The Jupiter Twin HD 154345b[1]

J. T. Wright[2], G. W. Marcy[3,4], R. P. Butler[5], S. S. Vogt[6], G. W. Henry[7], H. Isaacson[8], and A. W. Howard[3,9]

ABSTRACT

We announce the discovery of a twin of Jupiter orbiting the slightly metal-poor ([Fe/H] = −0.1) nearby (d= 18 pc) G8 dwarf HD 154345. This planet has a minimum mass of 0.95 M_{Jup} and a 9.2 year, circular orbit with radius 4.2 AU. There is currently little or no evidence for other planets in the system, but smaller or exterior planets cannot yet be ruled out. We also detect a $\sim$ 9-year activity cycle in this star photometrically and in chromospheric emission. We rule out activity cycles as the source of the radial velocity variations by comparison with other cycling late-G dwarfs.

Subject headings: planetary systems — techniques: radial velocities

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[2]Department of Astronomy, 610 Space Sciences Building, Cornell University, Ithaca, NY 14853
jtwright@astro.cornell.edu

[3]Department of Astronomy, 601 Campbell Hall, University of California, Berkeley, CA 94720-3411

[4]gmarcy@berkeley.edu

[5]Department of Terrestrial Magnetism, Carnegie Institute of Washington, 5241 Broad Branch Road NW, Washington, DC 20015-1305
butler@dtm.ciw.edu

[6]UCO/Lick Observatory, University of California, Santa Cruz, CA 95064
vogt@ucolick.edu

[7]Center of Excellence in Information Systems, Tennessee State University, 3500 John A. Merritt Blvd., Box 9501, Nashville, TN 37209, USA
henry@schwab.tsuniv.edu

[8]Department of Physics and Astronomy, San Francisco State University, San Francisco, CA 94132
isaacson@stars.sfsu.edu

[9]Townes Fellow, Space Sciences Laboratory, UC Berkeley
howard@astro.berkeley.edu

1. Introduction

One of the primary goals of our planet search at Keck Observatory, which began collecting precise radial velocities (RVs) of nearby Sun-like stars in earnest in April 1997, was to discover the first signpost of a true Solar System analog, a Jupiter twin. This would require high precision (< 3 m/s) measurements stable over $10 - 20$ years of regular observation to detect the 12 m/s (modulo $\sin i$), sinusoidal signal induced by a 1 $M_{\rm Jup}$ object over a ~ 10 year period. A survey would also have to measure the effects of stellar activity cycles on the long-term RV stability of Sun-like stars, since such cycles have periods of ~ 10 years, similar to those of the orbits of Jupiter-type planets.

Now, with the recent passage of the 10 year anniversary of our first observations at Keck, we announce that we have achieved these goals and present the first veritable Jupiter analog.

The 10 year baseline of precise velocities has already revealed several long-period planets, including the following with $P > 8$ yr: an $m \sin i = 3$ $M_{\rm Jup}$ planet in an eccentric orbit around HD 72659 (Butler et al. 2003); planets in eccentric orbits with interior gas giants around HD 190360 and HD 217107 (Vogt et al. 2005); and 55 Cnc *d* (Marcy et al. 2002), an $m \sin i = 4$ $M_{\rm Jup}$ planet in a circular orbit and the outermost member of an extraordinary 5-planet system (Fischer et al. 2008, *ApJ* accepted). The *Catalog of Nearby Exoplanets*[1] (Butler et al. 2006) counts 12 other nearby planets with $P > 6$ yr discovered to date.

Characterization of these planets is complicated by their long periods: while normally we prefer to observe multiple orbits before announcing a planet so that we can separate the effects of additional planets in the system, such caution can be impractical when orbital periods exceed 8 years. Wright et al. (2007) developed techniques for constraining the minimum mass of long-period planets, including HD 154345*b*, whose orbits were apparently nearly complete but nonetheless lacked well-constrained periods. Since that work's publication, HD 154345*b* has completed its orbit, revealing its minimum mass, period, and eccentricity all to be at the low end of the range of plausible values listed in Wright et al. (2007).

