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PRECISE RADIAL VELOCITIES OF GIANT STARS. II. POLLUX AND ITS PLANETARY COMPANION

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ABSTRACT

It has long been speculated that the observed periodic radial velocity pattern for the K giant Pollux might be explained in terms of an orbiting planetary companion. We have collected 80 high-resolution spectra for Pollux at Lick Observatory yielding precise radial velocities with a mean error of 3.8 m s^{-1}, providing the most comprehensive and precise data set available for this star. Our data confirm the periodicity previously seen in the radial velocities. We derive a period of 589.7 ± 3.5 days and, assuming a primary mass of 1.86 $M_{\odot}$, a minimum companion mass of $2.9 \pm 0.3 M_{\mathrm{Jup}}$, consistent with earlier determinations. No evidence for any periodicities is visible in our analysis of the shapes of the spectral lines via the bisector method, so we conclude that evidence is accumulating and compelling for a planet around Pollux. However, some final doubt remains about this interpretation, because nonradial pulsations that might be present in giant stars could in principle also explain the observed radial velocities, while the accompanying bisector variations might be too small to be detectable with current data.

Subject headings: line: profiles — planetary systems — stars: individual (Pollux) — stars: oscillations — techniques: radial velocities

Online material: color figures

1. INTRODUCTION

Pollux (β Gem, HR 2990, HD 62509, HIP 37826) is one of the brightest stars in the sky ($V = 1.16$ mag) and has been observed extensively in the past. Fundamental parameters from a detailed model atmosphere analysis of the spectrum have, for example, been provided by Drake & Smith (1991), and it is usually classified as K0 IIIb star (Keenan & McNeil 1989). The parallax determined by *Hipparcos* results in a distance of 10.3 ± 0.1 pc. In the *Hipparcos* Catalogue, Pollux was flagged as a possible microvariable with a photometric amplitude of less than 0.03 mag (but no obvious periodicity), as well as a possibly nonsingle star, maybe because of slightly different astrometric solutions from the two different data reduction consortia.

Walker et al. (1989) were the first to report significant radial velocity (RV) variations for Pollux, with a standard deviation of 26 m s^{-1} around the mean from RV measurements spread over about 5 years. Although they noted that based on a periodogram analysis significant periodicity was present in the data, they did not quote any period. Only after having monitored Pollux extensively over 12 years with a typical RV precision of 10–20 m s^{-1} did Larson et al. (1993) publish a RV period of 584.65 ± 3.3 days and discuss possible reasons for the observed periodicity. Possible explanations include an orbiting planetary companion or rotational modulation of surface features. The latter hypothesis was supported by a slight indication in the data for a periodicity in the equivalent width index data of the 8662 Å (Ca II) line with about the same period as found in the radial velocities, but with a very low amplitude and only a marginal statistical significance.

Finally, Hatzes & Cochran (1993) also presented strong evidence for a periodicity in the radial velocities, with a period of 558 days. The spectra were taken over a period of 3.5 years, and the typical RV accuracy was 20 m s^{-1}. The RV variations were consistent in amplitude and phase with the older data by Walker et al. (1989).

Here we present precise radial velocity measurements of Pollux that leave no doubt about a periodicity, determined from our data to 589.7 days. This RV set is the most comprehensive and precise one taken so far for this star, spanning almost 6 years. From the first measurements of Walker in 1981 to the latest ones by us in 2006, this adds up to 25 years of RV monitoring for Pollux, with no evidence for a change in phase or amplitude of the almost sinusoidal variations. Along with no detectable variations in the spectral line shapes, our data set thus lends further evidence for the companion hypothesis.

In § 2, we describe our observations, which are part of a larger program of monitoring giant stars for periodic RV changes, and present our orbital fit to the RV data. In § 3, we analyze the spectral

