistent with measurement uncertainties of 3–4 m s^{-1} and intrinsic stellar variability of 2–3 m s^{-1} (Saar, Butler, & Marcy 1998). Of these stars, the F8 dwarf HD 196378 (HR 7875) was previously reported to be a velocity variable. Kurster et al. (1999) report, "Our best candidate so far for having an orbiting planet is the F8V star ϕ^2 Pav (=HR 7875)." They report a velocity amplitude of 39.5 m s^{-1} and a probable period of 42.5 days. Our velocities would have revealed this planet, but we have failed to detect it.

Figure 2 shows AAT velocities of four stable mid-G dwarfs, while Figure 3 shows four stable stars ranging from late G to early K. These stars exhibit a velocity rms ranging from 2.3 to 5.0 m s^{-1}, consistent with measurement uncertainty of ~3 m s^{-1}. Of these stars, the G8 V star τ Ceti (HD 10700, HR 509) is frequently used as a velocity standard by precision velocity groups because it is bright, chromospherically inactive, and visible from both the northern and southern hemispheres. By the late 1980s the Canada-France-Hawaii Telescope precision velocity survey had shown an rms of 13 m s^{-1} for this star (Campbell, Walker, & Yang 1988; Walker et al. 1995). Measurements taken since 1994 November from the Lick precision velocity program show an rms of 4.6 m s^{-1} (Butler et al. 1996), while the ESO precision velocity program has reported an rms of 14 m s^{-1} for this star (Kurster et al. 2000). After 3 yr, the AAT velocities for this star have an rms of 3.9 m s^{-1}, as shown in Figure 3.

Slowly rotating, chromospherically inactive, main-sequence dwarf stars ranging in spectral type from early G to mid-M have been shown to be intrinsically stable at the 3 m s^{-1} level (Butler & Marcy 1997; Saar et al. 1998; Vogt et al. 2000; this paper). In addition, Fischer et al. (2001) have shown several class IV subgiants are stable at the 6 m s^{-1} level. In Figure 4 we present four stable subgiants from the AAT survey. These stars are stable at the 3–4 m s^{-1} level. With intrinsic stability at this level, it is possible to search for planets around subgiants using the precision Doppler technique. In addition, the stability of such stars makes these stars excellent targets for stellar seismology campaigns, especially as they are predicted to have larger ampli-

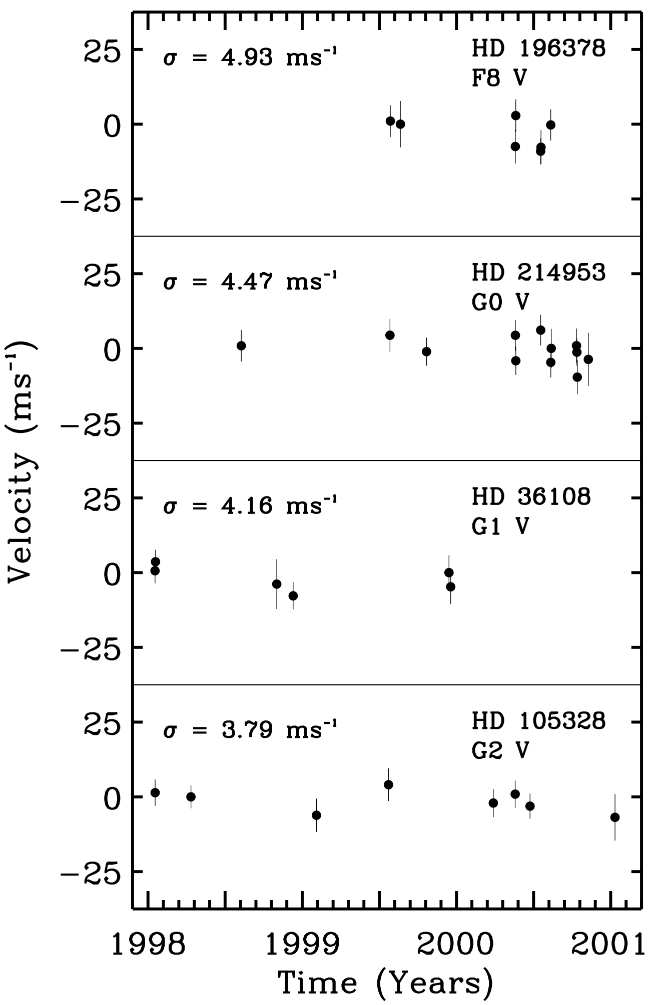

FIG. 1.—AAT Doppler velocities of stable late F and early G dwarfs. These observations span the 2.8 yr of the AAT Planet Search Project.