HD 154345 joins 55 Cnc in demonstrating that the architecture of the Solar System – a dominant, Jupiter-mass planet at 4–5 AU in a circular orbit with only lower-massed objects interior – while rare, is not unique.

[1]http: //exoplanets.org/

2. The HD 154345 System

HD 154345 (= GJ 651) is a bright, nearby, somewhat metal-poor G8 dwarf. Its Mount Wilson S-index of 0.18 is only slightly higher than the minimum seen for stars of similar $T_{\rm eff}$, metallicity, and evolutionary status (J. T. Wright, in prep.), indicating that it is likely an old (age > 2 Gyr), slowly-rotating [2] field star. Table 1 contains compiled stellar data for HD 154345 from the SPOCS catalog (Valenti & Fischer 2005), *Hipparcos* (Perryman & ESA 1997), and the activity catalog of Wright et al. (2004). Being metal poor, HD 154345 sits just below the main sequence, (it has negative ΔM_V) as computed in Wright (2005).

Stars of this color and activity level typically exhibit r.m.s radial velocity variations of 2-5.5 m s^{-1}(Wright 2005), an estimate which includes systematic errors as well as any astrophysical noise intrinsic to the star. This is an overestimate for the data presented here, because of the large number of data points taken since upgrades at HIRES in August 2004 decreased our systematic errors down to 1.5 m s^{-1} at worst. We thus adopt a uniform "jitter" estimate of 2.5 m s^{-1} for this work.

In Table 3 we present the 55 radial velocity measurements we have collected for this star since 1997, using the iodine technique (Butler et al. 1996). Typical exposure times in good weather were ∼ 1 minute.

We have fit the data under the assumption that HD 154345b is the only planet in the system, binning the data in 3-day bins before adding our jitter estimate in quadrature with random errors. The velocities are consistent with an $m \sin i \sim 1$ M$_{\rm Jup}$ planet in a circular 4.2 AU orbit and no other companions. Lower jitter estimates yield a best fit with slightly larger eccentricity. Fig. 1 shows the best fit, and Table 2 contains the best-fit parameters, with errors computed using the bootstrapping technique described in Butler et al. (2006).

3. Activity Cycles in Late G Dwarfs

We monitor all of our program stars for variations in chromospheric activity, extracting Mount Wilson S-indices from our RV science spectra (H. Isaacson, *in preparation*; Wright et al. 2004). We have found that HD 154345 shows clear evidence of a stellar cycle. Fig. 2 shows that the magnetic activity level of HD 154345 varies sinusoidally with a ∼ 9-year period. Photometric monitoring from Fairborn Observatory (Henry 1999) confirms

[2]The canonical age-rotation period formula of Noyes et al. (1984) yields a rotation period of 31 d, a period not seen in the periodogram of the RV residuals

the presence of this activity cycle: Fig. 3 shows a ~ 1 mmag photometric variation in phase with the chromospheric emission[3].

Deming et al. (1987) observed an apparent drift in line centroids of CO transitions at 2.3 μm in the integrated Solar spectrum over a 3-year span. They associated these shifts with changes in the activity level of the Sun over that period, and suggested that activity cycles on Sun-like stars could thus mimic the RV signature of a long-period exoplanet. The apparent coincidence of the phase of HD 154345's magnetic cycle with that of the radial velocities in the same sense at the shifts seen by Deming et al. (1987) therefore demands that we take a closer look at the effects of stellar activity cycles on radial velocities measured in the optical.[4]

The Mount Wilson H & K activity survey (Baliunas et al. 1995) identified several stars of similar color to HD 154345 as exhibiting activity variations consistent with cycles. We have over 6 years of RV data at Keck for a total of four of these stars[5]: HD 26965, HD 3795, HD 10476, and HD 185144, the latter three of which we have monitored regularly at Keck for over 10 years. HD 10476, HD 26965, and HD 185144 all have sufficiently strong cycles that we can confirm their continued coherence since the end of the published Mount Wilson data from our own activity measurements.

