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Extrasolar planets around HD 196050, HD 216437 and HD 160691

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ABSTRACT

We report precise Doppler measurements of the stars HD 216437, HD 196050 and HD 160691 obtained with the Anglo-Australian Telescope using the UCLES spectrometer together with an iodine cell as part of the Anglo-Australian Planet Search. Our measurements reveal periodic Keplerian velocity variations that we interpret as evidence for planets in orbit around these solar type stars. HD 216437 has a period of 1294 ± 250 d, a semi-amplitude of 38 ± 3 m s^{-1} and an eccentricity of 0.33 ± 0.09. The minimum (M sin i) mass of the companion is 2.1 ± 0.3 $M_{\rm JUP}$ and the semi-major axis is 2.4 ± 0.5 au. HD 196050 has a period of 1300 ± 230 d, a semi-amplitude of 49 ± 8 m s^{-1} and an eccentricity of 0.19 ± 0.09. The minimum mass of the companion is 2.8 ± 0.5 $M_{\rm JUP}$ and the semi-major axis is 2.4 ± 0.5 au. We also report further observations of the metal-rich planet bearing star HD 160691. Our new solution confirms the previously reported planet and shows a trend indicating a second, longer-period companion. These discoveries add to the growing numbers of mildly eccentric, long-period extrasolar planets around metal-rich Sun-like stars.

Key words: stars: individual: HD 196050 – stars: individual: HD 160691 – stars: individual: HD 216437 – planetary systems.

1 INTRODUCTION

Radial velocity programmes have now found around 80 extrasolar planets orbiting stars in the solar neighbourhood. As the time-baseline and precision of surveys improve, new realms of possible planets are being explored. Discoveries include the first system of multiple planets orbiting a Sun-like star (Butler et al. 1999); the first planet seen in transit (Henry et al. 2000; Charbonneau et al. 2000); the first two sub-Saturn-mass planets (Marcy, Butler & Vogt 2000); and the Anglo-Australian Planet Searches' (AAPS) discovery of the first planet in a circular orbit outside the 0.1-au tidal-circularization radius (Butler et al. 2001). The AAPS began operation in 1998, its southern hemisphere location completing all-sky coverage of the brightest stars at precisions reaching 3 m s^{-1}. The AAPS has already found a number of extrasolar planets (Butler et al. 2001, 2002; Tinney et al. 2001, 2002a; Jones et al. 2002). In this paper we present further results from this programme.

2 THE ANGLO-AUSTRALIAN PLANET SEARCH

The Anglo-Australian Planet Search (AAPS) is carried out on the 3.9-m Anglo-Australian Telescope using the University College London Echelle Spectrograph (UCLES), operated in its 31 line mm^{-1} mode together with an I_2 absorption cell. UCLES now uses the AAO's EEV 2048 × 4096 13.5-μm pixel CCD, which provides excellent quantum efficiency across the 500–620 nm I_2 absorption line region. Despite this search taking place on a common-user telescope with frequent changes of instrument, we achieve a 3 m s^{-1} precision down to the $V = 7.5$ mag limit of the survey (Butler et al. 2001; fig. 1 in Jones et al. 2002). The fundamental limit to the precision that can be achieved for our sample is set by a combination of signal-to-noise ratio (S/N) (which is dependent on seeing and weather conditions), and the intrinsic velocity stability of our target stars, rather than our observing technique (Butler et al. 1996). Intrinsic velocity instability in these stars – often called 'jitter' – is induced by surface inhomogeneities due to activity (e.g. spots, plages or flares) combined with rotation (Saar, Butler & Marcy 1998; Saar & Fischer 2000). It is difficult to tell whether a residual scatter of

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Table 1. Anglo-Australian planet search target list 1998 January to 2002 March. Doppler companions discovered so far are indicated in the final column.