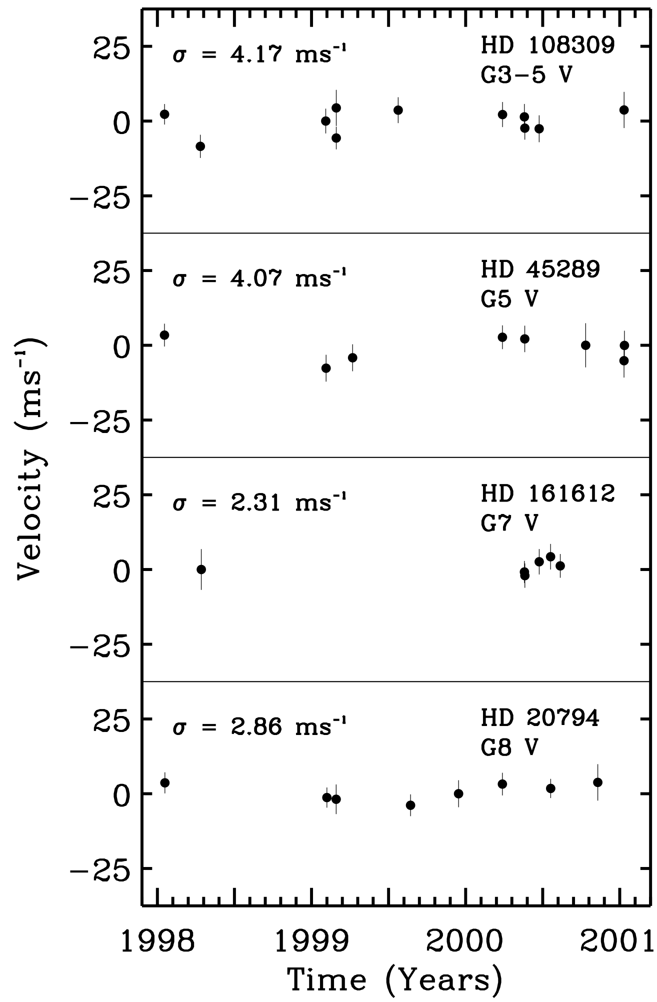

FIG. 2.—AAT Doppler velocities of stable G dwarfs

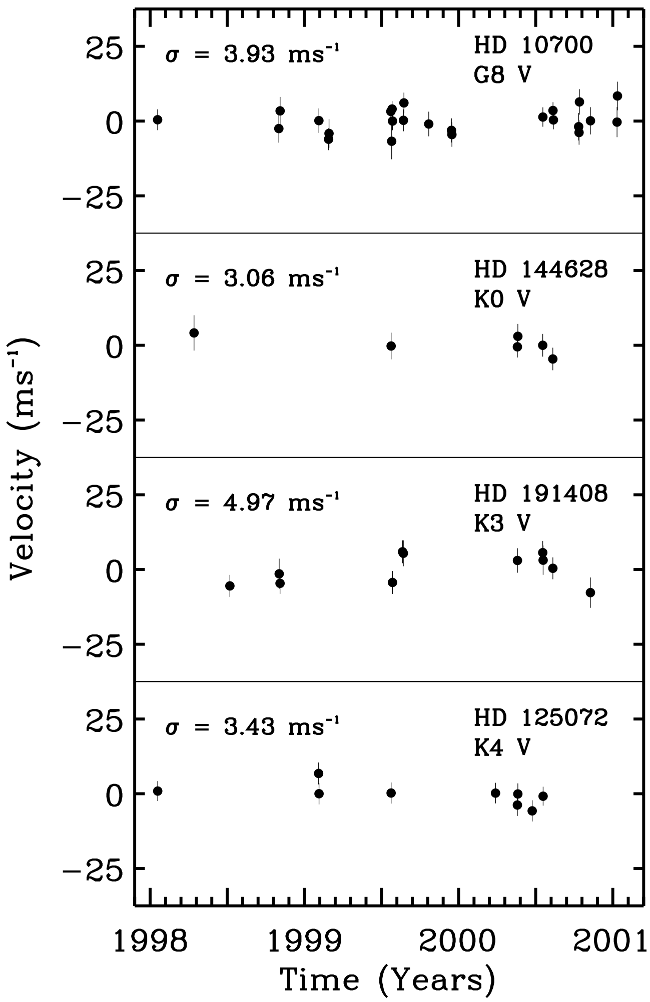

FIG. 3.—AAT Doppler velocities of stable late G and K dwarfs

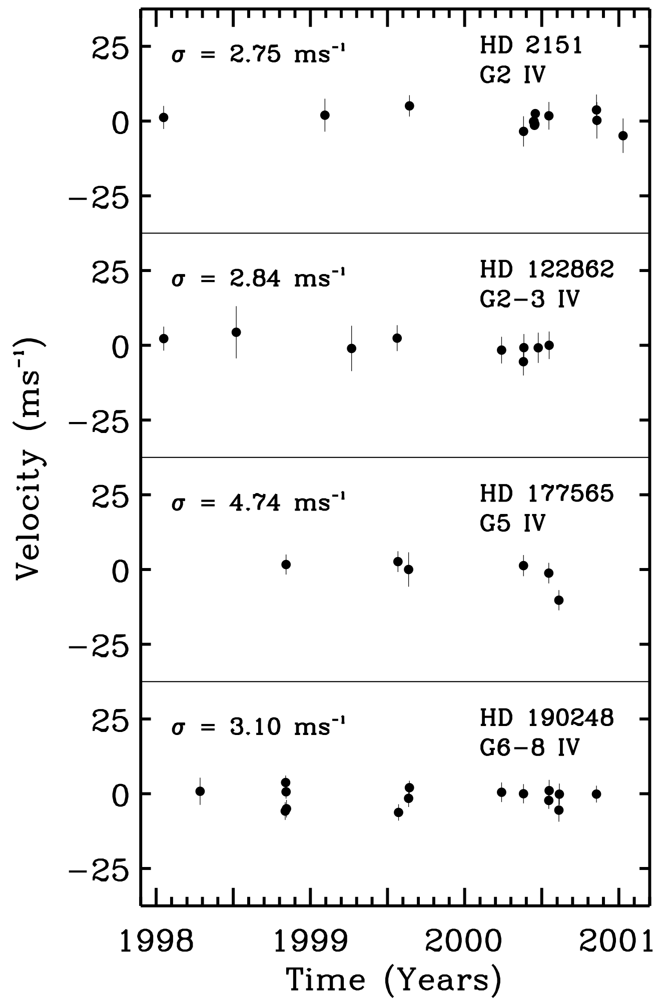

FIG. 4.—AAT Doppler velocities of stable G subgiants

tudes than main-sequence dwarfs. Bedding et al. (2001) have recently detected a 17 minute oscillation in HD 2151 using the AAT Planet Search hardware and software. They took 1200 velocity measurements over five nights with an rms of 3.3 m s^{-1}. On a timescale of hours the precision was 2.2 m s^{-1}.

3. STELLAR CHARACTERISTICS AND ORBITAL SOLUTIONS

3.1. *Stellar Characteristics of HD 160691*

A total of 140 observations of HD 160691 (HR 6585, HIP 86796, GL 691, μ Ara) have been made by *Hipparcos* (Perryman et al. 1997), yielding a distance of 15.3 pc and a V magnitude of 5.20. The resulting absolute magnitude is $M_V = 4.28$. The star is photometrically stable within *Hipparcos* measurement error, with photometric scatter of 0.002 mag. The Bright Star Catalog (Hoffleit & Jaschek 1982) assigns a spectral type of G3 IV–V, in reasonable agreement with the *Hipparcos* spectral type of G5 V. The star is chromospherically inactive, with $\log R'(HK) = -5.02$ (Henry et al. 1996). Its chromospherically inferred age is $\sim$6 Gyr. Combining *Hipparcos* astrometry of HD 160691 with the SIMBAD radial velocity (-9.0 km s^{-1}) yields an extremely low space velocity with respect to the local standard of rest: $U, V, W = -4, +3, +3$ km s^{-1}.

