Spectroscopic Monitoring of Rapidly Rotating Early-type Stars in the Pleiades Cluster

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Abstract
Radial velocities for the early-type stars in the Pleiades cluster have always been challenging to measure because of the significant rotational broadening of the spectral lines. The large scatter in published velocities has led to claims that many are spectroscopic binaries, and in several cases, preliminary orbital solutions have been proposed. To investigate these claims, we obtained and report here velocity measurements for 33 rapidly rotating B, A, and early F stars in the Pleiades region, improving significantly on the precision of the historical velocities for most objects. With one or two exceptions, we do not confirm any of the previous claims of variability, and we also rule out all four of the previously published orbital solutions, for HD 22637, HD 23302, HD 23338, and HD 24310. We do find HD 22637 to be a binary but with a different period (71.8 days). HD 23338 is likely a binary as well, with a preliminary 8.7 yr period also different from the one published. Additionally, we report a 3635 day orbit for HD 24899, another new spectroscopic binary in the cluster. From the 32 bona fide members in our sample, we determine a mean radial velocity for the Pleiades of 5.79 ± 0.24 km s⁻¹, or 5.52 ± 0.31 km s⁻¹ when objects with known visual companions are excluded. Adding these astrometric binaries to the new spectroscopic ones, we find a lower limit to the binary fraction among the B and A stars of 37%. In addition to the velocities, we measure v sin i for all stars, ranging between 69 and 317 km s⁻¹.

Unified Astronomy Thesaurus concepts: Open star clusters (1160); Binary stars (154); Spectroscopic binary stars (1557); Visual binary stars (1777); Radial velocity (1332); Stellar rotation (1629)

Supporting material: machine-readable table

1. Introduction
The Pleiades cluster has been the subject of numerous spectroscopic surveys of its brighter members going back more than a century (e.g., Adams 1904; Frost et al. 1926; Smith & Struve 1944; Abt et al. 1965; Pearce & Hill 1975; Liu et al. 1991; Mermilliod et al. 2009). One of the most extensive programs, summarized in the last of these references, focused on slowly rotating FGK stars and ran for nearly 20 years, leading to the discovery and orbit characterization of many new binary systems in the cluster (Mermilliod et al. 1992, 1997; Rosvick et al. 1992; Raboud & Mermilliod 1998). While these later-type stars typically offer no difficulty for the determination of their radial velocities (RVs), earlier stars of spectral types B and A are much more challenging. Not only do they display fewer lines in their spectra, but the features are typically very broad because these stars tend to be rotating very rapidly, some with projected rotational velocities v sin i in excess of 200 km s⁻¹. As a result, available RVs for B and A stars in the Pleiades, and for a few F stars, are of relatively poor quality and often show significant scatter. Over the years, more than a dozen of these objects have been claimed to be possible spectroscopic binaries, and in some cases, tentative orbits have been published, but few have ever been confirmed.

The main motivation for this paper is therefore to investigate some of these claims, based on new observations gathered in the course of a long-term spectroscopic survey of the Pleiades ongoing at the author’s institution. The ultimate goal of that survey is to achieve a more complete census of the spectroscopic binaries in the cluster, extending it to longer-period systems in the regime where spectroscopic and astrometric techniques overlap, thereby enabling the determination of absolute masses. In addition to the many later-type stars whose velocities can be derived using standard cross-correlation techniques, the target list in the Pleiades includes nearly three dozen rapidly rotating B, A, and early F stars, which experience has shown require a different approach in order to derive accurate RVs. These objects therefore separate themselves naturally from the rest of the survey and are the subject of this paper. A further motivation for this work is to derive accurate rotational velocities for all the fast rotators in a uniform way.

We begin by defining the sample in Section 2, which we follow with a description in Section 3 of our observations and the methodology for the determination of RVs. The same section explains how we infer the rotational broadening for each star. Next we present the results of our RV determinations (Section 4), including new spectroscopic orbits for three of the objects and detailed notes for many of the others. This section also includes a discussion of the mean RV of the cluster. Our new rotational velocity measurements are then reported in Section 5. Final thoughts are presented in Section 6.
The ICRS coordinates are taken from the Gaia DR2 catalog. The location of the targets in the color-magnitude diagram of the cluster is indicated in Figure 1, showing other objects from the membership list of Gao (2019).
nnumerous iron lines. This region (particularly the ~100 Å order centered on the Mg triplet) has been found from experience to provide the best information for the measurement of RVs, usually yielding results with internal errors of 0.5 km s\(^{-1}\) or less for stars with modest rotation. However, for early-type stars that constitute about 10% of the survey, the iron lines are no longer visible and the Mg I triplet is much weaker, particularly if the stars are rotating rapidly. The velocity measurements then become very difficult: they have individual formal uncertainties as large as 5–10 km s\(^{-1}\), or sometimes more, and result in a large scatter for any given object.

Methodologies involving cross-correlation with CCD detectors for rapidly rotating early-type stars have been investigated, e.g., by Morse et al. (1991). Those authors identified two regions about 140 Å wide that seemed most promising at their spectral resolution of 44 km s\(^{-1}\). One is centered around 3787 Å but is outside the range covered by our spectra. The other is centered around 4073 Å and features H\(\delta\) as well as several He I lines. This happens to be near the middle of one of our spectral orders. We explored the use of this region by creating synthetic spectra with the SPECTRUM code of Gray & Corbally (1994), using Kurucz model atmospheres for a range of temperatures appropriate for B, A, and early F stars, along with the line list provided with the program. However, we still found the velocities to be poor, perhaps because the order centered at 4073 Å in our spectra is only 70 Å wide, half of what Morse et al. (1991) used. We also investigated the use of an order containing the He I \(\lambda 4471\) and Mg II \(\lambda 4481\) lines (the latter being a blend of two Mg lines), which are strong in hot stars, but we obtained similarly disappointing results.

Least-squares deconvolution (LSD) is another technique with somewhat similar benefits to cross-correlation, in the sense that it can use all of the information available over a wide wavelength range and delivers a mean line profile for the star with a higher signal-to-noise ratio than the individual spectra (see, e.g., Kochukhov et al. 2010). However, our attempts with LSD did not result in much improvement compared to cross-correlation, giving only marginally smaller uncertainties for the RVs.