HD	RA	Dec	Equinox	*V*	Sp	Doppler companion?
225213	00 05 24.2	−37 21 31	2000.0	8.56	M2V	
142	00 06 19.0	−49 04 30	2000.0	5.70	G1IV	Planet (Tinney et al. 2002a)
1581	00 20 02.0	−64 52 39	2000.0	4.23	G0V	
2039	00 24 20.0	−56 39 00	2000.0	9.00	G4V	Planet (Tinney et al. 2002c)
2151	00 25 45.1	−77 15 15	2000.0	2.80	G2IV	
2587	00 29 10.0	−50 36 42	2000.0	8.46	G7V	
3277	00 35 34.0	−39 44 47	2000.0	7.45	G6V	Star (Blundell et al., in preparation)
3823	00 40 26.4	−59 27 16	2000.0	5.89	G1V	
4308	00 44 39.0	−65 38 52	2000.0	6.55	G4V	
6735	01 07 32.0	−41 44 50	2000.0	7.01	F9V	
7199	01 10 47.0	−66 11 16	2000.0	8.06	K0V	
7570	01 15 11.0	−45 31 56	2000.0	4.97	G0V	Star (Blundell et al., in preparation)
9280	01 31 14.0	−10 53 48	2000.0	8.03	G8V	
10180	01 37 54.0	−60 30 41	2000.0	7.33	G2V	
10360	01 39 47.4	−56 11 53	2000.0	5.87	K0V	
10361	01 39 47.8	−56 11 41	2000.0	5.76	K5V	
10647	01 42 29.0	−53 44 26	2000.0	5.52	F9V	
10700	01 44 04.0	−15 56 15	2000.0	3.50	G8V	
11112	01 48 20.0	−41 29 43	2000.0	7.13	G3V	
12387	02 00 32.0	−40 43 51	2000.0	7.37	G4V	
13445	02 10 25.6	−50 49 28	2000.0	6.12	K1V	Planet (Butler et al. 2001)
16417	02 36 58.6	−34 34 42	2000.0	5.79	G5IV	
17051	02 42 33.2	−50 48 03	2000.0	5.40	G3IV	Planet (Butler et al. 2001)
18709	02 58 59.0	−43 44 53	2000.0	7.39	G1V	
18907	03 01 37.7	−28 05 30	2000.0	5.89	G5IV	Star (Blundell et al., in preparation)
19632	03 08 52.0	−24 53 17	2000.0	7.29	G5V	
20029	03 11 53.0	−39 01 23	2000.0	7.05	F9V	
20201	03 12 55.0	−47 09 20	2000.0	7.27	G0V	
20766	03 17 45.0	−62 34 37	2000.0	5.53	G3V	
20794	03 19 55.7	−43 04 11	2000.0	4.27	G8V	
20807	03 18 12.9	−62 30 23	2000.0	5.24	G1V	
20782	03 20 04.0	−28 51 13	2000.0	7.36	G3V	
22104	03 27 37.0	−73 26 24	2000.0	8.32	G5V	
23127	03 39 24.0	−60 04 42	2000.0	8.58	G5V	
23079	03 39 43.0	−52 54 57	2000.0	7.12	G0V	Planet (Tinney et al. 2002a)
23484	03 44 09.0	−38 16 54	2000.0	6.99	K1V	
24112	03 48 47.0	−40 23 58	2000.0	7.24	F9V	
25874	04 02 27.0	−61 21 26	2000.0	6.74	G4V	
25587	04 02 43.0	−27 29 00	2000.0	7.40	F8V	
26491	04 07 21.6	−64 13 21	2000.0	6.38	G3V	Star (Blundell et al., in preparation)
26754	04 10 07.0	−61 35 56	2000.0	7.16	F9V	
27442	04 16 28.9	−59 18 07	2000.0	4.44	K2IV	Planet (Butler et al. 2001)
28255A	04 24 12.2	−57 04 17	2000.0	6.29	G4V	
28255B	04 24 12.2	−57 04 17	2000.0	6.60	G6V	
30177	04 41 54.0	−58 01 15	2000.0	8.41	G8V	Planet (Tinney et al. 2002c)
30295	04 42 20.0	−61 37 17	2000.0	8.86	G9V	
30876	04 49 53.0	−35 06 29	2000.0	7.49	K2V	
31527	04 55 38.0	−23 14 31	2000.0	7.49	G1V	
31827	04 56 18.0	−51 02 50	2000.0	8.26	G8V	
33811	05 10 43.0	−44 34 20	2000.0	8.71	G8V	
36108	05 28 21.0	−22 26 04	2000.0	6.78	G1V	
38283	05 37 02.0	−73 41 58	2000.0	6.69	G0V	
39091	05 37 09.8	−80 28 09	2000.0	5.65	G1V	Planet (Jones et al. 2002)
38110	05 42 59.0	−07 28 51	2000.0	8.18	G5V	
38382	05 44 28.0	−20 07 35	2000.0	6.34	G0V	
38973	05 46 28.0	−53 13 09	2000.0	6.63	G1V	
39213	05 49 16.0	−37 30 48	2000.0	8.96	G9V	Star (Blundell et al., in preparation)
40307	05 54 04.0	−60 01 24	2000.0	7.17	K2V	
42024	06 06 12.0	−45 48 58	2000.0	7.24	F9V	Star (Blundell et al., in preparation)
43834	06 10 14.4	−74 45 11	2000.0	5.09	G6V	
42902	06 11 14.0	−44 13 28	2000.0	8.92	G2V	
44447	06 15 06.0	−71 42 10	2000.0	6.62	F9V	
44120	06 16 18.5	−59 12 49	2000.0	6.43	G0V	
44594	06 20 06.0	−48 44 26	2000.0	6.61	G4V	