Like many of the planet-bearing stars, HD 160691 is extremely metal-rich. The [Fe/H] derived from high-resolution spectroscopy is 0.28 ± 0.04 (Favata, Micela, & Sciortino 1997), in good agreement with our photometric estimate of $+0.29$. The lithium line at 6707.8 Å was not detected in high-resolution ($R = 100{,}000$) spectra (Favata, Micela, & Sciortino 1996). The mass of HD 160691 estimated from $B-V$, M_{Bol}, and [Fe/H] is $1.08 \pm 0.05\ M_{\odot}$.

3.2. *Doppler Velocities and Orbital Fit for HD 160691*

The 21 Doppler velocity measurements of HD 160691 obtained between 1998 November and 2000 November are listed in Table 1 and shown graphically in Figure 5. The best-fit Keplerian yields an orbital period of 743.5 days, a velocity amplitude of 53.6 m s^{-1}, and an eccentricity of 0.62. The minimum ($M \sin i$) mass of the planet is 1.97 M_J, and the semimajor axis is 1.65 AU. The rms to the Keplerian fit is 2.98 m s^{-1}, yielding $\chi_\nu^2 = 0.98$.

3.3. *Stellar Characteristics of HD 27442*

A total of 107 observations of HD 27442 (HR 1355, HIP 19921, ϵ Ret) have been made by *Hipparcos*, yielding a distance of 18.2 pc and a V magnitude of 4.55. The resulting absolute magnitude is $M_V = 3.25$. The star is photometrically stable within *Hipparcos* measurement error, with photometric scatter of 0.003 mag. The Bright Star Catalog assigns this star a spectral type of K2 IVa.