In the end, we opted for a more classical approach, and measured the centroids of five strong Balmer lines manually, by fitting a Gaussian curve to the core of each line profile using the splot task within IRAF.1 We consider this procedure to be adequate for these stars given that all of the spectra appear effectively single lined, as mentioned earlier. The five lines considered are H\(\alpha\), H\(\beta\), H\(\gamma\), H\(\delta\), and H\(\epsilon\). The H\(\beta\) and H\(\delta\) lines are each present in two adjacent orders, and we measured both independently. The wavelengths adopted for these lines were taken from the NIST Atomic Spectra Database.2 Table 2 collects the individual velocities derived for each star, calculated from the straight average of the seven line measurements from each spectrum, with internal uncertainties given by the error of the mean. The average internal uncertainty for the 388 velocities is 1.7 km s\(^{-1}\), and most errors are under 3 km s\(^{-1}\).

In addition to measuring the velocities, we made a determination of the rotational broadening for the stars in our sample. One of them (HD 23323) appears to have no previous
determination of \(v \sin i\) in the literature, while others have sometimes wildly discrepant values from different sources. We cross-correlated each spectrum against synthetic templates calculated with the SPECTRUM code for a range of rotational broadenings up to 400 km s\(^{-1}\). We adopted a fixed temperature for each star appropriate for its spectral type, as we found that the \(v \sin i\) measurements are insensitive to that value. We explored several regions of the spectrum including the one featuring the Mg I b triplet, and an order containing the He I \(\lambda 4471\) and Mg II \(\lambda 4481\) lines, which are commonly used for this purpose. Even though the order with the latter lines did not yield useful velocities, as we indicated earlier, we found that it performed best for determining \(v \sin i\), giving fairly consistent answers from repeat observations of the same star. To be conservative, we adopted the standard deviation of the rotational broadenings as a measure of their uncertainty, rather than the error of the mean. To illustrate these results, Figure 2 shows the coadded spectra for each star in the region of the Mg II \(\lambda 4481\) line, compared against synthetic spectra with the measured \(v \sin i\) values, as labeled.

### 4. Radial Velocity Results

Table 3 summarizes the results of our RV determinations and includes the number of observations (\(N_{\text{obs}}\)), the average signal-to-noise ratio, the date range and time span, the mean RV, and the standard deviation \(\sigma_{\text{RV}}\) for each star. To be conservative, we have chosen to adopt \(\sigma_{\text{RV}}\) as the uncertainty for the mean velocities. The next column gives the predicted RV within the cluster to be discussed in Section 4.2. Some of the objects are known to have close visual companions, detected mostly by the lunar occultation technique or by other imaging methods. For those, the following column in the table provides the angular separation and magnitude difference. In all cases, the periods of these astrometric companions are likely to be decades long under reasonable assumptions for the masses and are generally not expected to induce measurable velocity variations over the duration of our observations. As seen in the table, more than half of the stars have been claimed to be velocity variables at one time or another over the last century, often by more than one author, and tentative spectroscopic orbital solutions have been published for four of them. However, the velocities on which those assessments are based are typically of relatively poor quality compared to those in this paper, and as it turns out, except for one or possibly two objects, our observations do not appear to support any of those claims of variability or any of the published orbits. In one case (HD 22637), we do find that the star has variable velocity, but the orbit is completely different from the one published. In another (HD 23338), we present a new orbit based on our own measurements combined

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1. IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
2. [https://physics.nist.gov/PhysRefData/ASD/lines_form.html](https://physics.nist.gov/PhysRefData/ASD/lines_form.html)
compared against the corresponding synthetic spectrum the measured days, showing a difference of 40-
features of interest. previously claimed or new spectroscopic orbits, or other variability from different authors, claims of double lines, information for stars in the table with unrecognized as a spectroscopic binary, for which we report a preliminary. There is also one case (proposed in the literature, although we still view the solution as another more distant star in the system. To our knowledge, no such companions have been detected so far. A speckle interferometry observation by Mason et al. (2009) yielded a negative result. At the distance to the Pleiades, the 71.8 day orbit should subtend an angle of about 4 mas, which is resolvable with long-baseline interferometers.

Figure 2: Coadded spectrum of each star centered on the MgII λ4481 line, compared against the corresponding synthetic spectrum (smooth red line) for the measured $v\sin i$, labeled on the right side of each panel.

with those of others, which is also different from the orbit proposed in the literature, although we still view the solution as preliminary. There is also one case (HD 24899) previously unrecognized as a spectroscopic binary, for which we report a new orbit. In the following, we present notes with additional information for stars in the table with conflicting claims of RV variability from different authors, claims of double lines, previously claimed or new spectroscopic orbits, or other features of interest.

4.1. Notes on Individual Objects

HD 22614: The velocity variability claim by Smith & Struve (1944) is based on only two measurements separated by 83 days, showing a difference of 40 km s$^{-1}$. Neither our nine observations over 590 days nor the three of Pearce & Hill (1975) over 92 days display anywhere near that level of variability.

HD 22637: Pearce & Hill (1975) reported an orbital solution with a period of 4.674 days. Our observations are inconsistent with this orbit (see Figure 3, top panel), and instead show clear RV variability with a much longer period of 71.8 days. As it turns out, most of the velocities from Pearce & Hill (1975) fit our orbit quite well, as do the older ones of Smith & Struve (1944). Our new spectroscopic orbit using the new and old velocities is shown in the bottom panel of the figure, and the elements from a weighted least-squares solution are listed in Table 4. The fairly large coefficient for the minimum secondary mass suggests that, for certain orbital inclination angles, the companion may be massive enough and therefore bright enough to make its lines visible in our spectra. If we adopt a primary mass of $\sim 2.4 M_\odot$ based on its spectral type and a conservative detection sensitivity of 1 mag for the brightness difference, we estimate that a secondary with a mass of 1.75 $M_\odot$ or larger should be bright enough to be detected in our spectra. Given the orbital elements, this would occur for inclination angles smaller than about 36°, with a $\sim 19\%$ probability under the assumption of random inclination angles. Our lack of detection of lines of the secondary (see Figure 2) would then imply an inclination angle larger than this limit. The center-of-mass velocity of the binary is lower than the cluster mean of about 6 km s$^{-1}$ (Liu et al. 1991; Morse et al. 1991; Rosvick et al. 1992; Raboud & Mermilliod 1998; Gaia Collaboration et al. 2018b; Gao 2019; ), which may be a sign of another more distant star in the system. To our knowledge, no such companions have been detected so far. A speckle interferometry observation by Mason et al. (2009) yielded a negative result. At the distance to the Pleiades, the 71.8 day orbit should subtend an angle of about 4 mas, which is resolvable with long-baseline interferometers.