Table 1 – *continued*

HD	RA	Dec	Equinox	V	Sp	Doppler companion?
45289	06 24 24.0	−42 50 28	2000.0	6.67	G5V	
45701	06 24 26.0	−63 25 44	2000.0	6.45	G4V	
52447	06 57 26.0	−60 51 05	2000.0	8.38	G1V	
53705	07 03 57.3	−43 36 29	2000.0	5.54	G3V	
53706	07 03 59.0	−43 36 44	2000.0	6.83	G8V	
55720	07 11 32.0	−49 25 29	2000.0	7.50	G6V	
55693	07 13 03.0	−24 13 33	2000.0	7.17	G4V	
59468	07 27 26.0	−51 24 09	2000.0	6.72	G5V	
61686	07 39 35.0	−26 28 28	2000.0	8.54	G5V	
64184	07 49 27.0	−59 22 52	2000.0	7.49	G5V	Star (Blundell et al., in preparation)
65907A	07 57 46.9	−60 18 12	2000.0	5.60	G0V	
67199	08 02 31.0	−66 01 18	2000.0	7.18	K1V	
67556	08 07 09.0	−36 22 54	2000.0	7.30	F8V	
69655	08 15 26.0	−52 03 37	2000.0	6.63	G0V	
70642	08 21 28.0	−39 42 21	2000.0	7.17	G5V	
70889	08 23 32.0	−27 49 21	2000.0	7.09	G1V	
72769	08 33 46.0	−23 21 18	2000.0	7.22	G7V	
73121	08 35 12.6	−39 58 12	2000.0	6.47	G1V	
73526	08 37 17.0	−41 19 10	2000.0	8.99	G7V	Planet (Tinney et al. 2002c)
73524	08 37 20.0	−40 08 51	2000.0	6.53	G1V	
74868	08 44 51.0	−44 32 34	2000.0	6.56	F9V	
75289	08 47 41.0	−41 44 14	2000.0	6.35	G0V	Planet (Butler et al. 2001)
76700	08 53 54.0	−66 48 05	2000.0	8.16	G7V	Planet (Tinney et al. 2002c)
78429	09 06 39.0	−43 29 32	2000.0	7.31	G4V	
80913	09 12 26.0	−81 46 08	2000.0	7.49	F9V	
80635	09 20 27.0	−17 25 29	2000.0	8.80	G6V	
82082	09 27 32.0	−58 05 40	2000.0	7.20	G1V	
83443	09 37 12.0	−43 16 19	2000.0	8.23	G9V	Planet (Butler et al. 2002)
83529A	09 37 29.0	−49 59 27	2000.0	6.97	G0V	
84117	09 42 15.0	−23 54 58	2000.0	4.93	F8V	
85683	09 51 41.0	−54 39 35	2000.0	7.34	F8V	
86819	10 00 06.0	−36 02 36	2000.0	7.38	G0V	
88742	10 13 25.0	−33 01 55	2000.0	6.38	G1V	
92987	10 43 36.0	−39 03 31	2000.0	7.03	G3V	
93385	10 46 15.0	−41 27 52	2000.0	7.49	G1V	
96423	11 06 20.0	−44 22 24	2000.0	7.23	G5V	
101614	11 41 27.0	−41 01 06	2000.0	6.86	G1V	
101959	11 43 57.0	−29 44 51	2000.0	6.97	F9V	
102117	11 44 50.0	−58 42 12	2000.0	7.47	G6V	
102365	11 46 31.1	−40 30 02	2000.0	4.91	G3V	
102438	11 47 15.7	−30 17 13	2000.0	6.48	G5V	
105328	12 07 39.0	−23 58 33	2000.0	6.72	G2V	
106453	12 14 42.0	−24 46 34	2000.0	7.47	G6V	
107692	12 22 45.0	−39 10 38	2000.0	6.70	G3V	
108147	12 25 46.0	−64 01 22	2000.0	6.99	F8V	
108309	12 26 48.2	−48 54 48	2000.0	6.26	G3-5V	
109200	12 33 32.0	−68 45 20	2000.0	7.13	K0V	
114613	13 12 03.2	−37 48 11	2000.0	4.85	G3V	
114853	13 13 52.0	−45 11 10	2000.0	6.93	G3V	
117618	13 32 26.0	−47 16 18	2000.0	7.17	G1V	
118972	13 41 04.0	−34 27 50	2000.0	6.92	K0V	
120237	13 48 55.0	−35 42 14	2000.0	6.56	F9V	
120690	13 51 20.0	−24 23 27	2000.0	6.43	G6V	Star (Blundell et al., in preparation)
121384	13 56 33.0	−54 42 16	2000.0	6.00	G6IV-V	Star (Blundell et al., in preparation)
122862	14 08 27.1	−74 51 01	2000.0	6.02	G2-3IV	
125072	14 19 05.0	−59 22 37	2000.0	6.66	K4V	
GL551	14 29 42.2	−62 40 48	2000.0	11.01	M5V	
128620	14 39 35.9	−60 50 07	2000.0	−0.01	G2V	
128621	14 39 36.1	−60 50 08	2000.0	1.33	K1V	
129060	14 44 14.0	−69 40 28	2000.0	6.99	F9V	
131923	14 58 08.8	−48 51 47	2000.0	6.35	G3-5V	Star (Blundell et al., in preparation)
134331	15 10 42.0	−43 43 48	2000.0	7.01	G2V	
134330	15 10 43.0	−43 42 58	2000.0	7.60	G6V	
134060	15 10 44.6	−61 25 21	2000.0	6.30	G2V	