None of these four stars shows RV variations similar to HD 154345, or any correlation of S-index with RV. In fact, all of these stars show r.m.s. RV variations of less[6] than 5 m s^{-1}, and one, HD 185144, is among the most RV-stable stars in our entire sample.

We focus here on HD 185144 because its activity cycle is so clear and it is one of the best-observed stars on our program. Fig. 2 shows that this star has a similar cycle

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[3]For G stars, visible luminosity varies on order 0.1% in phase with chromospheric emission such that the star is brightest during activity maximum (Lockwood et al. 2007).

[4]A bisector analysis to distinguish line profile variations from true Doppler shifts is impractical for this system. A Doppler shift can be described as a shift in the first moment of a line profile, distinguished from a profile change, which is a change in the higher moments. Measurements of line profile changes will therefore have inherently lower precision than measurements of Doppler shifts. We estimate that our sensitivity to these higher moments for our data in hand is only 25 m/s, insufficient to distinguish them from 14 m/s Doppler shifts.

[5]We have only 2.5 years of data for a fifth star, HD 115616, too little to sample an entire activity cycle. We also have 6 years of Lick velocities for a sixth star, HD 103095, which is a cycling subdwarf exhibiting a complex RV history with no long-term coherence.

[6]HD 3795, has a binary companion; we have therefore measured its r.m.s. RV variations after subtraction of a strong linear trend.

period to that of HD 154345, but with a higher mean activity level and larger variations.[7]. Fig. 4 shows Fairborn Observatory photometry of HD 185144 which confirms the existence, strength, period, and phase of this cycle.

Despite these clear activity variations, HD 185144 is one of the most stable stars on our program. We have monitored HD 185144 intensely at Keck Observatory since 1997 and made more than 350 observations on more than 60 nights over the past 10 years (since the activity and RV measurements are taken from the same spectra, Fig. 2 also shows the temporal coverage of our RV observations). The r.m.s. scatter of the RV variations over this entire period is less than 2.5 m s^{-1}.

Based on these four stars, we conclude that long-term radial velocity variations are generally not seen in the optical absorption lines of late G stars undergoing magnetic activity cycles, even cycles as strong as those in HD 185144. We note that the Sun's 11-year activity cycle has a period similar to that of Jupiter's orbit, and that the Mount Wilson survey demonstrated that decadal activity cycles are a common feature of old G stars (Baliunas et al. 1995). We thus consider the fact that HD 154345 exhibits an activity cycle with a period and phase similar to that of its Jupiter twin to be an inevitable coincidence.

4. Discussion

The orbital solution presented here is sensitive to the assumption that the signal from any other planets in the system is not significant. The residuals to this fit show no significant periodicities, consistent with there being no interior planets with $m \sin i \gtrsim 0.3\mathrm{M_{Jup}}$. Our intense monitoring of this system at 1 m s^{-1} precision since 2007 will provide increasingly stringent limits on the existence of any interior giant planets.[8]

One of the difficulties of having only observed a single orbit is in excluding the possibility of a detectable exterior planet. For instance, a Saturn analog in this system would contribute a low-amplitude, long-term signal which might be absorbed in the eccentricity term of the orbital solution above. Long-term monitoring of this system will eventually break this degeneracy.

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[7]The phase and period we measure is consistent with that measured at Mount Wilson (Fig. 1*f* of Baliunas et al. 1995, left column, fifth panel from top)

[8]The highest peaks in a periodogram of the residuals to this fit are near 18, 40, and 45 days and have formal false alarm probabilities of a few percent. The best two-planet fits at these periods involve planets on eccentric orbits with $m \sin i \sim 25\mathrm{M_{\oplus}}$. While signals such as these are intriguing, they are not persuasive, and any conclusions drawn from them would be highly speculative.