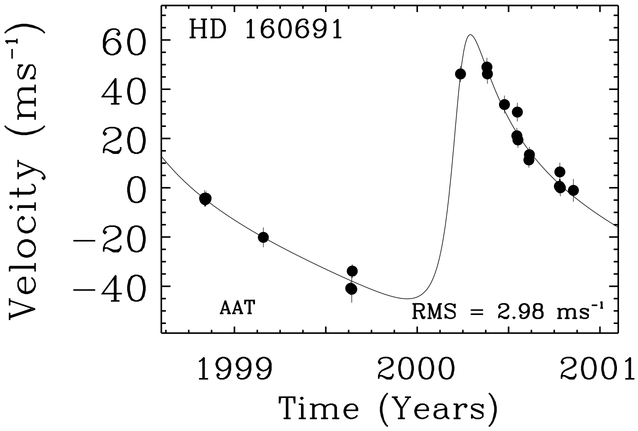

FIG. 5.—Doppler velocities for HD 160691. The rms to the best-fit Keplerian (*solid line*) is 3 m s^{-1}. The period is 743.5 days, and the semiamplitude is 53.6 m s^{-1}. Assuming the mass of HD 160691 is 1.08 $M_{\odot}$, the minimum (M sin i) mass of the companion is 1.97 M_J, and the semimajor axis is 1.65 AU. The orbital eccentricity is 0.62, similar to other planets orbiting beyond 1 AU.

On the basis of measured equivalent widths of Fe lines observed at high resolution ($R \sim 60{,}000$), Randich et al. (1999) determined the metallicity of HD 27442 to be [Fe/H] = 0.22. This is somewhat more metal-rich than earlier estimates, including Elgaroy, Engvold, & Lund (1999), who report [Fe/H] = 0.00 based on averaging several previous estimates, and the photometric estimate of Eggen (1993), who found [Fe/H] = 0.06. On the basis of evolutionary tracks, Randich et al. (1999) find the mass of HD 27442 to be 1.2 ± 0.1 $M_{\odot}$ and the age to be 10 Gyr, consistent with subgiant status. They also report an upper limit for the equivalent width of Li at 3 mÅ.

3.4. *Doppler Velocities and Orbital Fit for HD 27442*

Table 2 lists the 14 Doppler velocity measurements of HD 27442 obtained between 1998 January and 2001 January. These measurements are graphically shown in Figure 6. The best-fit Keplerian yields an orbital period of 415.2 days, a velocity amplitude of 32.5 m s^{-1}, and an eccentricity of 0.058. The minimum (M sin i) mass of the planet is 1.35 M_J, and the semimajor axis is 1.16 AU. The rms to the Keplerian fit is 2.96, yielding $\chi_\nu^2 = 1.65$. This is

TABLE 1

VELOCITIES FOR HD 160691

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
1,118.8874......	−4.3	3.3
1,119.9022......	−4.8	2.9
1,120.8870......	−4.7	2.8
1,121.8928......	−4.3	2.9
1,236.2864......	−20.1	4.0
1,410.8977......	−40.8	2.8
1,412.9773......	−41.2	5.5
1,413.8981......	−33.8	2.8
1,630.3042......	46.2	3.3
1,683.0926......	49.0	3.8
1,684.1320......	46.2	4.0
1,718.1184......	33.8	3.6
1,742.9096......	21.1	3.2
1,743.9240......	30.7	3.8
1,745.0440......	19.4	3.2
1,766.9330......	11.3	3.1
1,767.9689......	13.4	3.2
1,827.8973......	0.6	3.0
1,828.8866......	6.4	3.8
1,829.8890......	0.0	3.5
1,855.9058......	−1.1	4.6

TABLE 2

VELOCITIES FOR HD 27442

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
831.0816........	−47.5	2.4
1,118.1404......	−11.5	2.2
1,525.9634......	2.1	2.0
1,527.0333......	−7.5	2.4
1,630.9035......	−44.4	2.2
1,745.3341......	−23.1	2.3
1,767.3337......	−13.5	2.8
1,768.3132......	−17.3	2.5
1,828.1498......	13.2	2.5
1,830.0084......	11.8	3.2
1,856.1407......	19.6	2.6
1,857.0932......	20.1	3.9
1,919.0796......	0.0	2.7
1,921.1039......	3.6	2.3

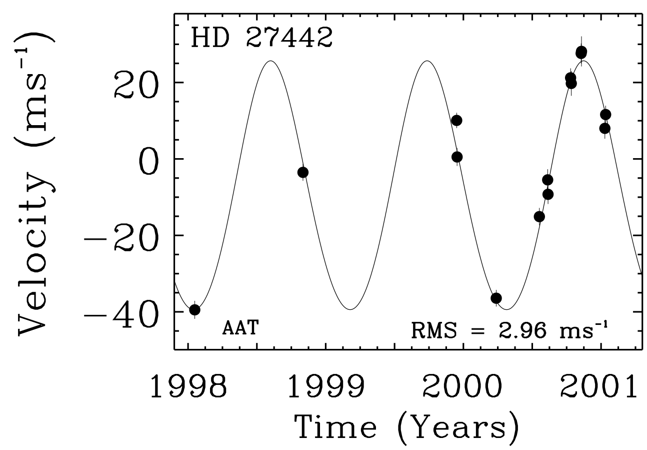

FIG. 6.—Doppler velocities for HD 27442. The rms to the best-fit Keplerian (*solid line*) is 2.9 m s^{-1}. The period is 415.2 days, and the semiamplitude is 32.5 m s^{-1}. Assuming the mass of HD 27442 is 1.2 $M_{\odot}$, the minimum (M sin i) mass of the companion is 1.35 M_J. The orbit of this planet is similar to the Earth in both semimajor axis, $a = 1.16$ AU, and eccentricity, $e = 0.058$. This is the only known planet orbiting beyond 0.15 AU that is in a circular orbit, similar to solar system planets.