Table 1 – *continued*

HD	RA	Dec	Equinox	*V*	Sp	Doppler companion?
134987	15 13 28.7	−25 18 33	2000.0	6.45	G4V	Planet (Vogt et al. 2000)
134606	15 15 15.0	−70 31 11	2000.0	6.86	G7V	
136352	15 21 48.2	−48 19 04	2000.0	5.65	G3-5V	
140901	15 47 29.0	−37 54 59	2000.0	6.01	G6V	
143114	15 59 38.0	−29 37 58	2000.0	7.34	G1V	
144628	16 09 43.0	−56 26 43	2000.0	7.11	K0V	
145825	16 14 12.0	−31 39 47	2000.0	6.55	G3V	Star (Blundell et al., in preparation)
147722	16 24 39.6	−29 42 12	2000.0	6.50	G0IV	
147723	16 24 39.7	−29 42 17	2000.0	5.84	G0IV	
150248	16 41 50.0	−45 22 07	2000.0	7.03	G4V	Star (Blundell et al., in preparation)
154577	17 10 11.0	−60 43 42	2000.0	7.38	K1V	
155974	17 16 21.5	−35 44 58	2000.0	6.12	G0IV-V	
156274A	17 19 03.0	−46 38 13	2000.0	7.0:	M0V	Star (Blundell et al., in preparation)
156274B	17 19 04.3	−46 38 10	2000.0	5.52	K0V	
158783	17 34 12.0	−54 53 43	2000.0	7.09	G4V	Star (Blundell et al., in preparation)
160691	17 44 08.7	−51 50 03	2000.0	5.15	G3IV-V	Planet (Butler et al. 2001, this paper)
161050	17 47 46.0	−63 33 45	2000.0	7.16	G1V	
161612	17 47 57.0	−34 01 07	2000.0	7.20	G7V	
162255	17 51 08.0	−22 55 14	2000.0	7.15	G3V	Star (Blundell et al., in preparation)
164427	18 04 43.0	−59 12 36	2000.0	6.88	G2V	Brown dwarf (Tinney et al. 2001)
168871	18 24 33.0	−49 39 10	2000.0	6.45	G1V	
169586	18 26 41.0	−30 23 37	2000.0	6.75	F8V	Star (Blundell et al., in preparation)
GL729	18 49 49.0	−23 50 10	2000.0	10.46	M4V	
175345	18 56 00.0	−25 02 48	2000.0	7.37	F9V	Star (Blundell et al., in preparation)
177565	19 06 52.5	−37 48 37	2000.0	6.16	G5IV	
179949	19 15 33.0	−24 10 45	2000.0	6.25	F8V	Planet (Tinney et al. 2001)
181428	19 21 39.0	−29 36 19	2000.0	7.10	F9V	
183877	19 32 40.0	−28 01 11	2000.0	7.14	G5V	
187085	19 49 34.0	−37 46 50	2000.0	7.22	G0V	
189567	20 05 32.8	−67 19 15	2000.0	6.07	G3V	
190248	20 08 43.6	−66 10 55	2000.0	3.56	G6-8IV	
191408	20 11 11.9	−36 06 04	2000.0	5.32	K3V	
192310	20 15 17.4	−27 01 58	2000.0	5.73	K0V	
193193	20 19 45.0	−25 13 43	2000.0	7.20	G1V	
192865	20 21 36.0	−67 18 46	2000.0	6.91	F9V	
193307	20 21 41.0	−49 59 58	2000.0	6.27	G0V	
194640	20 27 44.0	−30 52 00	2000.0	6.61	G6V	
196050	20 37 52.0	−60 38 03	2000.0	7.50	G4V	Planet (this paper)
196800	20 40 22.0	−24 07 04	2000.0	7.21	G2V	
196068	20 41 45.0	−75 20 46	2000.0	7.18	G3V	
196378	20 40 02.3	−60 32 51	2000.0	5.11	F8V	
199288	20 57 40.0	−44 07 37	2000.0	6.52	G0V	
199190	21 00 06.0	−69 34 45	2000.0	6.86	G3V	
199509	21 09 22.0	−82 01 37	2000.0	6.98	G2V	
202560	21 17 15.0	−38 52 04	2000.0	6.69	M0V	
202628	21 18 27.0	−43 20 05	2000.0	6.75	G3V	
204385	21 30 48.0	−62 10 06	2000.0	7.14	G1V	
204961	21 33 34.0	−49 00 25	2000.0	8.66	G1V	
205390	21 36 41.0	−50 50 46	2000.0	7.15	K1V	
205536	21 40 31.0	−74 04 28	2000.0	7.07	G7V	
206395	21 43 02.0	−43 29 46	2000.0	6.67	F9V	
207129	21 48 15.8	−47 18 13	2000.0	5.58	G0V	
207700	21 54 46.0	−73 26 17	2000.0	7.43	G5V	
208487	21 57 20.0	−37 45 52	2000.0	7.47	F9V	
208998	22 01 37.0	−53 05 36	2000.0	7.12	G0V	
209268	22 03 35.0	−55 58 38	2000.0	6.88	F9V	
209653	22 07 31.0	−68 01 23	2000.0	6.99	G0V	
210918	22 14 38.6	−41 22 54	2000.0	6.23	G5V	Star (Blundell et al., in preparation)
211317	22 18 50.0	−68 18 47	2000.0	7.26	G4V	
212330	22 24 56.4	−57 47 50	2000.0	5.32	G3IV	
212168	22 25 51.0	−75 00 56	2000.0	6.04	G3V	
212708	22 27 25.0	−49 21 58	2000.0	7.48	G7V	
213240	22 31 00.0	−49 26 00	2000.0	6.81	G1V	Planet (Santos et al. 2001)
214759	22 40 55.0	−31 59 23	2000.0	7.41	G8V	

2002MNRAS.337.1170J

Table 1 – *continued*

HD	RA	Dec	Equinox	V	Sp	Doppler companion?
214953	22 42 36.9	−47 12 38	2000.0	5.98	G0V	
216435	22 53 37.9	−48 35 53	2000.0	6.04	G0V	
216437	22 54 39.4	−70 04 25	2000.0	6.05	G2-3IV	Planet (this paper)
217958	23 04 33.0	−25 41 27	2000.0	8.05	G4V	
217987	23 05 51.2	−35 51 11	2000.0	7.35	M2V	
219077	23 14 06.6	−62 42 00	2000.0	6.12	G8V	
220507	23 24 42.0	−52 42 08	2000.0	7.59	G5V	
221420	23 33 19.5	−77 23 07	2000.0	5.81	G2V	
222237	23 39 37.0	−72 43 19	2000.0	7.09	K3V	
222335	23 39 51.0	−32 44 34	2000.0	7.18	G9V	
222480	23 41 08.0	−32 04 14	2000.0	7.11	G4V	
223171	23 47 21.0	−48 16 33	2000.0	6.89	G4V	

larger than 3 m s^{-1} is due to a small-amplitude planet, or jitter induced by star spots and/or activity. Only observations over a long enough period to allow the search for long-term periodicities can reveal the presence of such relatively small-amplitude long-period signals such as Jupiter. We intend to monitor all our targets for the lifetime of the survey, not just those that initially appear to be good planet candidates.