HD 154345b will likely not be detected by other methods within the next few years. Its large orbital distance makes transits extremely unlikely, but interior planets may be detectable if their inclination is favorable and their orbital radius small. Measurement of the > 250 μas astrometric signature of HD 154345b over its 9-year orbit would determine the orientation of the orbital plane of this system and resolve the $\sin i$ ambiguity in the RV-derived mass[9]. The planet is separated from its parent star by a maximum of $0\farcs2$ with a prohibitive contrast of ~ 21 magnitudes (the age of the planet means it has little intrinsic infrared luminosity and at 4.2 AU the planet will reflect and reprocess very little light).

The brightness and proximity of HD 154345, however, will make this system a natural target for future spaceborne efforts, such as SIM and TPF. The large, apparently empty region interior to HD 154345b should be a prime target for these and other efforts to detect terrestrial planets in the Habitable Zone around a Sun-like star.

We wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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[9]For randomly oriented orbits, the median value of $1/\sin i$ is 1.15, and the true value for any given system will be within 20% of that number, with 68% confidence.

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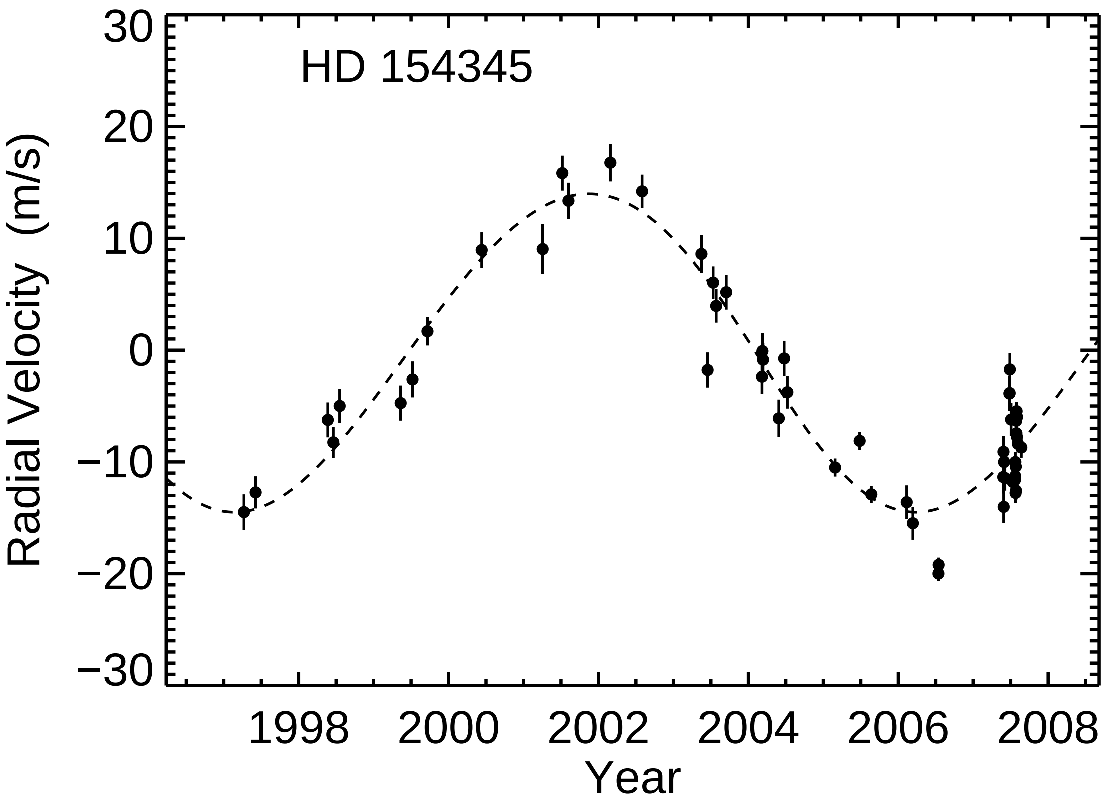

Fig. 1.— Radial velocity vs. time for HD 154345.