HD 22702: Our RVs seem to be the first to be obtained for this star. Our 10 measurements show no meaningful change over a period of 2 yr.

HD 23155: The claim by Smith & Struve (1944) that the velocity is variable is based on only two measurements separated by 4 days, showing a change of 30 km s$^{-1}$. Our own 10 observations show no significant change over nearly 590 days, and the four measurements of Pearce & Hill (1975) spanning 40 days also show little variation.

HD 23302: This is Electra (17 Tau). Abt et al. (1965) reported a tentative 100.46 day spectroscopic orbit with a velocity semiamplitude of 26 km s$^{-1}$, based on their own observations and others from the literature, but noted that it was poorly determined. Pearce & Hill (1971) were skeptical, as their independent observations did not follow that orbit particularly well. Our own, more precise observations show no significant velocity variability over a nearly 800 day time span, ruling out the orbit. Chini et al. (2012) also found the star to be constant in RV from five unpublished measurements. We demonstrate the conflict between our observations and the Abt orbit in the top panel of Figure 4. Jarad et al. (1989) also doubted the orbit based on their new RV measurements but proposed two alternative solutions with much shorter periods of 3.83 and 4.29 days, and semiamplitudes of about 13 and 10 km s$^{-1}$, respectively. Although full details were not given, our constant velocities clearly reject both of those orbits as well. These claims of RV variability in rapidly rotating stars are not surprising. Even for a bright and easily observable object such as HD 23302 ($V = 3.70$), the very large dispersion of the historical velocities, compounded by differences in velocity zero-points between the various data sets, makes it tempting to interpret the scatter as implying real variability if the observational uncertainties are not well known or are underestimated. The lower panel of Figure 4 gathers all available velocities for HD 23302 and is representative of the situation common to many of the other stars in our sample. Corresponding figures for other objects that have also been claimed or suspected to have variable RVs look qualitatively the same and
Given for HD

HD 23950

HD 23585

HD 23388

HD 23323

HD 23315

HD 23302

HD 23242

HD 24340

HD 24310

HD 24042

HD 23409

HD 23432

HD 23430

HD 23489

HD 23512

HD 23585

HD 23629

HD 23643

HD 23735

HD 23763

HD 23852

HD 23863

HD 23912

HD 23913

HD 23950

HD 24013

HD 24178

HD 24711

HD 24899

Name

HD 21744

HD 22578

HD 22614

HD 22637

HD 22702

HD 23155

HD 23302

HD 23324

HD 23338

HD 23323

HD 23361

HD 23388

HD 24022

HD 24101

HD 24049

HD 23432

HD 24300

HD 24042

HD 23409

HD 23432

HD 23430

HD 23489

HD 23512

HD 23585

HD 23629

HD 23643

HD 23735

HD 23763

HD 23852

HD 23863

HD 23912

HD 23913

HD 23950

HD 24013

HD 24178

HD 24711

HD 24899

N_{\text{obs}} (S/N)

11 78

8 162

9 127

32 125

10 61

10 110

31 352

9 227

14 308

7 54

10 132

9 89

8 98

10 144

19 135

11 188

8 72

12 116

9 84

24 96

9 155

8 111

9 247

23 136

8 91

6 95

5 64

7 137

13 238

11 111

7 92

5 76

16 135

\langle RV \rangle (\text{km s}^{-1})

711

719

590

743

719

589

799

594

680

1771

572

328

567

2184

700

594

2498

702

3333

596

377

3280

710

2830

359

594

2877

660

344

324

3394

\sigma_{\text{RV}} (\text{km s}^{-1})

1.75

1.00

0.91

0.78

1.55

1.47

10.00

1.72

0.34

3.78

1.89

1.63

2.80

1.81

1.06

0.84

0.84

1.37

1.07

1.73

2.32

1.83

1.20

1.02

0.67

1.37

0.48

2.48

1.29

1.38

0.07

RV_{\text{obs}} (\text{km s}^{-1})

4.23

6.07

5.02

6.53

4.80

5.07

5.64

5.27

5.47

4.20

7.20

6.43

5.73

5.02

5.65

5.99

5.82

6.00

6.19

5.70

6.67

4.6

6.27

6.73

6.90

6.73

5.00

6.75

6.34

Binarity

2\sigma, 6.1 (1)

var(S)

or(P1); New orbit

var(AJ), var(H,P,P1,L)

var(A,H,P,P1,L)

var(A), var(P1); New orbit

var(P1,L)

var(P1)

var(L)

var(L)

var(L)

var(L)

var(F,P1)

var(A,P1,L)

var(H)

0.0155, 1.1 (7)

var(L); Nonmember

var(S)

var(S)

\text{New orbit}

Binary

RV Variability

Note. Asterisks after the names call attention to notes in the text. Subsequent columns give the number of observations, the average signal-to-noise ratio per resolution element, the Julian day interval, and the time span. Next, we list the average radial velocity, \langle RV \rangle, and the standard deviation of the velocities for each star, \sigma_{\text{RV}}, which we adopt here as the error of the mean velocity, to be conservative. For HD 22637, HD 23338, and HD 24899, the velocities and uncertainties listed correspond to the center-of-mass velocity of the binary, based on the new orbital solutions in this paper (Tables 4 and 5). RV_{\text{obs}} is the predicted radial velocity within the cluster, based on the position of the convergent point and the mean distance and proper motion of the Pleiades from the Gaia mission (Gaia Collaboration et al. 2018b). It is not given for HD 24013, which is a background star and not a cluster member. Uncertainties for the predicted velocities are very small (<0.1 km s\textsuperscript{-1}). The Binarity column identifies stars reported to be close astrometric binaries and gives the angular separation and magnitude difference of the pair (when available). An asterisk following the separation indicates the measurement is from a lunar occultation event, in which case it corresponds strictly to a separation projected in the direction of the lunar motion. Codes in parentheses refer to the following sources: (1) Washington Double Star Catalog (Mason et al. 2001); (2) Richichi et al. (2002); (3) Richichi et al. (1994); (4) Guerrero et al. (2020); (5) McGraw et al. (1974); (6) Richichi et al. (2012); (7) Qian & Fan (1991); (8) ESA (1997). The last column indicates previous claims of velocity variability from the literature ("var"), or published orbital solutions ("orb"). Codes in parentheses correspond to the following sources: (F) Frost et al. (1926); (S) Smith & Struve (1944); (A) Abt et al. (1965); (H) Hube (1970); (P) Pearce & Hill (1971); (P1) Pearce & Hill (1975); (J) Jarad et al. (1989); and (L) Liu et al. (1991). The three objects with new orbits from this work are also noted.