Our target sample which we have observed since 1998 is given in Table 1. It includes 178 late (IV–V) F, G and K stars with declinations below $\sim -20°$ and is complete to $V < 7.5$. We also observe sub-samples of 16 metal-rich ([Fe/H] > 0.3) stars with $V < 9.5$ and 7 M dwarfs with $V < 7.5$ and declinations below $\sim -20°$. The sample has been increased to around 300 solar-type stars to be complete to a magnitude limit of $V = 8$. Where age/activity information is available from $R'_{\rm HK}$ indices (Henry et al. 1996; Tinney et al. 2002b) we require target stars to have $R'_{\rm HK} < -4.5$ corresponding to ages greater than 3 Gyr. Stars with known stellar companions within 2 arcsec are removed from the observing list, as it is operationally difficult to get an uncontaminated spectrum of a star with a nearby companion. Spectroscopic binaries discovered during the programme have also been removed and are reported by Blundell et al. (in preparation). Otherwise there is no bias against observing multiple stars. The programme is also not expected to have any bias against brown dwarf companions. The observing and data processing procedures follow those described by Butler et al. (1996, 2001). The first observing run for the AAPS was in 1998 January, and the last run for which observations are reported here was in 2002 June.

Table 2. Radial Velocities (RV) for HD 216437 are referenced to the Solar system barycentre but have an arbitrary zero-point determined by the radial velocity of the template. The JDs are topocentric.

JD (−2 450 000)	RV (m s^{-1})	Uncertainty (m s^{-1})
830.9420	−37.7	4.7
1034.2251	−34.8	4.8
1386.3051	−2.7	5.6
1472.9552	5.5	4.1
1683.3146	36.4	4.7
1684.3276	34.9	4.2
1743.2343	51.7	6.0
1767.2046	38.4	4.3
1768.2248	34.2	5.2
1828.0427	43.6	5.2
1828.9634	41.8	5.1
1829.9568	44.4	5.6
1856.0478	31.5	7.4
1919.9294	29.7	5.2
1920.9255	30.2	6.5
2061.2884	−20.7	4.9
2092.2206	−14.5	5.0
2127.1981	−24.0	5.6
2154.1065	−29.2	4.6
2188.0807	−43.0	3.9
2387.3194	−21.1	4.2
2388.3068	−16.6	2.2
2389.2962	−22.1	6.6
2390.3183	−26.5	4.5
2422.3086	−27.4	3.9
2425.3260	−22.8	3.6
2456.2802	−20.8	4.0

3 STELLAR CHARACTERISTICS AND ORBITAL SOLUTION FOR HD 216437

HD 216437 (ρ Ind, HR 8701, HIP 113137) is a chromospherically inactive ($R'_{\rm HK} = -5.01$, Tinney et al. 2002b) G4IV–V star (Cayrel de Strobel et al. 1997). Its *Hipparcos* parallax of 37.7 ± 0.6 mas together with a V magnitude of 6.04 implies an absolute magnitudes of $M_V = 3.92 \pm 0.03$ (ESA 1997) and $M_{\rm bol} = 3.88 \pm 0.03$ (Cayrel de Strobel et al. 1997). There is no evidence for significant photometric variability in the 160 measurements made by the *Hipparcos* satellite. HD 216437 is known to be somewhat metal-enriched relative to the Sun (e.g. [Fe/H] = 0.1, Cayrel de Strobel et al. 1997). Recent high-resolution observations by Randich et al. (1999) have found HD 216437 to have a metallicity of [Fe/H] = 0.21 and a lithium abundance of 26 mÅ that is consistent with other similar metal-rich sub-giants. Interpolation between the tracks of Fuhrmann, Pfeiffer & Bernkopf (1997, 1998) indicates a mass of 1.15 ± 0.1 for metallicities between solar and [Fe/H] = 0.3.

The 27 Doppler velocity measurements of HD 216437, obtained between 1998 November and 2002 June, are listed in Table 2 and shown graphically in Fig. 1, along with the best-fitting Keplerian. The third column in Table 2, labelled ‘uncertainty’, is the velocity uncertainty produced by our least-squares fitting. This uncertainty includes the effects of photon-counting uncertainties, residual errors in the spectrograph PSF model, and variation in the underlying spectrum between the template and iodine epochs. All velocities are measured relative to the zero-point defined by the template

Table 3. Orbital parameters for the companions to HD 216437, HD 196050 and HD 160691. The solution for HD 160691b is for the case of a single Keplerian fit to the data whereas the fit for HD 160691c is based on a two Keplerian fit. HD 160691c is uncertain so its best fit values are shown in parentheses.

	HD 216437b	HD 196050b	HD 160691b	HD 160691c
Orbital period (d)	1294 ± 250	1300 ± 230	637 ± 8	(1500)
Eccentricity	0.33 ± 0.09	0.19 ± 0.09	0.31 ± 0.08	(0.8)
ω (°)	78 ± 9	200 ± 40	320 ± 30	(99)
Radial velocity semi-amplitude K (m s^{-1})	38 ± 3	49 ± 8	40 ± 5	(34)
Periastron time (HJD)	50679 ± 300	50955 ± 180	50959 ± 25	(51613)
$M \sin i$ (M_{JUP})	2.1 ± 0.3	2.8 ± 0.5	1.7 ± 0.2	(>1.5)
a (au)	2.4 ± 0.5	2.4 ± 0.5	1.5 ± 0.1	(>2.5)
rms residuals to fit (m s^{-1})	6.40	7.89	5.28	(5)