Table 1. Stellar Properties of HD 154345

Parameter	Value
Spectral Type	G8 V
Hipparcos ID	83389
RA	$17^{\mathrm{h}}02^{\mathrm{m}}36\overset{\mathrm{s}}{.}404$
Dec.	$+47°04'54\overset{''}{.}77$
B-V	0.73
V	6.76
Distance	18.06 ± 0.18 pc
M_V	5.48
T_{eff}	5468 ± 44 K
$\log g$ [cms^2]	4.537 ± 0.06
[Fe/H]	-0.105 ± 0.03
$v \sin i$	1.21 ± 0.5 km s^{-1}
Mass	0.88 ± 0.09 $M_{\odot}$
Radius	0.94 ± 0.03 $R_{\odot}$
S	0.18
R'_{HK}	-4.91
ΔM_V	-0.21 mag

Table 2. Orbital Properties of HD 154345*b*

Parameter	Value
P	9.15 ± 0.26 yr
e	$0.044 \pm 0.046^{\dagger}$
ω	68° †
$T_{\rm p}$ (JD)	2452830 ± 330
K	14.03 ± 0.75 m s^{-1}
$m \sin i$	0.947 ± 0.090 $M_{\rm Jup}$
a	4.19 ± 0.26 AU
r.m.s.	2.7 m s^{-1}
χ^2_ν	0.89
$N_{\rm obs}$	55
$N_{\rm obs,\ binned}$	41

Note. — Errors in the orbital elements assume no other planets in the system and a uniform stellar jitter of 2.5 m s^{-1} added after grouping the data in 3-day bins.

†Eccentricity consistent with zero. See Butler et al. (2006) for error explanation. Holding e fixed at 0 yields a fit with nearly identical parameters, differing by no more than 1 m s^{-1} from this one.

Table 3. Radial Velocities for HD 154345

Time JD-2440000	Velocity m s^{-1}	Uncertainty m s^{-1}
10547.11003	-14.5	1.6
10603.95584	-12.7	1.4
10956.01562	-6.2	1.6
10982.96363	-8.2	1.4
11013.86865	-5.0	1.5
11311.06548	-4.7	1.6
11368.78949	-2.6	1.6
11441.71387	1.7	1.3
11705.91783	9.0	1.6
12003.07818	9.0	2.2
12098.91653	15.8	1.6
12128.79781	13.4	1.6
12333.17329	16.8	1.7
12487.86019	14.2	1.5
12776.98546	8.6	1.7
12806.95185	-1.8	1.6
12833.80103	6.0	1.4
12848.77203	4.0	1.5
12897.77656	5.2	1.6
13072.04692	-2.4	1.6
13074.07776	-0.1	1.6
13077.12809	-0.9	1.5
13153.94317	-6.1	1.7
13179.99245	-0.7	1.6
13195.81919	-3.8	1.5
13428.16210	-10.50	0.81
13547.91395	-8.12	0.81
13604.83043	-12.90	0.76
13777.15534	-13.6	1.5
13807.07725	-15.5	1.5