are not shown. Finally, we note that a visual companion to HD 23302 is known from lunar occultation observations (e.g., Richichi et al. 1996), at a projected separation of about 0''2 and with a brightness difference of ΔK = 3.5. The orbital period is expected to be of the order of a century.

HD 23324: 18 Tau. Abt et al. (1965) suspected double lines at two of their epochs but reported the velocities were not measurable. Pearce & Hill (1975) also mentioned double lines. We see no evidence of this in our spectra (see Figure 2). We are also unable to find any significant periodicity in the historical velocities. Our own observations show no change over nearly 600 days, and neither do nine unpublished RVs from Chini et al. (2012). A close companion is known from lunar occultations. It may be responsible for the fact that our mean velocity is about 2 km s\textsuperscript{-1} higher than the cluster mean.

HD 23338: This is Taygeta, or q Tau. Abt et al. (1965) reported a tentative orbit with P = 1313 days and a velocity semiamplitude of 8 km s\textsuperscript{-1}, but pointed out that it was not completely convincing. Pearce & Hill (1971) cast doubt on the binary nature of the object, as their own observations were essentially constant. Chini et al. (2012) reached a similar conclusion based on eight spectra. Our own velocities over an interval of 680 days also show little change (see Figure 5, top panel), but we note that they are all significantly lower than the mean velocity for the cluster, averaging 0.95 ± 1.48 km s\textsuperscript{-1}. HD 23338 is known from lunar occultation measurements to have a companion about 2.3 mag fainter in the K band.
Figure 3. Top: orbit model proposed by Pearce & Hill (1975) for HD 22637, with a period of 4.674 days, compared with our own measurements. The dotted line is the reported center-of-mass velocity of the system. Our velocities are seen not to follow predictions. Bottom: new orbital solution with $P = 71.8$ days, shown with our own measurements (filled circles) as well as historical velocities from the literature. Those of Smith & Struve (1944) have been adjusted to place them on the same system as the ones of Pearce & Hill (1975), following the prescription from those authors. As before, the dotted line marks the center-of-mass velocity, and phase 0.0 corresponds to periastron passage.

Figure 4. Top: our velocity measurements for HD 23302 plotted against predictions from the 100.46 day orbit of Abt et al. (1965). The orbit is spurious. Bottom: historical velocities for HD 23302 showing a large scatter typical of B and A stars in the Pleiades, along with our own measurements.

Table 4
Orbital Elements for Two New Spectroscopic Binaries in the Pleiades

| Parameter | HD 22637 | HD 24899 |
|-----------|----------|----------|
| $P$ (day) | $71.8198 \pm 0.0084$ | $5635 \pm 19$ |
| $\gamma$ (km s$^{-1}$) | $3.94 \pm 0.78$ | $7.183 \pm 0.068$ |
| $K_1$ (km s$^{-1}$) | $21.2 \pm 1.3$ | $3.72 \pm 0.16$ |
| $e$ | $0.284 \pm 0.048$ | $0.528 \pm 0.035$ |
| $\omega_1$ (degree) | $111 \pm 11$ | $207.8 \pm 3.4$ |
| $T_{\text{ref}}$ (HJD-2,400,000) | $58403.4 \pm 2.0$ | $49190 \pm 47$ |
| $M_2 \sin i / (M_1 + M_2)^{3/2}$ ($M_0$) | $0.396 \pm 0.022$ | $0.2280 \pm 0.00088$ |
| $a_1 \sin i$ (10$^5$ km) | $20.1 \pm 1.1$ | $157.8 \pm 6.0$ |
| $N_{\text{obs}}$ | $32 \pm 9$ | $16 \pm 5$ |
| rms (km s$^{-1}$) | $5.83$ | $0.35$ |

Note. The symbols $\omega_1$ and $a_1 \sin i$ represent the longitude of periastron and projected semimajor axis of the primary component, respectively. Other symbols have their usual meaning.

Richichi et al. (1994) discussed the available measurements, some of which they considered of marginal quality, and from two events they viewed as the most reliable, they inferred a true angular separation of about 0'19 at a mean epoch of 1989.29, and a position angle of 156°. At the distance of the Pleiades, this separation corresponds to an orbital period of decades, which could well explain both why our velocities seem constant and why their average differs by $\sim$5 km s$^{-1}$ from the cluster mean.

We have reexamined the historical velocities for HD 23338 going back more than a century and discovered that it is possible to obtain a spectroscopic orbital solution with a period of about 8.7 yr that satisfies most of the available RVs, including our own. This solution is shown graphically in the bottom panel of Figure 5, and the elements are listed in Table 5. The RV observations span nearly 118 yr and cover 13.6 cycles of the binary. At the present time, we consider this solution for HD 23338 to be preliminary, for two reasons. First, a few measurements by several authors were found to deviate significantly from the fit and were excluded: one by Jung (1914), one by Smith & Struve (1944), five by Abt et al. (1965), and also all four measurements by Beardsley (1969; one being very uncertain). Velocities from the latter source tend to show more scatter than those by other authors. Second, the solution was found to be somewhat sensitive to the weighting of the observations. Many of the old measurements have no published errors, and we have arbitrarily assigned them uncertainties of 3 km s$^{-1}$. For the ones that do, we have converted from the published probable errors to mean errors where necessary. To guard against the possibility that our own
The predicted angular separation at the epoch of the HD 0777, with little dependence on projected separation recorded during that event. The predicted angular separation at the epoch of the first of the lunar occultation measurements discussed by Richichi et al. (1994; 1988.97) is then $\sim 0.040$, with little dependence on the unknown inclination angle. This is smaller than the $0.0777 \pm 0.0005$ projected separation recorded during that event. Thus, the spectroscopic companion does not appear to be the same as the astrometric companion. We point out also that, in order to infer a true angular separation of $0.040$ from two one-dimensional lunar occultation measurements at epochs 1988.97 and 1989.72, Richichi et al. (1994) had to assume the companion did not move appreciably in the intervening 9 months. However, to the extent that our spectroscopic orbit is correct, it indicates that the companion did in fact move significantly over that period, which may invalidate the $0.040$ estimate of the true angular separation. Additional astrometric observations resolving the wide pair are needed to gain a better understanding of its orbit.