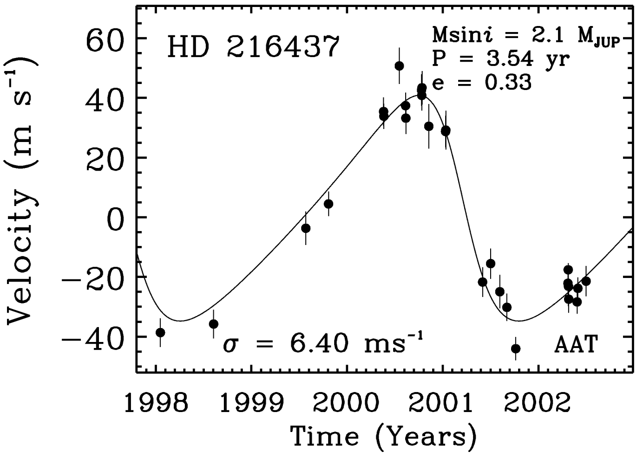

Figure 1. AAT Doppler velocities for HD 216437 from 1998 August to 2002 June. The solid line is a best-fitting Keplerian orbit with the parameters shown in Table 3. The rms of the velocities about the fit is 6.40 m s^{-1} consistent with our errors. Assuming 1.15 ± 0.10 M$_\odot$ for the primary, the minimum ($M \sin i$) mass of the companion is 2.1 ± 0.3 M_{JUP} and the semi-major axis is 2.4 ± 0.5 au.

observation. Only observations where the uncertainty is less than twice the median uncertainty are listed. The best-fitting Keplerian curve yields an orbital period of 1294 ± 250 d, a velocity amplitude of 38 ± 3 m s^{-1} and an eccentricity of 0.33 ± 0.09. The minimum ($M \sin i$) mass of the planet is 2.1 ± 0.3 M_{JUP}, and the semi-major axis is 2.4 ± 0.5 au. The rms to the Keplerian fit is 6.40 m s^{-1}, yielding a reduced chi-squared of 1.4. The properties of the extra-solar planet in orbit around HD 216437 are summarized in Table 3.

4 STELLAR CHARACTERISTICS AND ORBITAL SOLUTION FOR HD 196050

HD 196050 (HIP 101806) is a chromospherically inactive ($R'_{\mathrm{HK}} = -5.04$, Henry et al. 1996) G3V star (Houck & Cowley 1975). Its *Hipparcos* parallax of 21.3 ± 0.9 mas (ESA 1997) implies absolute magnitudes of $M_V = 4.14 \pm 0.05$ and $M_{\mathrm{bol}} = 3.94 \pm 0.05$ (Drilling & Landolt 2000). The fundamental parameters of HD 196050 have been examined via $B - V$ and Strömgren *ubvy* photometry (Olsen 1994). These suggest $T_{\mathrm{eff}} = 5590$ K. Based on interpolation between the evolutionary tracks by Fuhrmann et al. (1998) HD 196050 is thus estimated to have a metallicity of [Fe/H] = 0.3 ± 0.2 and a mass of 1.13 ± 0.1 M$_\odot$. HD 196050 is not detected as variable in the 144 measurements made by *Hipparcos*. It has recently been used as an infrared spectroscopic standard by the SOFI instrument on the New Technology Telescope at the European Southern Observatory in Chile.

Table 4. Radial Velocities (RV) for HD 196050 are referenced to the Solar system barycentre but have an arbitrary zero-point determined by the radial velocity of the template. The JDs are topocentric.

JD (−2451000)	RV (m s^{-1})	Uncertainty (m s^{-1})
118.9450	7.8	10.7
411.0456	52.8	8.0
472.9298	57.6	5.6
683.1958	56.8	6.2
706.1291	50.4	7.5
743.0754	49.5	6.0
745.1895	47.0	5.3
767.0285	37.3	5.7
770.1480	43.9	6.4
827.9868	16.4	6.7
855.9770	22.4	9.3
1010.2975	−18.0	6.6
1061.1955	−22.1	5.7
1092.1221	−15.6	6.4
1127.1045	−27.0	5.9
1128.0595	−29.9	7.9
1130.0415	−20.7	5.8
1151.9802	−25.7	6.0
1153.8857	−36.7	4.7
1186.9195	−40.6	4.0
1187.9811	−46.3	3.4
1188.9391	−44.4	11.3
1189.9371	−33.9	5.2
1360.2972	−11.9	6.1
1387.3049	−1.3	4.8
1388.2519	−6.7	4.7
1389.2115	−5.6	5.4
1390.2928	−6.9	5.3
1421.2467	23.1	5.7
1425.2942	19.2	4.7
1455.1542	5.6	3.7

The 31 Doppler velocity measurements of HD 196050, obtained between 1998 November and 2002 June, are listed in Table 4 in the same manner as for HD 216437 and shown graphically in Fig. 2. The best-fitting Keplerian curve yields an orbital period of 1300 ± 230 d, a velocity amplitude of 49 ± 8 m s^{-1} and an eccentricity of 0.19 ± 0.09. The minimum ($M \sin i$) mass of the planet is 2.8 ±