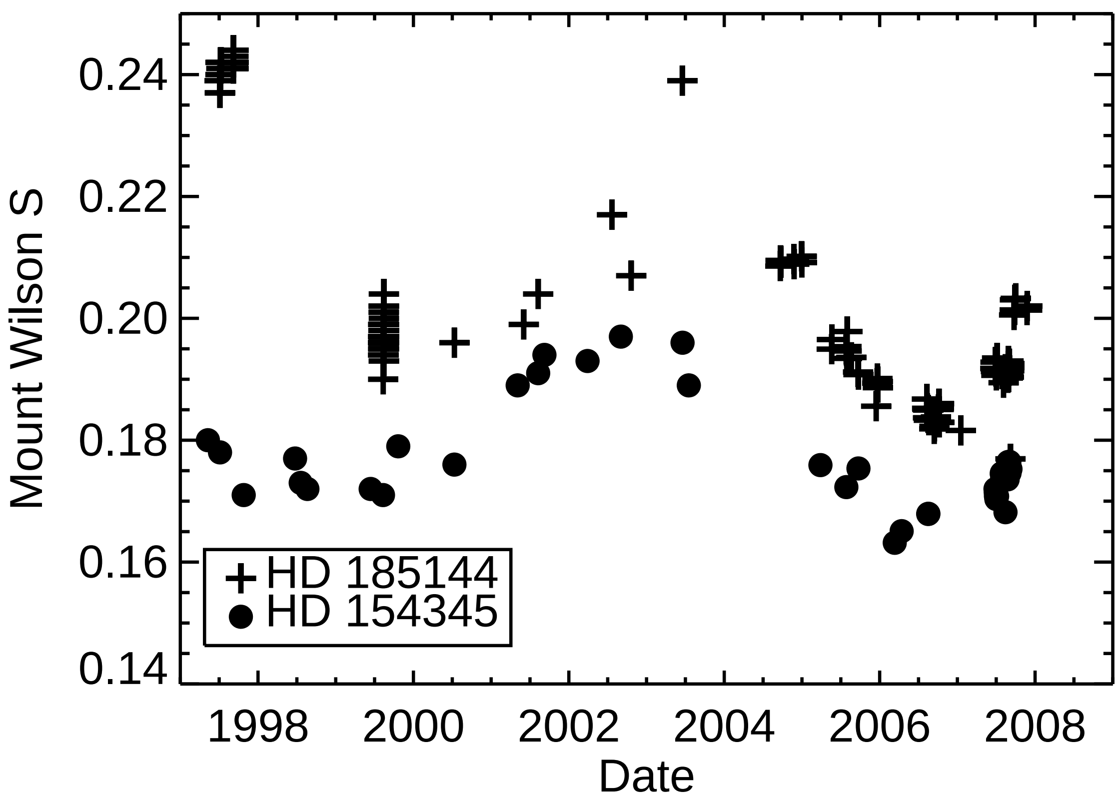

Fig. 2.— Mount Wilson activity index measured from RV science spectra taken at Keck Observatory. Except for a few small discrepancies, the temporal coverage of these data are the same as that of the RV data for both of these stars. Data from prior to 2004 are taken from the "differential" measurements in Wright et al. (2004); subsequent data have been extracted in a similar manner (H. Isaacson, in preparation). Both HD 154345 and the RV-stable star HD 185144 show strong evidence of activity cycles, though the cycle strength and overall activity level in HD 185144 is considerably larger. Cycles such as these are not uncommon in old G dwarfs, typically have ~ 10 year periods, and are not observed to have an effect on long-term RV stability. Data for the two stars are plotted on the same scale.