**Figure 5.** Top: orbit model for HD 23338 proposed by Abt et al. (1965), with a period of 1313 days, compared with our own measurements (shown as filled symbols) and those of others (Adams 1904; Jung 1914; Campbell & Moore 1928; Smith & Struve 1944; Abt et al. 1965; Abt 1970; Pearce & Hill 1971, 1975; Andersen & Nordström 1983; Liu et al. 1991, all represented with open symbols). The observations are seen not to follow predictions. The dotted line is the proposed center-of-mass velocity of the system. Bottom: new orbital solution (preliminary) with $P = 3172.4$ days based on the same velocities as above. The measurements of Smith & Struve (1944) have been adjusted to place them on the same system as the ones of Pearce & Hill (1975), following the prescription from those authors. As before, the dotted line marks the center-of-mass velocity, and phase 0.0 corresponds to periastron passage.

### Table 5

Preliminary Spectroscopic Orbital Elements for HD 23338

| Parameter | Value |
|-----------|-------|
| $P$ (day) | 3172.4 ± 9.9 |
| $\gamma$ (km s$^{-1}$) | 5.66 ± 0.34 |
| $K_1$ (km s$^{-1}$) | 7.64 ± 0.88 |
| $e$ | 0.391 ± 0.079 |
| $\omega_1$ (degree) | 350 ± 11 |
| $T_0$ (HJD−2,400,000) | 37784 ± 82 |
| $M_2$ sin i / (M$_1$ + M$_2$)$^{1/3}$ (M$_\odot$) | 0.485 ± 0.044 |
| $a_1$ sin i (10$^6$ km) | 307 ± 28 |
| $N_{hs}$ | 14 ± 45 |
| rms (km s$^{-1}$) | 2.44 |

**Note.** The symbols $\omega_1$ and $a_1$ sin i represent the longitude of periastron and projected semimajor axis of the primary component, respectively. Other symbols have their usual meaning. A total of 45 observations from the literature have been included in this orbital solution, along with 14 of our own.

errors are underestimated, we also added 2 km s$^{-1}$ in quadrature to all observations. While changes to this error scheme do not affect the orbital period very much, they do impact the

eccentricity and velocity semiamplitude. Confirmation of our tentative solution would therefore benefit from new spectroscopic observations during the next periastron passage, which we predict should occur in early 2023.

Adopting a mass for the primary of 4 $M_\odot$ based on its spectral type and a range of secondary masses, we estimate the angular semimajor axis of this preliminary orbit to be about $0.06^\circ$. The predicted angular separation at the epoch of the first of the lunar occultation measurements discussed by Richichi et al. (1994; 1988.97) is then $\sim 0.040$, with little dependence on the unknown inclination angle. This is smaller than the $0.0777 \pm 0.0005$ projected separation recorded during that event. Thus, the spectroscopic companion does not appear to be the same as the astrometric companion. We point out also that, in order to infer a true angular separation of $0.040$ from two one-dimensional lunar occultation measurements at epochs 1988.97 and 1989.72, Richichi et al. (1994) had to assume the companion did not move appreciably in the intervening 9 months. However, to the extent that our spectroscopic orbit is correct, it indicates that the companion did in fact move significantly over that period, which may invalidate the $0.040$ estimate of the true angular separation. Additional astrometric observations resolving the wide pair are needed to gain a better understanding of its orbit.

HD 23323: We are not aware of any RV measurements for this star in the literature other than our own. We see no significant change over more than 4 yr.

HD 23361: No significant periodicity could be found in the historical velocities for this star. Our 10 measurements over more than 5 yr do not support the variability claims in the literature.

HD 23410: A double-lined orbit for this object was reported by Abt et al. (1965), with a period of 7.15 days, a large eccentricity, and large semiamplitudes of 86 and 144 km s$^{-1}$ for the primary and secondary (with the latter being more uncertain). The authors indicated it was based only on the Ca II K line and that the components are of nearly the same brightness, leading to confusion and uncertainty in deriving the orbital elements. The center-of-mass velocity they gave, $-23$ km s$^{-1}$, is inconsistent with its well-established cluster membership (Gao 2019), and indeed our velocities show no change from an average of 6.4 km s$^{-1}$ over about a year and a half, indicating the proposed orbit is spurious. Double lines are not apparent in our spectra (see Figure 2). Measurements by Smith & Struve (1944) and by Pearce & Hill (1975) also disagree with the orbit. We illustrate this in Figure 6. This is a known visual binary with a separation of about 3$''$5 and a brightness difference of about 3 mag in the visible.

HD 23409: Liu et al. (1991) suspected double lines, but this is not obvious in our spectra (see Figure 2). Our RV measurements show no significant change over nearly 6 years. We are unable to find any coherent periodicity in the previously published velocities.

HD 23489: Abt et al. (1965) reported that although the scatter appeared large, they could not discover any periodicity in the velocities. Seven other measurements have been published since, but no orbit has emerged. Our own velocities

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3 Lunar occultation events do not yield the true angular separation of a binary, only its projection along the direction of the lunar motion. The true separation at this epoch could therefore be larger than $0.0777$, making it even more inconsistent with the prediction from the spectroscopic orbit.
are constant. A wide companion is known from speckle interferometry.

HD 23512: Although Smith & Struve (1944) thought the velocity might be variable, Abt et al. (1965) saw no change in their own measurements. Liu et al. (1991) suspected double lines; we see no evidence of that (see Figure 2). Our own velocities are constant within the measurement uncertainties, over nearly 2 years. The star is listed as a visual binary with a separation of about 0\degree/1 and a brightness difference of 2 mag (Mason et al. 2001).