TABLE 1
Measured Radial Velocities for Pollux

JD − 2,450,000	$v_{\rm rad}$ (m s^{-1})	$\sigma_{v_{\rm rad}}$ (m s^{-1})
1808.039	35.4	3.1
1812.039	32.7	2.9
1854.073	41.5	3.1
1898.060	56.0	3.8
1898.940	57.3	3.1
1899.899	55.1	3.2
1901.898	50.5	3.7
1929.819	38.7	3.5
1930.893	42.9	3.2
1931.723	34.4	4.5
1949.771	39.4	5.7
1990.667	21.2	3.3
1992.693	32.3	3.8
2015.697	13.9	3.2
2032.681	−6.9	3.3
2046.656	−5.9	3.6
2047.657	0.3	3.7
2048.659	3.8	3.5
2175.055	−42.5	2.9
2177.047	−48.8	3.3
2193.021	−44.7	3.6
2193.983	−42.8	3.2
2205.968	−36.6	3.3
2206.970	−47.1	4.1
2207.995	−38.4	3.5
2222.917	−34.3	3.4
2223.924	−37.8	3.1
2258.832	−23.9	3.7
2259.898	−13.9	4.0
2295.812	−17.2	3.9
2297.873	1.5	4.2
2307.749	−0.3	3.7
2362.729	14.2	4.3
2363.740	14.5	4.4
2384.701	27.9	4.9
2393.676	26.2	3.9
2529.043	44.8	3.3
2542.035	13.7	3.8
2544.004	14.6	3.1
2560.031	37.6	5.4
2561.051	18.6	3.2
2562.023	29.2	3.1
2572.020	25.0	3.1
2590.000	15.0	3.4
2603.974	8.2	3.7
2604.957	12.3	3.8
2605.893	6.7	3.5
2615.882	2.0	4.0
2616.889	−6.4	3.7
2627.889	−20.9	3.2
2665.800	−25.5	4.1
2667.840	−27.8	4.7
2699.669	−26.2	4.8
2765.687	−35.8	5.6
2933.021	13.1	3.8
2935.010	6.7	3.0
2964.043	42.7	4.9
2964.938	36.3	4.0
2966.919	27.8	3.4
2985.912	43.4	5.8
3022.829	40.2	4.9
3025.893	41.6	4.0
3089.732	33.4	5.3
3111.687	37.5	4.5
3290.027	−27.1	3.0
3323.988	−46.7	3.8
3324.988	−37.6	3.9
3355.851	−56.1	3.3
3357.988	−55.3	3.2
3400.828	−58.3	3.3
3424.734	−60.8	3.7
3442.703	−49.5	3.6
3446.642	−31.1	4.0
3447.665	−41.5	4.1
3492.671	−15.7	3.4
3651.058	37.7	3.5
3703.043	20.2	4.3
3741.009	22.7	4.3
3790.775	1.9	3.7
3792.756	−0.8	3.9

line shapes with the help of the bisector method, and in § 4 we present a discussion and our final conclusions.

2. OBSERVATIONS

The observations were carried out as part of a larger program measuring precise radial velocities of several hundred G and K giant stars at Lick Observatory. The early objectives of this program have been described in Frink et al. (2001), and the first substellar companion from the survey (around the K giant ι Dra) was announced in Frink et al. (2002). Hekker et al. (2006) characterize the giant stars with the most stable radial velocities in our survey, and D. S. Mitchell et al. (2007, in preparation) present evidence for four more K giant stars harboring one or more substellar companions.

As part of this ongoing program, we have obtained 80 spectra for Pollux covering about 5.5 years. All observations were taken using the Hamilton high-resolution echelle spectrograph ($R \approx 60{,}000$ at 6000 Å) at Lick Observatory, attached to the 0.6 m Coudé Auxiliary Telescope (CAT). Typical exposure times were 1.5 minutes for Pollux, yielding a S/N of up to 200. However, some observations were taken with cloud cover, when exposure times can be considerably longer and the S/N somewhat smaller (around 150). The individual radial velocities, obtained as described in Butler et al. (1996), are listed in Table 1, along with their formal errors. Figure 1 shows the measurements together with a Keplerian fit to the data; the orbital elements are listed in Table 2. There is no doubt about the clear periodicity in the data, as has already been observed by Walker et al. (1989), Larson et al. (1993), and Hatzes & Cochran (1993).

Nevertheless, there is some additional scatter at a level of 9 m s^{-1} present in the data, which is larger than expected based on the formal measurement errors. It is possible that this stems from radial pulsations, but with the theoretical period for the fundamental mode shorter than 1 day (Hatzes & Cochran 1993), our sampling is inadequate to provide any further constraints. Solar-like oscillations in late G giants have been found by Frandsen et al. (2002) and de Ridder et al. (2006), and it is not unreasonable to assume that similar oscillations in Pollux are responsible for the excess jitter. The amplitude, however, is not large enough to affect the derivation of the orbital parameters of the putative companion. Furthermore, there are no indications for any additional periodicities, as can be seen in the lower part