TABLE 3

ORBITAL PARAMETERS

Parameter	HD 160691	HD 27442
Orbital period P (days)	743 (10)	415.2 (5)
Velocity amplitude$K$ (m s^{-1})......	53.6 (2)	32.5 (2)
Eccentricity e........................	0.62 (0.05)	0.058 (0.05)
ω (deg)...........................	305 (5)	347 (20)
Periastron time (JD)................	2,451,626.8 (5)	2,451,849.3 (4)
M sin i (M_J)........................	1.97 (0.14)	1.35 (0.11)
a (AU)..............................	1.65 (0.12)	1.16 (0.11)
rms (m s^{-1})........................	2.98	2.96

the only planet found to date orbiting beyond 0.15 AU in an orbit as circular as solar system planets. Orbital parameters for both HD 160691 and HD 27442 are listed in Table 3.

4. ORBITAL SOLUTIONS FOR HD 134987, HD 13445, HD 75289, AND HD 17051

Keplerian orbital parameters for four previously announced planet candidates have been confirmed by our AAT observations. The high precision of these data will be a powerful tool in the search for additional planetary companions to these stars.

4.1. *HD 134987*

The planet orbiting HD 134987 (HR 5657, G5 V) was announced from the Keck survey in 1999. As outlined in Vogt et al. (2000), this star is similar to 51 Pegasi in spectral type, enhanced metallicity, and low chromospheric activity.

A total of 11 observations of this star have been made by the AAT between 1998 April and 2000 July. These observations are listed in Table 4 and shown graphically in Figure 7. The AAT derived orbital parameters are consistent with Vogt et al. (2000).

4.2. *HD 13445*

A planet orbiting the nearby star HD 13445 (GL 86, HIP 10138, K1 V) was announced by the CORALIE team in 1999 (Queloz et al. 2000). In addition to the short-period Keplerian orbit, they report a long-term linear trend of -0.36 m s^{-1} day^{-1}. The rms to their Keplerian fit plus linear trend is 7 m s^{-1}.

This star has been observed 23 times as part of the Anglo-Australian Survey. These observations are listed in Table 5. The first observation was made in 1998 January, and the observations span 3 yr. As shown in Figure 8, these observations confirm the CORALIE result (Queloz et al. 2000). The rms to our fit of a Keplerian plus linear trend is 3.66 m s^{-1}, yielding $\chi_\nu^2 = 0.86$, slightly better than expected based on our estimated measurement error.

TABLE 4

VELOCITIES FOR HD 134987

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
917.2282........	0.0	5.6
1,003.0032......	−14.6	7.2
1,213.2775......	−12.1	4.7
1,276.0475......	−19.2	6.5
1,382.9573......	75.2	5.4
1,413.8811......	30.9	2.5
1,630.2677......	89.3	4.1
1,683.0609......	25.5	5.0
1,706.0960......	−0.6	5.9
1,717.9564......	−4.8	4.3
1,742.9340......	−8.2	3.5

TABLE 5

VELOCITIES FOR HD 13445

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
831.0350........	83.5	4.0
1,211.9651......	338.2	5.7
1,213.9815......	398.5	5.3
1,214.9298......	349.9	4.7
1,235.9312......	−277.2	5.2
1,236.9078......	−333.5	5.5
1,383.2736......	0.0	4.8
1,387.3139......	356.6	4.0
1,411.2467......	−406.7	4.9
1,413.2313......	−255.3	4.0
1,414.3164......	−88.1	4.2
1,473.0974......	−403.8	4.3
1,525.9320......	79.6	4.9
1,526.9613......	207.6	4.8
1,743.3292......	−459.4	6.5
1,745.2853......	−204.5	5.3
1,828.1337......	228.2	5.2
1,829.0121......	213.2	5.4
1,829.9880......	150.5	6.3
1,856.1052......	−160.9	6.2
1,918.9660......	−209.3	4.6
1,919.9811......	−41.7	4.8
1,921.0019......	97.0	5.0