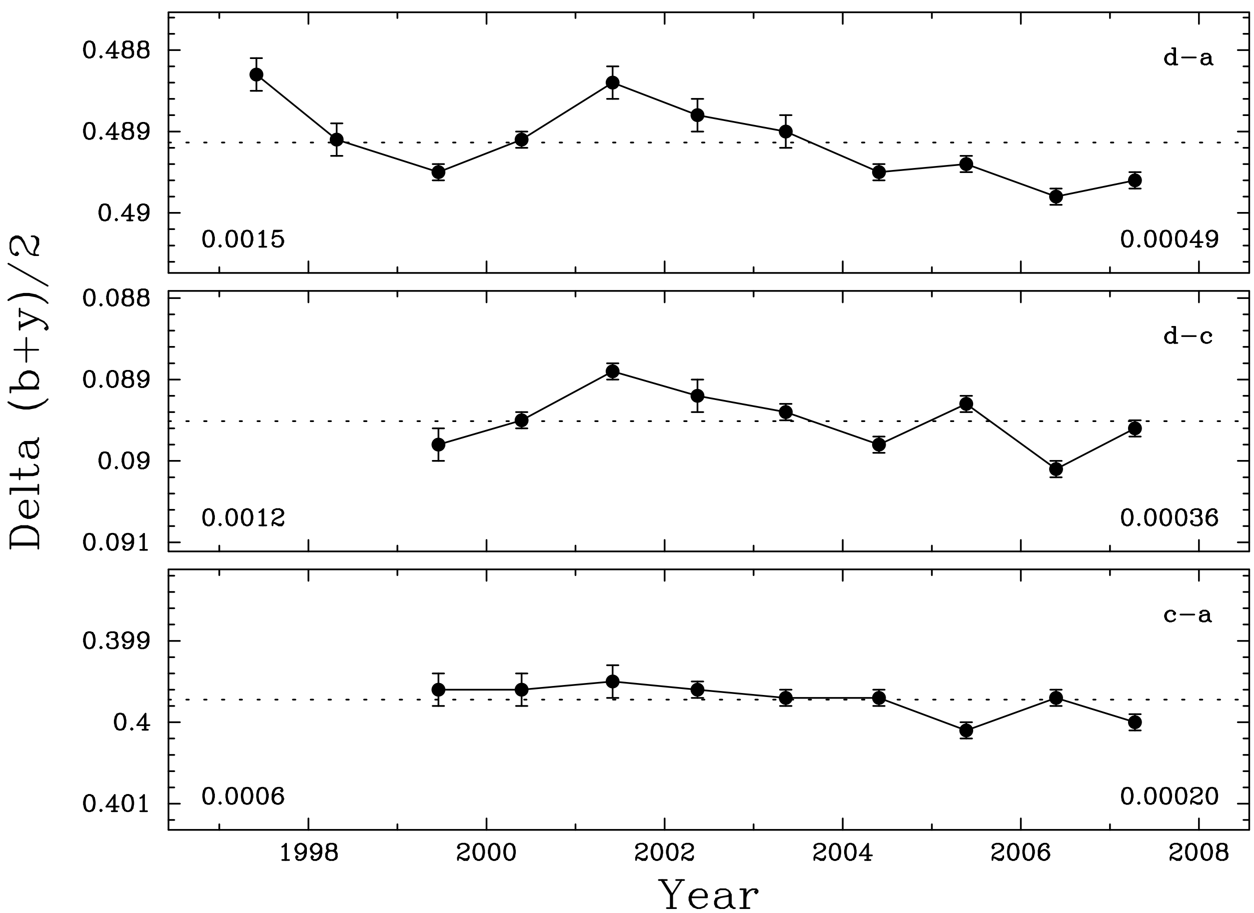

Fig. 3.— Eleven years of Strömgren photometry for HD 154345 (star *d*) and two comparison stars (*a* and *c*). The plotted points represent yearly mean differential magnitudes between the stars indicated in the upper right of each panel. The top two panels thus indicate the brightness variations of HD 154345 with respect to two photometric standards, and the bottom panel demonstrates the long-term stability of those standards. The dotted line indicates the mean, and the number in the lower left corner indicates the total range of the plotted points. The number in the lower right corner gives the standard deviation of the individual seasonal means about the mean. A third comparison star (*b*) proved unsuitable for long-term photometric work, and comparison star (*c*) has only been observed since 1999. Note that the period and phase of the photometric signal are the same as that of the chromospheric activity measurements in Fig. 2.