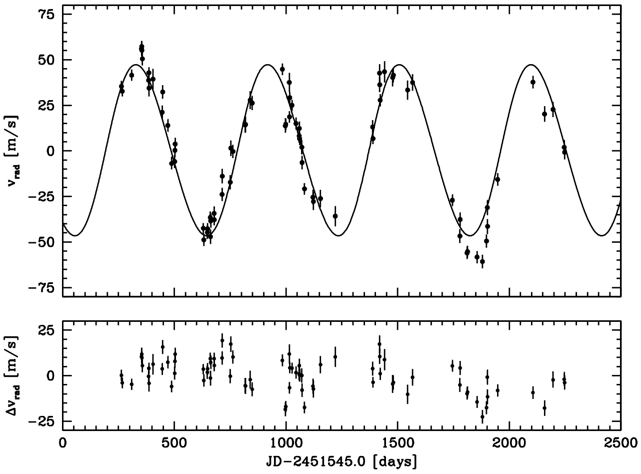

Fig. 1.—*Top*: Radial velocities measured at Lick Observatory, along with error bars, covering about 5.5 yr from 2000 September to 2006 February. The best-fit Keplerian is overplotted, with a period of 589.7 days. *Bottom*: Radial velocity residuals after the best-fit Keplerian has been subtracted. The remaining radial velocity scatter has a standard deviation of 9 m s^{-1}, and no systematics are visible in the residuals, neither by eye nor in the periodogram of the residuals in the lower part of Fig. 2. [*See the electronic edition of the Journal for a color version of this figure.*]

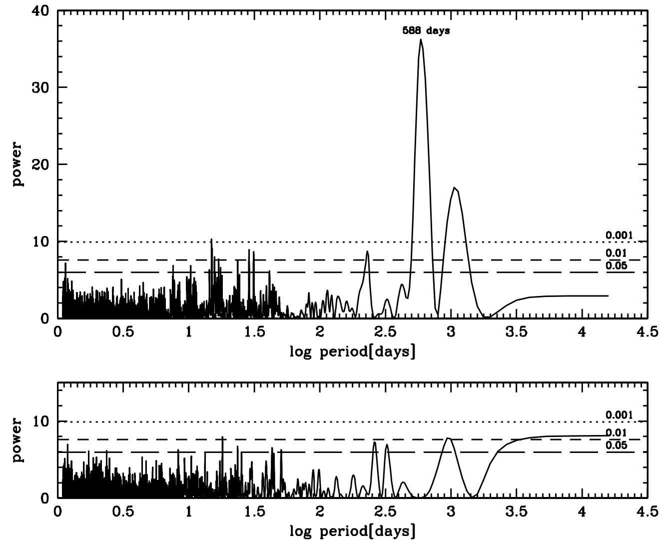

Fig. 2.—*Top*: Periodogram of the measured radial velocities. The highly significant peak occurs at 588 days; a Kepler fit to the data reveals a best-fit period of 589.7 days. The next significant peak to the right, at about $\log P[\mathrm{days}] = 3.07$, corresponds to twice the value of the most significant period. The numbers at the right indicate the false alarm probabilities of the labeled lines; a highly significant peak in the periodogram would sit clearly above the highest line, indicating a false alarm probability of less than 0.1%. *Bottom*: Same as above, but with the Kepler fit corresponding to 589.7 days removed from the radial velocities. No significant peak is left in the periodogram of the radial velocity residuals. [*See the electronic edition of the Journal for a color version of this figure.*]

of Figure 1, where the orbital fit has been subtracted from the data, and the corresponding Lomb-Scargle periodogram in the lower part of Figure 2.

Our period for the orbital fit is 589.7 ± 3.5 days and compares very well with the value of Larson et al. (1993) (584.65 ± 3.3 days), while it is somewhat larger than the period derived by Hatzes & Cochran (1993) (554 ± 8 days). All previous measurements are consistent in amplitude and phase with our result; Figure 3 shows a phased plot of our measurements along with the earlier ones by Larson et al. (1993) and Hatzes & Cochran (1993). (Note that we measure only relative radial velocities with an arbitrary zero point, so that a vertical shift had to be applied before plotting them along with the other data sets. This vertical shift is a free parameter in our fit; its formal error is 1.1 m s^{-1} and should be negligible for the comparison.) A combined fit to all RV data produces orbital parameters very similar to those of a fit to our RV data alone; the period from the combined fit is larger by 1.6 days as compared to the period quoted in Table 2 based on our RV data alone, very well within the formal error.