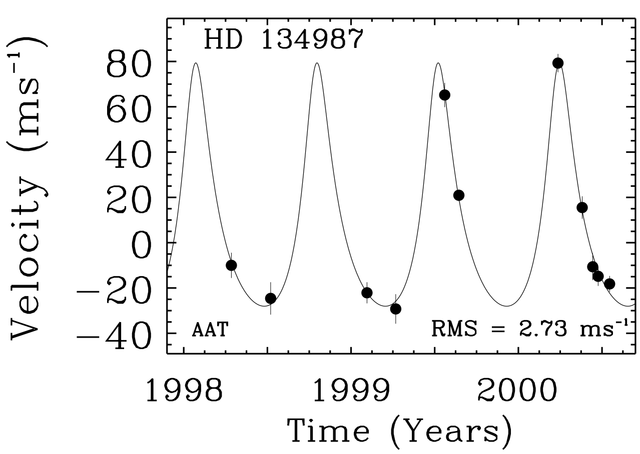

FIG. 7.—Doppler velocities for HD 134987 (G5 V). The solid line is a Keplerian orbital fit with a period of 264.6 days, a semiamplitude of 53.7 m s^{-1}, and an eccentricity of 0.37, yielding a minimum ($M \sin i$) of 1.63 M_J for the companion. The rms of the Keplerian fit is 2.7 m s^{-1}. These results are consistent with Vogt et al. (2000).

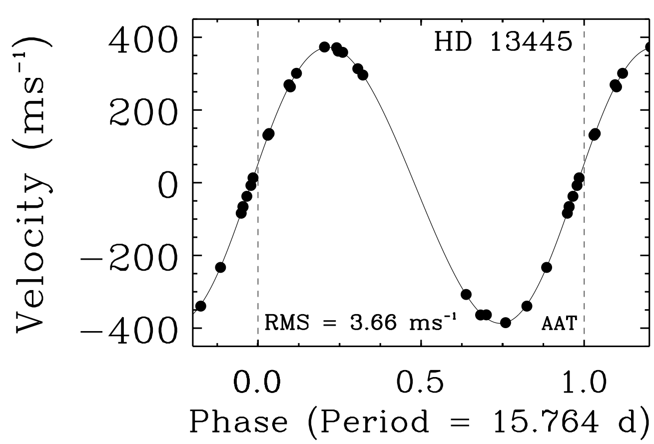

FIG. 8.—Phased Doppler velocities for HD 13445 (K1 V). The solid line is a Keplerian orbital fit with a period of 15.764 days, a semiamplitude of 379 m s^{-1}, and an eccentricity of 0.046, yielding a minimum ($M \sin i$) of 4.04 M_J for the companion. The rms of the Keplerian fit is 3.7 m s^{-1}. A linear trend of -108.1 m s^{-1} yr^{-1} has been removed from these velocities. These results are consistent with Queloz et al. (2000), with the possible exception of the linear trend.

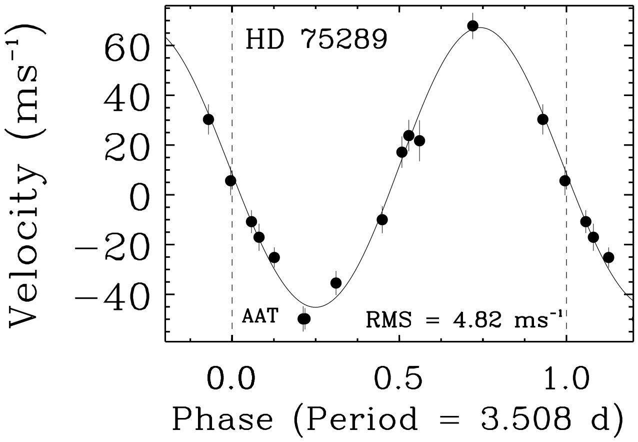

FIG. 9.—Phased Doppler velocities for HD 75289 (G0 V). The solid line is a Keplerian orbital fit with a period of 3.508 days, a semiamplitude of 56 m s^{-1}, and an eccentricity of 0.01, yielding a minimum (M sin i) of 0.45 M_J for the companion. The rms of the Keplerian fit is 4.8 m s^{-1}. These results are consistent with Udry et al. (2000).

Our derived orbital parameters agree with the CORALIE results within measurement error, with the possible exception of the linear trend. The simultaneous best fit to the AAT velocities gives a linear trend of -0.296 ± 0.005 m s^{-1} day^{-1}, about 20% smaller than that, -0.36 m s^{-1} day^{-1}, found by Queloz et al. (2000) from their CORALIE data. With their lower precision CORAVEL data, they find a steeper linear trend of -0.5 m s^{-1} day^{-1} spanning 1980 to the present. The trend for HD 13445 implies the presence of an additional companion with a period much longer than 10 yr and an amplitude greater than 1 km s^{-1}. It could be a low-mass stellar companion (Queloz et al. 2000).

4.3. *HD 75289*

The CORALIE team (Udry et al. 2000) have announced a "51 Peg–like" planet orbiting the star HD 75289 (HR 3497, HIP 43177, G0 V). Their observations were carried out between 1998 November and 1999 October and yield an rms to a Keplerian fit of 7.5 m s^{-1}. This star has been observed 13 times as part of the Anglo-Australian Planet Search. The first observation was made in 1998 January, and the observations span 3 yr. These velocities are listed in Table 6. As shown in Figure 9, these observations confirm the CORALIE result. The rms velocity residual to our Keplerian fit is 4.82 m s^{-1}, yielding $\chi_\nu^2 = 1.13$.