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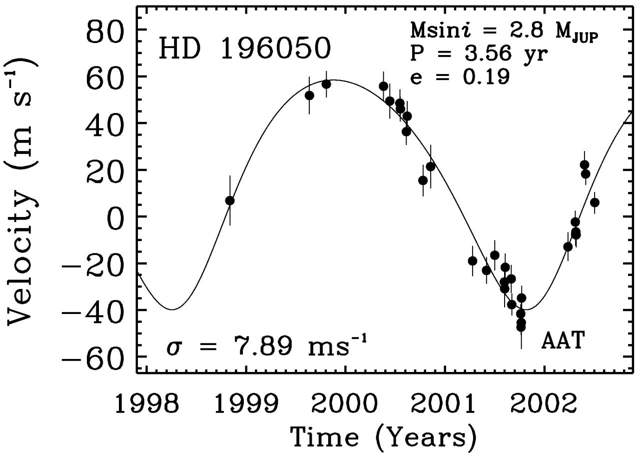

Figure 2. AAT Doppler velocities for HD 196050 from 1998 July to 2002 June. The solid line is a best-fitting Keplerian orbit with the parameters shown in Table 3. The rms of the velocities about the fit is 7.89 m s^{-1} consistent with our errors. Assuming 1.13 ± 0.1 M$_\odot$ for the primary, the minimum (M sin i) mass of the companion is 2.8 ± 0.5 $M_{\rm JUP}$ and the semi-major axis is 2.4 ± 0.5 au.

0.5 $M_{\rm JUP}$ and the semi-major axis is 2.4 ± 0.5 au. The rms to the Keplerian fit is 7.89 m s^{-1}, yielding a reduced chi-squared of 1.4. The properties of the extrasolar planet in orbit around HD 196050 are summarized in Table 3.

5 A NEW ORBITAL SOLUTION FOR HD 160691

We previously announced a companion to HD 160691 (Butler et al. 2001) based on data taken from 1998 November to 2000 November. Table 5 includes our data up until 2002 May. All the radial velocities presented in Table 5 have been computed using an improved template observation of HD 160691 and supersede those given previously. The best-fitting single Keplerian curve yields an orbital period of 637 ± 8 d, a velocity amplitude of 41 ± 4 m s^{-1} and an eccentricity of 0.31 ± 0.08. The minimum (M sin i) mass of the planet is 1.7 ± 0.2 $M_{\rm JUP}$ and the semi-major axis is 1.5 ± 0.1 au. The rms to the Keplerian fit is 5.28 m s^{-1}, yielding a reduced chi-squared of 1.5. The properties of the extrasolar planet in orbit around HD 160691 are summarized in Table 3.

The new velocities confirm the planet presented by Butler et al. (2001), though in addition, Fig. 3 also shows a trend indicating a second companion. The period of such an outer object is poorly constrained. Examination of the parameter space using the sum of two Keplerians indicates that the rms is currently minimized for the 'trend' being due to an eccentric (0.8) outer planet with a period of >kyr and M sin $i > 1.5$ $M_{\rm JUP}$ and an inner planet with an eccentricity of 0.3 period of 600 d and mass of 1.6 $M_{\rm JUP}$. However, the data are currently inadequate to provide a convincing case for this outer planet. The rms of the two-planet fit is 4.9 m s^{-1}, lower than the 5.3 m s^{-1} from the single planet plus linear trend fit, but not statistically compelling at this time. Thus these parameters for the putative outer planet are speculative pending further velocity measurements. Any follow-up observations should take this into account. We are mentioning the possibility of this object at this very early stage in order that any high precision imaging of HD 160691 may take this trend into account.

Table 5. Radial Velocities (RV) for HD 160691 are referenced to the Solar system barycentre but have an arbitrary zero-point determined by the radial velocity of the template. The JDs are topocentric.

JD (−2450000)	RV (m s^{-1})	Uncertainty (m s^{-1})
915.2911	−12.3	6.3
1118.8874	−11.0	3.3
1119.9022	−11.1	2.8
1120.8870	−11.7	2.9
1121.8928	−10.8	2.9
1236.2864	−26.8	4.0
1410.8977	−48.3	2.9
1412.9780	−48.1	5.6
1413.8981	−41.2	2.7
1630.3042	39.9	3.0
1683.0926	43.4	3.7
1684.1320	40.3	4.1
1718.1184	28.4	3.6
1742.9096	15.2	3.1
1743.9240	25.4	3.8
1745.0440	13.5	3.2
1766.9330	5.6	3.2
1767.9689	7.3	3.2
1827.8973	−6.1	2.9
1828.8866	−0.5	3.6
1829.8890	−6.8	3.5
1855.9058	−7.4	4.9
1984.2618	−20.6	3.5
2010.2829	−16.2	6.1
2061.1132	−28.0	3.1
2091.9807	−30.0	3.6
2126.9766	−12.6	3.7
2151.9693	−7.3	3.4
2152.9493	3.8	2.4
2153.8626	−1.0	2.9
2186.9095	21.0	2.6
2187.8879	16.5	2.7
2360.3243	34.6	2.3
2387.1722	34.2	2.7
2388.2097	30.9	3.0
2421.1696	15.4	2.7
2425.1226	20.0	3.1
2455.0437	11.2	3.3

6 DISCUSSION

Although many extrasolar planets had been discovered prior to 2000 December it was unclear whether giant planets in circular, or near-circular, orbits outside 0.1 au would be found *at all* outside the Solar system (e.g. Boss 2001). The AAPS identification of ϵ Ret (Butler et al. 2001) clearly showed that such planets exist.[1] Since our announcement, a further seven 'ϵ Ret-class' (fig. 4, Tinney et al. 2002a) have been announced so clearly that such planets are not as unusual as once thought.

The newly discovered companions to HD 216437 and HD 196050 announced here have masses at least several times that of Jupiter and have mildly eccentric orbits with periods roughly twice that of Mars or one-third of Jupiter. These discoveries serve to realize

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[1] 47 Uma was discovered by Butler & Marcy (1996) but was only realized to have a long-period circular orbit when it was discovered to have two planets in orbit (Fischer et al. 2002).