The minimum companion mass derived from our orbital fit is $2.9M_{\mathrm{Jup}}$ assuming a stellar mass for Pollux of 1.86 $M_{\odot}$. The stellar mass was derived from the location of the star in the color-magnitude diagram as determined from *Hipparcos* data and compared to the evolutionary tracks from Girardi et al. (2000). Solar metallicity was assumed for the comparison, which is a good approximation (Drake & Smith 1991). Allende Prieto & Lambert (1999) derive a value of 1.7 $M_{\odot}$ for the mass of Pollux with a method very similar to that described above, and Drake & Smith (1991) also derive a mass of 1.7 $M_{\odot}$ from a detailed model atmosphere analysis. Using this value for the stellar mass would yield a minimum mass of $2.7M_{\mathrm{Jup}}$. The error on the minimum companion mass due to the error in the knowledge of the primary mass is thus about $0.2M_{\mathrm{Jup}}$, so that the total error (including the formal error derived from the orbital fit, see Table 2) amounts to about $0.3M_{\mathrm{Jup}}$.

Together, the radial velocities cover about 25 years, and the variations have been rather consistent over that time. Nevertheless, although we consider the interpretation of the observed RV changes as the result of an orbiting companion as likely, it is possible that another mechanism might cause the observed RV variations. In § 3, we take a closer look at the spectral line shapes, which might provide further hints at the underlying mechanism.

TABLE 2

Fitted and Derived Orbital Parameters

Parameter	Value
Period (days)	589.7 ± 3.5
T_0 (JD − 2,450,000)	2337.9^{+70}_{-52}
Eccentricity	0.06 ± 0.04
ω (deg)	277 ± 8
$f(m)$ (10^{-9} $M_{\odot}$)	6.2 ± 0.6
$m_2 \sin i$ (M_{Jup})[a]	2.9 ± 0.1
Semimajor axis (AU)	1.69 ± 0.03
RV semiamplitude (m s^{-1})	46.9 ± 1.5
Reduced χ^2	6.3
rms scatter around fit (m s^{-1})	9.0

[a] The companion mass error does not include the uncertainty in the stellar mass.

3. LINE SHAPE ANALYSIS

In order to investigate whether the observed RV variations are caused by a shift of the spectral lines as a whole (as expected in the presence of a companion) or by a change in the symmetry of the spectral lines giving rise to a net change in RV (as expected in the presence of pulsations), bisectors of the cross-correlation profile have been analyzed. We used all spectral lines between about 6540 and 9590 Å from 29 spectral orders and obtained an average line profile by correlation with a synthetic template obtained from the VALD database (Kupka et al. 1999),[1] matching the effective temperature and surface gravity of Pollux. The spectral range from about 5000 to 5800 Å could not be used because it

[1] Available at http://ams.astro.univie.ac.at/vald/.