TABLE 6

VELOCITIES FOR HD 75289

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
830.1656	−0.8	4.6
914.9334	−39.8	4.3
1,212.1495	40.3	6.1
1,213.1426	−39.9	5.1
1,214.2518	33.8	6.3
1,236.9418	15.6	5.8
1,274.0100	31.7	8.2
1,275.9947	−15.2	4.1
1,631.0085	−25.4	4.9
1,717.9152	−7.1	5.5
1,856.2491	27.1	6.3
1,919.1969	0.0	5.4
1,920.1472	77.9	5.2

TABLE 7

VELOCITIES FOR HD 17051

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
1,118.1146	−55.1	4.4
1,235.9437	39.5	5.0
1,383.2779	−71.5	7.4
1,413.2245	−72.3	6.2
1,473.1000	0.0	4.8
1,525.9348	47.9	4.6
1,526.9763	76.1	5.9
1,743.3364	−32.3	5.9
1,745.2936	−50.1	5.0
1,828.1295	66.7	5.6
1,856.1093	62.5	5.3
1,856.9355	44.5	8.6
1,918.9703	−2.7	5.4

4.4. *HD 17051*

In 1998 June the ESO Precise Radial Velocity Survey announced a planet orbiting HD 17051 (ι Hor, HR 810, HIP 12653, G0 V) with a 600 day orbit (Kurster et al. 1999; see also Glanz 1998). On the basis of the same data, they later announced the planet had a period of 320 days (Kurster et al. 2000). Their data set consists of 95 measurements taken between late 1992 and early 1998. They report a Keplerian semiamplitude of 67 m s^{-1}. The rms velocity residual to their Keplerian fit is 27 m s^{-1}, while they estimate their measurement error to be 17 m s^{-1}. They attribute the difference to stellar activity. A stellar Doppler "jitter" of 20 m s^{-1} would account for the difference between the internal measurement error and the observed scatter to a Keplerian fit.

The Anglo-Australian Planet Search began observing HD 17051 in 1998 November. A total of 13 observations

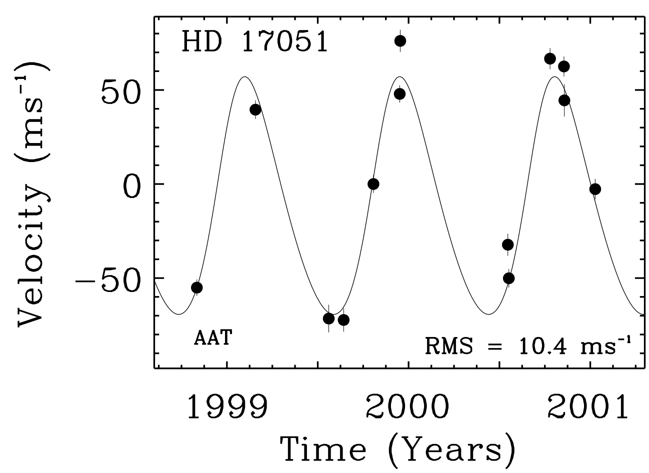

FIG. 10.—Doppler velocities for HD 17051 (G0 V). The solid line is a Keplerian orbital fit with a period of 312 days, a semiamplitude of 63 m s^{-1}, and an eccentricity of 0.15, yielding a minimum (M sin i) mass of 2.13 M_J for the companion. The rms of the Keplerian fit, 10.4 m s^{-1}, is twice the internal measurement error, consistent with the observed chromospheric activity and youth of this star. These results are consistent with Kurster et al. (2000).

TABLE 8

Orbital Parameters

Parameter	HD 134987	HD 13445[a]	HD 75289	HD 17051
Orbital period P (days)	264.6 (5)	15.764 (0.005)	3.508 (0.001)	312 (5)
Velocity amplitude K (m s^{-1})......	53.7 (4)	379 (1)	56 (1)	63 (4)
Eccentricity e	0.37 (0.12)	0.046 (0.002)	0.014 (0.005)	0.15 (0.05)
ω (deg)	345 (10)	260 (3)	0	309 (5)
Periastron time (JD)	2,451,628.8 (4)	2,451,225.1 (0.2)	2,451,214.5 (0.001)	2,451,492.8 (4)
$M_{\rm Star}$ $(M_\odot)^{\rm b}$	1.05	0.8	1.15	1.03
M sin i (M_J)	1.63	4.04	0.46	2.13
a (AU)	0.82	0.114	0.047	0.91
rms (m s^{-1})	2.73	3.66	4.82	10.4

[a] Additional slope is -108.1 ± 2 m s^{-1} yr^{-1}.
[b] Stellar masses from discovery papers.

have been made through 2001 January, as listed in Table 7 and shown in Figure 10. The solid line in Figure 10 is the best-fit Keplerian to the measured Doppler velocities. Within measurement error, we confirm the orbital parameters of Kurster et al. (2000). The rms to the Keplerian fit to the AAT data is 10.4 m s^{-1}, about twice the estimated measurement error.