HD 23585: Liu et al. (1991) reported a 15 km s\(^{-1}\) RV change from two observations separated by 700 days. We see no change in our 24 measurements over 9 yr, nor are we able to detect any periodicity in the historical velocities.

HD 23629: 24 Tau. Abt et al. (1965) cast doubt on the velocity variability claim of Smith & Struve (1944). We also see little change in the RVs over a year and a half. The detection of a lunar occultation companion 1.1 mag fainter in \(B\) was reported by McGraw et al. (1974), at a projected separation of 0\degree0019.

HD 23643: Only Liu et al. (1991) have claimed this is a velocity variable, based on 700 measurements showing no change apart showing a difference of 23 km s\(^{-1}\). Neither our observations nor those of others confirm this.

HD 23753: While some authors have considered this star to be a velocity variable, Chini et al. (2012) reported a constant velocity from their six spectra. Our own measurements over about a year also show little change. A companion is known from lunar occultations. The rotational velocity of this star is the largest in our sample.

HD 23763: Although RV variability has been claimed for this object, we are unable to find a satisfactory orbital solution using the previously published velocities. Our own 23 measurements over 9 years show no change.

HD 23863: Another object with no significant RV variation from our own observations over nearly 8 yr and a large scatter but no coherent motion that we can discern in the historical RVs.

HD 23950: Hube (1970) flagged the star as a velocity variable, but Chini et al. (2012) reported that their seven measurements show no significant change. We also see no RV variation in almost 8 yr. Our mean velocity is higher than the cluster mean. The changes seen by Hube (1970) are likely due to measurement errors, as two of their published velocities obtained on the same night within half an hour of each other differ by 23 km s\(^{-1}\).

HD 24013: Liu et al. (1991) claimed the detection of double lines. This is a known nonmember, which Gaia confirms from a parallax and proper motion that disagree with the mean values for the cluster. It was observed here only because it was on the original list of possible cluster members with which the project started. Our velocities show little change within the errors over 660 days, and we see no sign of double lines in our spectra (Figure 2). Qian & Fan (1991) reported the detection of a companion from lunar occultations that is 1.1 mag fainter than the primary in \(B\), at a projected separation of 0\degree00155.

HD 24711: Aside from our own five measurements, we are aware of only three others in the literature: two from Smith & Struve (1944) and one from Pearce & Hill (1975). The two from Smith & Struve (1944) are 81 days apart and differ by 33 km s\(^{-1}\). Ours show little scatter over 324 days.

HD 24899: There is a clear long-term variability in the velocities from this work, with a period of about 10 yr. This appears to have gone unnoticed until now. Three velocity measurements from Pearce & Hill (1975) and two from Smith & Struve (1944) are actually consistent with the trend. The new orbital solution incorporating all measurements is shown in Figure 7, and the elements are listed in Table 4. If we assume that the primary has a mass near 2.6 \(M_\odot\) based on its spectral type, and if we adopt the same conservative sensitivity limit to companions as used for HD 22637 (1 mag), we estimate that the minimum mass for the secondary to be bright enough to be detected is about 1.9 \(M_\odot\) For this to be the case, the inclination angle must be smaller than about 19°, which would be expected to occur only \(\sim\)5% of the time for an isotropic distribution. This seems consistent with the fact that we see no evidence of double lines (Figure 2). The Hipparcos mission detected and measured a significant astrometric acceleration (i.e., curvature in the proper motion) over the 2 yr duration of the observations for this star, which is likely a reflection of the orbit we report here. The same effect was detected from proper motion differences between Hipparcos and Tycho-2 by Makarov & Kaplan (2005), and between Hipparcos and Gaia by Kervella.
et al. (2019). To our knowledge, there has been no direct
detection of the companion as yet. At the distance to the
Pleiades, we expect the angular separation to be of the order of
50 mas.

4.2. The Mean Velocity of the Cluster

The RVs from Table 2 for the B, A, and F stars in our sample
fall close to the known mean value for the Pleiades of about
6 km s\(^{-1}\) (see Figure 8). Ignoring binarity for the moment, the
average of the 32 stars, with the nonmember HD 24013
excluded, is 5.79 ± 0.24 km s\(^{-1}\). This is in very good
agreement with determinations by others (e.g., Gao 2019; Gaia
Collaboration et al. 2018b). However, the standard deviation of
1.37 km s\(^{-1}\) is much larger than the internal velocity dispersion
of the cluster, which is estimated to be only about 0.5 km s\(^{-1}\)
(e.g., Jones 1970; Rosvick et al. 1992; Makarov & Robichon
2001).

There are at least three possible reasons for the larger scatter.
One is of course measurement errors, which we address below.
Another is that the angular extent of the Pleiades on the sky is
quite large (∼10°), and changes in the projection of the mean
space velocity of the cluster along the line of sight from one
to the other will cause an RV gradient of several km s\(^{-1}\).
To show this more quantitatively, we have listed the predicted
RV of each star in Table 2, calculated from the position of the
convergent point and the mean distance and proper motion of
the Pleiades from the Gaia mission (Gaia Collaboration et al.
2018b). The uncertainty in those predictions is negligible for
our purposes (<0.1 km s\(^{-1}\)). We find, however, that even after
accounting for this gradient, the RV dispersion for our stars is
1.52 km s\(^{-1}\), not very different than before. Figure 9 shows the
predicted RV of each star against the observed velocities. With
few exceptions, the agreement is very good. Objects with
known astrometric companions are represented with triangles.
A third possible reason for the large scatter around the
cluster’s mean velocity is binarity, whether recognized or not.
For the two new confirmed spectroscopic binaries (HD 22637
and HD 24899), the velocities we are using correspond to the
center of mass, so the effect of the companions is already
accounted for. In addition, there are 11 other targets known to
have close astrometric companions, as indicated in Table 2.
This excludes HD 24013, and we do not count HD 24899