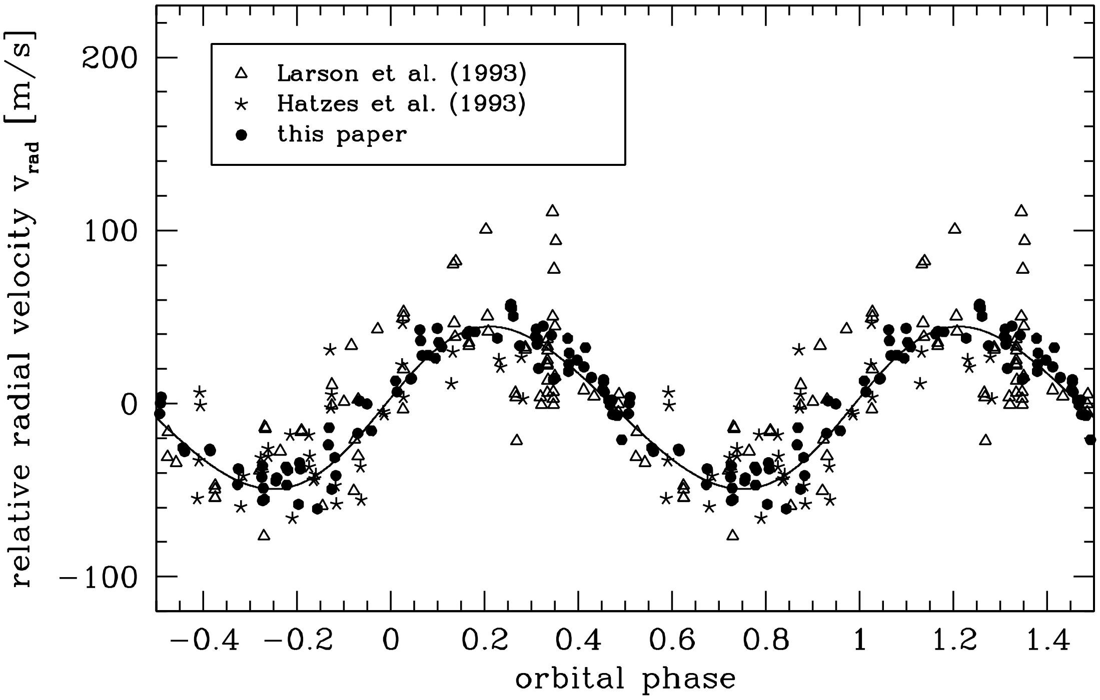

FIG. 3.—Radial velocities from Larson et al. (1993) (*open triangles*) and Hatzes & Cochran (1993) (*asterisks*) phased to the period determined from our own measurements (*filled circles*). Our orbital fit is also shown (*solid line*). No changes in period or amplitude of the periodic RV signal is apparent from that plot. For clarity, no individual error bars have been included in the plot. The data in Larson et al. (1993) consist of two separate data sets; data from CFHT have mean internal errors of 12 m s^{-1}, data from DAO 27 m s^{-1}. The majority of the data points in Hatzes & Cochran (1993) have mean internal errors of around 20 m s^{-1}, while a few data points have mean internal errors of 7 m s^{-1}. Note that not all of the measurements in Hatzes & Cochran (1993) have been used; the second set of 13 measurements in their Table 1C is identical to the first 13 measurements and thus obviously wrong, so it has been omitted. Errors for the DAO data set from Larson et al. (1993) are rather inhomogeneous and reach up to around 80 m s^{-1} for some measurements, which explains the few data points that seem to be outliers in this graph. [*See the electronic edition of the Journal for a color version of this figure.*]

is affected by iodine lines, and the spectral range around 6300 Å was avoided because it is dominated by strong telluric oxygen lines (which give rise to a spurious 1 yr period when included in the analysis). Otherwise, as many lines as possible from a continuous spectral range were used, since it is known (Gray 1983, 1984) that different lines in the same star can display different bisector behavior.

For the cross correlation with the synthetic template, our individual spectra had to be wavelength-calibrated, for which we used the thorium-argon exposure that was taken closest in time to each spectrum, from either the beginning or the end of the night. Altogether, about 1110 spectral lines with theoretical depths between 0.1 and 0.9 were used for the cross correlation. Of course many blended lines are included in the cross correlation, but by using many lines we are confident that the effects average out. Furthermore, as long as the same lines are used for all observations, and only variations in the shape are of interest, blends by stellar lines do not affect the final result.

After having obtained the cross-correlation profiles, we determined bisectors by stepping down the blue side of the profile, linearly interpolating the line depth at the red side for the same flux level as observed at the blue side (in the center of the profile, a parabolic fit was used instead of the linear one), and derived the midpoints between the velocities on the blue and red side of the profile. The connection of midpoints determined in this way is the bisector; see Povich et al. (2001) for more details on the method.

In order to analyze possible variations in the bisector, two quantities are defined that characterize its shape: the velocity span and the velocity displacement. While the bisector span is the difference between the width of the bisector at two different flux levels (30% and 75% were used here), the velocity displacement is the average width of the bisector at three different flux levels (30%, 60%, and 75% were used).

Periodograms of both quantities are shown in Figure 4. No significant periods whatsoever are present in these periodograms; all trial periods have extremely small significance levels. In particular, no peak is present at the RV period, so that we conclude that there is no evidence for any variations in the shapes of the spectral lines in our Pollux spectra.

This finding is consistent with the one by Hatzes & Cochran (1998), who also analyzed the bisectors of two different spectral lines in their Pollux data without discovering any periodicities similar to the RV period (they used 554 days). However, they caution that low-order nonradial pulsation modes, which might be able to account for the observed RV variations, might produce