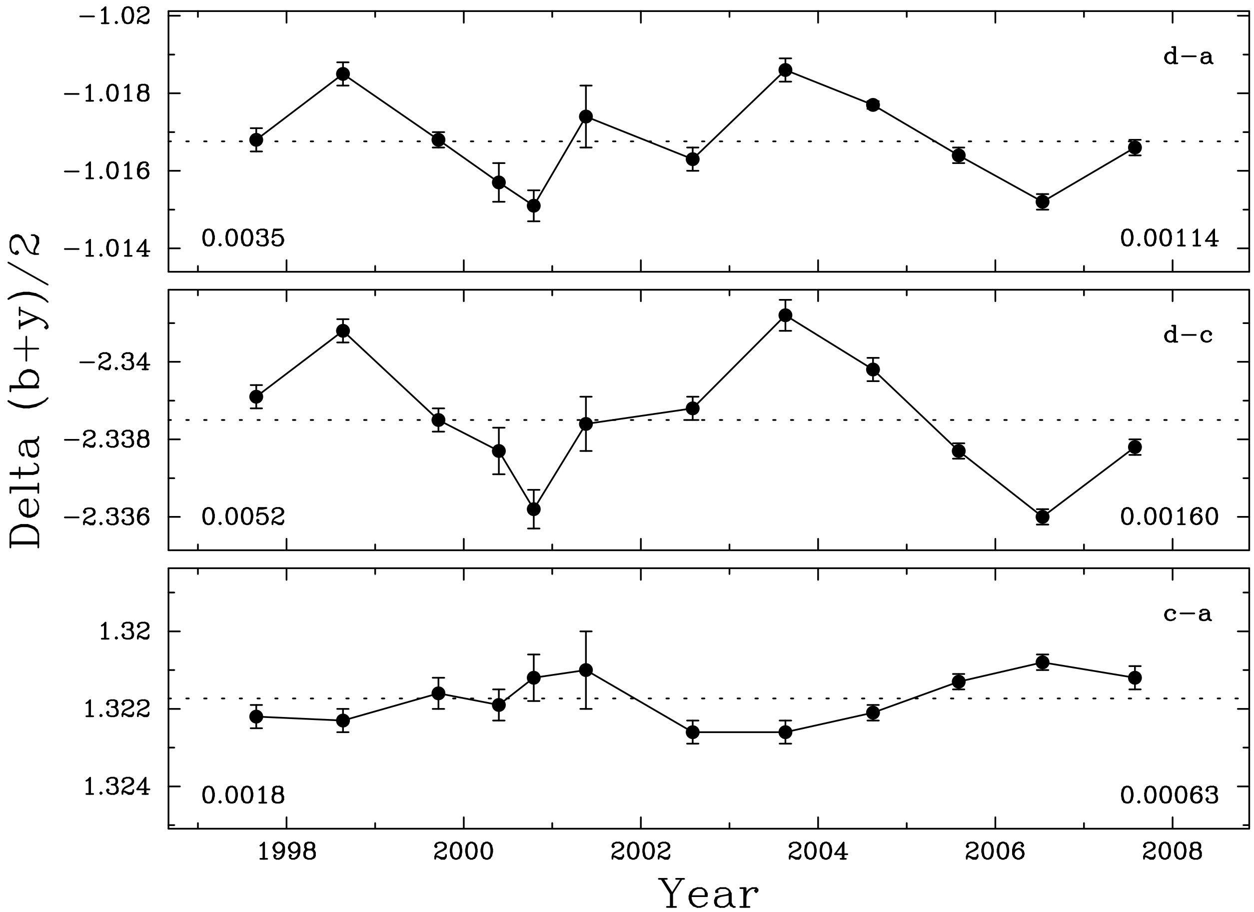

Fig. 4.— As Fig 3, but for the RV stable star HD 185144 (star d) and two different comparison stars c and a. Note that the photometric variations here are again consistent with the measurements in Fig. 2, and show a higher amplitude than those of HD 154345.

Table 3—Continued

Time JD-2440000	Velocity m s^{-1}	Uncertainty m s^{-1}
13931.95487	-19.99	0.66
13932.91301	-19.21	0.65
14248.02704	-11.4	1.5
14248.99488	-9.1	1.4
14249.94937	-14.0	1.4
14252.03683	-10.0	1.1
14255.93248	-11.4	1.1
14277.86162	-3.9	1.6
14278.90519	-3.8	1.4
14279.94294	-1.7	1.5
14285.90395	-6.2	1.5
14294.89078	-11.8	1.4
14304.87636	-11.60	0.88
14305.88185	-11.27	0.92
14306.87718	-10.01	0.88
14307.92613	-12.78	0.90
14308.90402	-10.42	0.87
14309.88576	-12.57	0.86
14310.87849	-6.31	0.79
14311.86895	-7.44	0.80
14312.86461	-5.47	0.80
14313.86609	-7.74	0.92
14314.89786	-5.98	0.87
14318.93217	-8.37	0.78
14335.81712	-8.71	0.91

Note. — The orbital fit in Table 2 assumes an additional 2.5 m s^{-1} of stellar jitter.