either because the astrometric signature mentioned in the notes
corresponds to the same companion detected spectroscopically.
In principle, it is possible that these 11 wide companions could
be affecting the measured velocities to some extent, although
the evidence for this is not always obvious in the table. In any
case, we choose to remove them as a precaution. Note that we
also remove HD 23338 even though it has a spectroscopic
orbit, and even though its center-of-mass velocity agrees with
the prediction, because the spectroscopic companion appears to
be different from the astrometric one (see previous section).
The average RV of the remaining 21 objects is
5.52 ± 0.31 km s\(^{-1}\), close to the previous value, and the
dispersion is not very different from before: 1.44 km s\(^{-1}\). The
excess over the internal dispersion for the cluster,
\(\sigma_{\text{excess}} \approx \sqrt{1.44^2 - 0.5^2} \approx 1.35 \text{ km s}^{-1}\), is comparable to our
measurement errors, which average 1.26 km s\(^{-1}\) over the 21
stars considered. We may conclude, then, that our RV
measurements are not inconsistent with a small internal
velocity dispersion for the cluster, of the order of that
determined by the authors listed above, i.e., that the
measurement errors play a significant role and the discrepancy
between the observed scatter and the true internal velocity
dispersion is only apparent.

5. Rotation Results

Our \(v \sin i\) determinations are presented in Table 6, together
with other measurements from sources in the literature with the
most stars in common with our sample. Three of those sources are
compared separately in Figure 10 against our own
measurements. Of those three, the determinations of Anderson
et al. (1966) and the more recent ones of Kounkel et al. (2019)
are independent and can each be considered to have been
carried out in a homogeneous way. On the other hand, the
values from the large catalog of Głąbocki & Gnaciński (2005)
are averages of historical measurements by many different
authors, including Anderson et al. (1966). Even though
Table 6
Rotational Velocity Measurements for Our Sample

| Name       | $v\sin i$ | S1944 | A1965 | A1966 | A2002 | G2005 | K2019 | Other |
|------------|-----------|-------|-------|-------|-------|-------|-------|-------|
| HD 21744   | 140 ± 5   | ...   | ...   | ...   | ...   | ...   | ...   | Ku:152|
| HD 22578   | 230 ± 14  | 150   | ...   | ...   | ...   | 120   | ...   | ...   |
| HD 22614   | 118 ± 5   | 0     | ...   | ...   | ...   | 25.7  | 123 ± 13| Ku:161|
| HD 22637   | 132 ± 5   | 50    | ...   | ...   | ...   | 55.6  | ...   | ...   |
| HD 22702   | 148 ± 6   | ...   | ...   | ...   | ...   | 72.8  | 230 ± 7| ...   |
| HD 23155   | 214 ± 5   | 75    | ...   | ...   | ...   | 190   | ...   | ...   |
| HD 23320   | 175 ± 12  | 200   | 230   | 205   | 85, 90| 155   | ...   | F:170(12); S:180; V:215; Y:189(7); Z:170(16) |
| HD 23324   | 210 ± 15  | 150   | 235   | 255   | 185   | 206   | ...   | Z:212(8) |
| HD 23338   | 112 ± 7   | 150   | 140   | 130   | 105   | 114   | ...   | Ku:246; S:107, 108; Z:118(8) |
| HD 23323   | 138 ± 5   | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
| HD 23361   | 231 ± 9   | 100   | ...   | 235   | ...   | 184   | 241 ± 10| M:186,0, Mo:150 |
| HD 23388   | 213 ± 10  | 50    | ...   | ...   | ...   | 68.5  | ...   | ...   |
| HD 23402   | 285 ± 11  | 150   | ...   | ...   | ...   | 120   | ...   | ...   |
| HD 23410   | 173 ± 7   | 100   | 185   | 200   | ...   | 158   | ...   | ...   |
| HD 23499   | 223 ± 6   | 75    | ...   | 170   | ...   | 133   | ...   | ...   |
| HD 23432   | 161 ± 8   | 150   | 210   | 235   | 160   | 176   | ...   | S:158, 159; Z:183(8) |
| HD 23430   | 141 ± 5   | 75    | ...   | ...   | ...   | 81.3  | 133 ± 4 | Ku:149 |
| HD 23489   | 127 ± 5   | 50    | ...   | 110   | ...   | 85.6  | 141 ± 8| ...   |
| HD 23512   | 168 ± 5   | 50    | 155   | 145   | ...   | 120   | 179 ± 16| Ku:276 |
| HD 23585   | 116 ± 5   | 75    | ...   | 100   | ...   | 85.6  | 119 ± 4 | K:113(3); M:107.5 |
| HD 23629   | 171 ± 15  | 100   | 155   | 170   | ...   | 133   | ...   | ...   |
| HD 23643   | 241 ± 10  | 100   | ...   | 185   | ...   | 185   | 285 ± 13| R:219; Ro:175(9) |
| HD 23753   | 317 ± 25  | 300   | 305   | 240   | 290   | 292   | ...   | Z:335(8) |
| HD 23763   | 108 ± 5   | 50    | 100   | 110   | ...   | 85.6  | 177 ± 9| ...   |
| HD 23852   | 153 ± 6   | 75    | ...   | ...   | ...   | 72.8  | ...   | ...   |
| HD 23863   | 174 ± 5   | 100   | ...   | 160   | ...   | 137   | 172 ± 7| ...   |
| HD 23912   | 162 ± 10  | 100   | ...   | 130   | ...   | 125   | 154 ± 2| ...   |
| HD 23913   | 188 ± 11  | 150   | ...   | ...   | ...   | 137   | ...   | ...   |
| HD 23950   | 71 ± 4    | 75    | ...   | ...   | 50, 60| 73.9  | ...   | ...   |
| HD 24013   | 283 ± 15  | ...   | ...   | ...   | ...   | ...   | 271 ± 14| ...   |
| HD 24178   | 225 ± 15  | 75    | ...   | ...   | ...   | 72.8  | ...   | ...   |
| HD 24711   | 152 ± 5   | 25    | ...   | ...   | ...   | 34.2  | ...   | ...   |
| HD 24899   | 69 ± 4    | 0     | ...   | ...   | ...   | 25.7  | ...   | ...   |

Note. All values are in units of km s\(^{-1}\). Column 2 reports the new $v\sin i$ determinations from this work. The main literature sources in the columns that follow are S1944 = Smith & Struve (1944); A1965 = Abt et al. (1965); A1966 = Anderson et al. (1966); A2002 = Abt et al. (2002); G2005 = Glöckler & Gnaciński (2005); and K2019 = Kounkel et al. (2019). Codes for the literature sources in the last column, which have fewer measurements of the stars in our sample, are: F = Frémat et al. (2005); K = Kahraman Alicay et al. (2016); Ku = Kunder et al. (2017); M = Margheim (2007); Mo = Morse et al. (1991); R = Royer et al. (2002); Ro Rodríguez et al. (2000); S = Simón-Díaz et al. (2017); V = van Belle (2012); Y = Yudin (2001); Z = Zorec & Royer (2012); Zorec et al. (2016). They are followed by the colon by the $v\sin i$ measurement (occasionally more than one) and the uncertainty in parentheses, when available, in units of the last significant digit.