As Kurster et al. (2000) note, HD 17051 is a young, chromospherically active G0 V star, consistent with the measured log $R'(HK) = -4.65$ (Henry et al. 1996), and a rotation period of 8 days (Saar & Osten 1997; Saar et al. 1997). Saar et al. (1998) find the Doppler "jitter" corresponding to this level of activity to be 10 m s^{-1}, consistent with the rms to the Keplerian fit to the AAT data. Table 8 lists the orbital parameters for these four stars based on the AAT measurements.

5. DISCUSSION

The two newly detected planets announced here both orbit beyond 1 AU. HD 160691 is typical of the examples of such planets discovered to date, moving on a highly elliptical orbit. In contrast, HD 27442 is in an Earth-like orbit, with a semimajor axis of 1.16 AU and an eccentricity of 0.058 ± 0.05 (consistent with circular). This is the first planet to be discovered orbiting beyond 0.15 AU in a circular orbit like the planets of our solar system.

The AAT data provide the first confirmation of orbital parameters of four planets recently announced from the Keck, CORALIE, and ESO planet searches. In addition, the AAT data appear to rule out the claimed planet around HD 196378.

Two broad strategies are being pursued by the various groups carrying out precision velocity surveys. Several groups are carrying out surveys with precision of 10–20 m s^{-1}. There are several advantages to this strategy. Relatively low S/N ($\sim$70) spectra, or small wavelength coverage ($\sim$50 Å), are required to achieve this level of precision, and data reduction strategies are simplified. A precision of 10 m s^{-1} allows the reliable detection of planets that induce amplitudes of 30 m s^{-1} or larger. Since only these large-amplitude signals are detectable, chromospherically active stars with associated Doppler "jitter" of 10–20 m s^{-1}, such as HD 17051, remain viable candidates.

The other strategy is to pursue much higher precision, 3 m s^{-1} or better. This strategy carries several penalties, including the need for large wavelength coverage ($\gtrsim$1000 Å), high S/N ($\gtrsim$200), and complex data analysis. The payoff for such a strategy is the ability to detect lower mass planets in short-period orbits and Jupiter-like planets in distant (>4 AU) orbits.

To illustrate this, consider the problem of detecting a Jupiter analog. Jupiter induces a Doppler velocity variation in the Sun with an amplitude of 12.5 m s^{-1}. However, the mean expectation value for sin i of $\pi/4$ reduces this to a typical amplitude of 10 m s^{-1} in a Doppler velocity survey. The top panel of Figure 11 shows synthetic observations of a Jupiter analog with a measurement uncertainty of 5 m s^{-1}. The solid line is a best-fit Keplerian to this data. The result is an unconvincing 2 σ detection with no constraint on orbital eccentricity. The lower panel shows the same situation but for 2 m s^{-1} measurement uncertainties. In this case a solid 5 σ detection is made, and the eccentricity is determined to within $\pm$0.05. The eccentricity of a 3 σ detection is poorly constrained to within $\pm$0.2. Without knowledge of the orbital eccentricity, it is not possible to categorize a Jupiter-mass companion at 5 AU as a solar system analog. True solar system analogs must reside in circular orbits.

The Anglo-Australian Planet Search has been surveying the 200 brightest dwarf and subgiant stars ranging in spectral type from late F to early M and south of declination $-20°$ since 1998 January. Long-term photon-limited precision of 3 m s^{-1} has been achieved, unique among the southern hemisphere precision velocity surveys. The long-

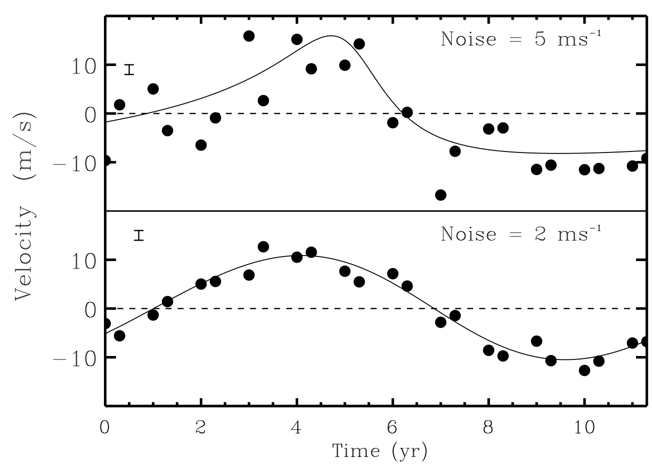

Fig. 11.—Simulated Jupiter signal observed with a precision of 5 and 2 m s^{-1}. Solid lines are best-fit Keplerians to the simulated data sets. With measurement precision of 5 m s^{-1}, an unreliable 2 σ detection is obtained with no information on the orbital eccentricity. With precision of 2 m s^{-1}, a solid 5 σ detection is made, and the eccentricity is determined to within $\pm$0.05.

term goal of this project is to maintain and improve this precision for another decade to allow for the detection of true solar system analogs, Jupiter-mass planets orbiting beyond 4 AU.

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