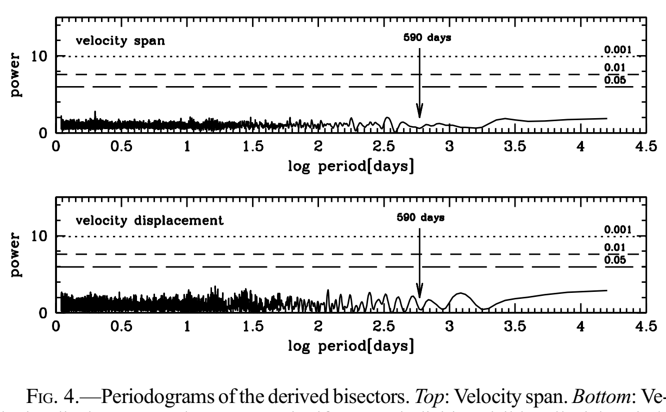

FIG. 4.—Periodograms of the derived bisectors. *Top*: Velocity span. *Bottom*: Velocity displacement. There are no significant periodicities visible; all trial periods have an extremely small probability of being real. The period present in the RV data is indicated. [*See the electronic edition of the Journal for a color version of this figure.*]

changes in the bisector velocity span of only 5 to 20 m s^{-1}. While we estimate the errors in a single bisector velocity span to lie between 50 and 100 m s^{-1} in our analysis (50 m s^{-1} in the analysis of Hatzes & Cochran 1998), the sensitivity to a real periodic signal in the data increases if one uses a large number of spectra for the periodogram, to about the relevant level. However, we conclude that nonradial pulsations cannot be completely ruled out with the observational material or analysis methods currently available.

4. CONCLUSIONS

The currently available data on Pollux are all compatible with an orbiting substellar companion around this bright and nearby star. The minimum mass of the companion is $2.9 \pm 0.3\, M_{\rm Jup}$, which makes it most likely a planet and not a brown dwarf. From the nondetection of the companion in the *Hipparcos* data, one can derive an upper limit on the companion mass, since it would have been detected by *Hipparcos* if it had been massive enough. The lower limit on the inclination that we derive from *Hipparcos* is about 5°, which translates into an upper mass limit of $33 M_{\rm Jup}$, constraining the companion to be of substellar nature (if the companion interpretation of the RV pattern is correct). Its period is 589.7 ± 3.5 days, and it orbits at a distance of 1.69 ± 0.03 AU from the star in an almost circular orbit. The RV pattern has been stable over the last 25 years. An analysis of the spectral line shapes shows no evidence for any changes with the RV period nor any other periods, which one might expect in the presence of pulsations. *Hipparcos* has picked up excess scatter in the astrometric standard solution (without a companion), but it is unlikely that this is the signature of the planetary companion, since its expected minimum astrometric signature is only 50 μas.

Detailed theoretical predictions of the expected amount of bisector asymmetry in the presence of nonradial *g*- or *r*-mode pulsations in giant stars are currently not available. However, the numerical simulations conducted by Hatzes (1996) show that it is in principle possible to explain the observed RV variations in Pollux by low-order nonradial pulsation modes, while the accompanying bisector variations would be too small to be detected with current techniques (Hatzes & Cochran 1998). This is the main reason why some last doubt remains about the interpretation of the RV variations in terms of an orbiting companion, even if it would be a bit surprising to find only one single long-period pulsation mode. Note that the small eccentricity that we find (0.06 ± 0.04) is barely significantly different from zero, so that it cannot be used to rule out pulsations as the reason for the observed RV variations as has been done for highly eccentric giant star orbits (Frink et al. 2002).

In contrast to that, rotational modulation of starspots can be excluded as the reason for the observed RV changes, since otherwise some photometric variability larger than the microvariability actually seen should have been detected by *Hipparcos*. Also, it would be difficult to explain how a single or several starspots could produce RV variations that are so close to sinusoidal over the rotation period, as well as being stable over the last 25 years.

We conclude that while evidence is accumulating and compelling for an orbiting planet around Pollux, the final confirmation has to await a theoretical prediction of the amount of spectral line asymmetry in the presence of nonradial *g*- or *r*-mode pulsations in giant stars, much increased sensitivity in bisector analyses or photometry, or the detection of the companion with independent techniques such as, e.g., precise astrometry.

After this paper was first submitted we learned of the similar paper by Hatzes et al. (2006). Hatzes et al. (2006) present 55 new radial velocity measurements of Pollux with mean internal errors between 11 and 17 m s^{-1} taken between 1998 and 2006 and analyze them together with the older data sets by Larson et al. (1993) and Hatzes & Cochran (1993), also used in the present paper. Their orbital elements are in excellent agreement with the ones derived here, and both papers arrive at the same conclusions regarding the interpretation of the observed RV periodicity in terms of an orbiting planetary companion.

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