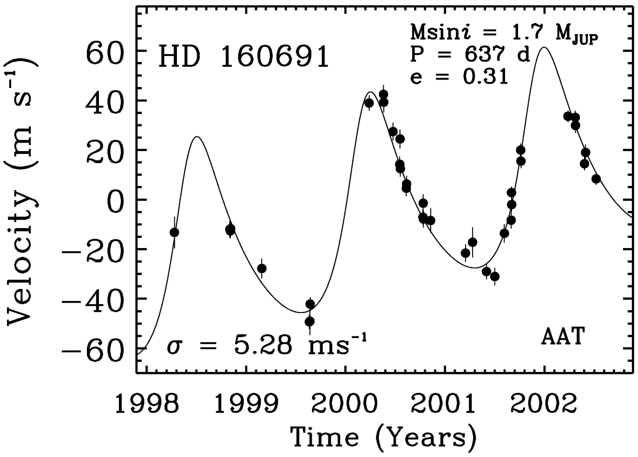

Figure 3. AAT Doppler velocities for HD 160691 from 1998 November to 2002 May. The solid line is a best-fitting Keplerian orbit with the parameters shown in Table 3. The rms of the velocities about the fit is 5.28 m s^{-1} consistent with our errors. Assuming 1.08 ± 0.05 $M_\odot$ for the primary, the minimum ($M \sin i$) mass of the companion is 1.7 ± 0.2 $M_{\rm JUP}$ and the semi-major axis is 1.5 ± 0.1 au.

the trend that an increasing fraction of the extrasolar planets discovered have orbital parameters closer to those in our Solar system than was typical for earlier announcements of extrasolar planets. In Table 6, we classify the extrasolar planets reported up until 2002 July. Nearly 20 per cent of extrasolar planetary systems have orbital parameters within the range of the planets of our Solar system. It should be noted that this is probably a lower bound as we expect that typical orbital parameters and detection frequencies will evolve considerably as survey baselines and precisions improve. Furthermore eccentricity solutions tend to decrease with time (Marcy et al. 2002).

7 CONCLUSIONS

We report extrasolar planets in orbit around the stars HD 216437 and HD 196050, and further observations of HD 160691, which give the preliminary indication of a second planet. These detections serve to further emphasize that planetary systems with orbital parameters similar to those of our own Solar system are not as rare as suggested by the early extrasolar planet discoveries (e.g. Boss 2001). These discoveries confirm the preponderance (1) of relatively low-mass $M \sin i$ planets and (2) planets around metal-rich objects. The detection of these relatively long-period planets gives us confidence in the stability of our search and gives added impetus for the continuation of the AAPS to longer periods. We now must endeavour to continue to improve the precision and stability of the AAPS to be sensitive to the 10+ yr periods where analogues of the gas giants in our own Solar system may become detectable around other stars (e.g. Marcy et al. 2002).

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Table 6. Extrasolar planetary systems classified by orbital parameters of period and eccentricity (from http://exoplanets.org). The boundaries for classification are chosen in terms of the Solar system, so eccentricity is chosen as 0.25 (cf. Pluto) and period as 88 d (cf. Mercury). Where there is more than one planet present around a star the classification is made in terms of the inner planet. Outer planets in the system are recorded in the appropriate section though their entry is in italics to indicate that they are not included in the count.

Class	Number	Objects
51 Peg b – like ‘circular short-period’ $e < 0.25$, $T < 88$ d	25	HD 83443b, HD 46375b, HD 179949b, HD 187123b, Tau Boo b, BD −103166b, HD 75289b, HD 209458b, HD 76700b, 51 Peg b, Ups And b, HD 49674b, HD 68988b, HD 168746b, HD 217107b, HD 130322b, HD 38529b, 55 Cnc b, GJ 86b, HD 195019b, Rho Cr Bb, GJ 876b, HD 121504b, HD 178911Bb, HD 16141b
HD 114762 – like ‘eccentric short-period’ $e > 0.25$, $T < 88$ d	5	HD 162020b, HD 6434b, *GJ 876c,* HD 74156b, HD 168443b, HD 114762b
70 vir b – like ‘eccentric long-period’ $e > 0.25$, $T > 88$ d	41	HD 80606b, 70 Vir b, HD 52265b, HD 1237b, HD 37124b, HD 73526b, *HD 82943c,* HD 8574b, HD 169830b, HD 12661b, HD 89744b, HD 40979b, HD 202206b, HD 134987b, HD 150706b, HD 92788b, HD 142b, HD 177830b, HD 4203b, HD 210277b, HD 82943b, HIP 75458b, HD 147513b, HD 222582b, HD 141937b, HD 160691b, HD 213240b, 16 Cyg B b, HD 114386b, HD 114729b, HD 190228b, HD 2039, HD 136118b, HD 50554b, HD216437b, *Ups And d, HD 12661c,* HD 33636b, HD 23596b, HD 106252b, HD 145675b, HD 72659b, HD 39091b, *HD 38529c, HD 74156c,* Eps Eri b
Solar system – like $e < 0.25$, $T > 88$ d	16	HD 37124b, *Ups And c,* HD 17051b, HD 28185b, HD 108874b, HD 128311b, HD 27442b, HD 19994b, HD 20367b, HD 114783b, HD 23079b, HD 4208b, HD 10697b, HD 196050b, 47 Uma b, HD 30177b, GL 777A, HD 168443c, 47 Uma c, 55 Cnc c

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