Glöckler & Gnaciński (2005) made an effort to place all of the determinations on a common system, the large variety of measurement techniques and instrumentation involved makes that task exceedingly difficult. This may explain the poor agreement with the determinations in the present paper (middle panel of Figure 10). Additionally, the VizieR database (Ochsenbein et al. 2000) warns about possible misidentifications caused by erroneous coordinates in some of the original sources of the catalog.

The $v\sin i$ measurements of Anderson et al. (1966), and especially those of Kounkel et al. (2019; A1966 and K2019 in Table 6, respectively), are much more consistent with ours, although there are a few outliers that we have labeled. For example, our value for HD 23753 (317 ± 25 km s\(^{-1}\)) is considerably larger than that of A1966 (240 km s\(^{-1}\)), though we note that other measurements from the literature are all also higher than A1966 and agree better with ours (see Table 6). For HD 23763, we measure a lower rotational velocity (108 ± 5 km s\(^{-1}\)) than K2019 (177 ± 9 km s\(^{-1}\)), which seems to be supported by other determinations that are also lower. For HD 23643 we also measure a smaller $v\sin i$ value (241 ± 10 km s\(^{-1}\)) than K2019 (285 ± 13 km s\(^{-1}\)), and other published values go in the same direction.

The last column of Table 6 collects other determinations from recent sources that have fewer stars in common with our sample. Uncertainties are given in parentheses when available.

6. Discussion and Final Remarks

The bright, early-type stars in the Pleiades have been observed spectroscopically since the beginning of the 20th century. Because they tend to rotate rapidly, the RV measurements have always been difficult, and the resulting scatter for many of these objects has led to claims of variability, or even tentative orbital solutions in four cases. Most of those assertions have persisted in the literature to this day, despite the fact that several have been doubted over the years. The velocity measurements in the present work for a sample of 33 rapidly rotating B, A, and early F stars represent a significant improvement in terms of precision and are inconsistent with nearly all claims of variability published in the past for these objects. They additionally rule out all four tentative orbital
solutions in the literature, one from Pearce & Hill (1975), and three from Abt et al. (1965).

Among the previously claimed velocity variables, only in the cases of HD 22637 and HD 23338 do we detect significant RV changes, but our spectroscopic orbits are very different from the ones published. For HD 22637, we do not confirm the 4.67 day orbit of Pearce & Hill (1975). Our new solution has a completely different period of 71.8 days, which accommodates the previous observations as well. For HD 23338, the 1313 day orbit of Abt et al. (1965) is not supported by our data either, or by other observations in the literature. Instead, combining the earlier observations and our own, we determine a preliminary orbit with a period of 8.7 yr. We additionally find HD 24899 to be a single-lined binary with an orbital period of 10 yr. Velocity variability had not been recognized before for this object.

These three are therefore new spectroscopic binaries in the Pleiades. For HD 22637 and HD 24899, astrometric observations from the ground could permit the determination of the dynamical masses for the components, independently of any models. The estimated 4 mas angular separation of HD 22637 may be resolvable with existing long-baseline interferometers such as CHARA, and adaptive optics or speckle interferometry observations for HD 24899 should easily resolve the expected ~50 mas separation of this pair. In the case of HD 23338, the spectroscopic companion appears to be different from the previously known and wider lunar occultation companion, making this a triple system. With an estimated 60 mas semimajor axis for the inner orbit, the new spectroscopic companion should also be resolvable with adaptive optics or speckle interferometry techniques. At the end of operations, the Gaia mission is expected to provide complete astrometric orbital solutions for the photocentric motion of all three of these objects, which should at least yield the inclination angles of their orbits, though not the relative semimajor axes needed to compute assumption-free masses.

Early-type stars in the field are known to display a very high frequency of binary and higher multiplicity systems (e.g., Duchêne & Kraus 2013; Moe & di Stefano 2017). The latter authors estimate that 37% ± 6% of stars of spectral type late B and A are binaries with mass ratios \( q \) larger than 0.1, and another 22% ± 7% are triple or quadruple systems, for a total of about 60%. Among mid-B stars, this fraction rises to 76%, and it reaches close to 100% for the O stars. In our sample of 32 B- and A-type stars that are members of the cluster, we have found 2 spectroscopic binaries (HD 22637 and HD 24899), 1 system that is possibly triple (HD 23338), and 10 more targets that are known to have companions from astrometric observations. This adds up to 12 binary systems and 1 triple. The implied frequency of binaries is then 12/32 ≈ 37%, which happens to coincide with the estimate above. Our one triple system yields a lower occurrence rate than expected (1/32 ≈ 3%). We note, however, that most of our targets only have ~1–2 yr of spectroscopic coverage, so both of these estimates are probably only lower limits, as additional spectroscopic binaries or triples could be present that we are not sensitive to. Also, other astrometric binary or multiple systems may emerge from the Gaia mission that would increase the frequencies even more.

A further conclusion of the study of Moe & di Stefano (2017) is that the frequency of \( q > 0.1 \) companions to late-B and A stars per decade of orbital period (in units of days) peaks at around log \( P \sim 4.5 \) (\( P \sim 90 \) yr, or separations of ~35 au, or ~9")25 at the distance to the Pleiades), and that the peak is rather broad, extending between log \( P \approx 3.5–5.5 \) (see their Figure 37). Two of our spectroscopic systems (HD 24899 with \( P = 3635 \) days and HD 23338 with \( P = 3172 \) days) fall in this regime (log \( P = 3.56 \) and 3.50, respectively), as do all of the targets with astrometric companions we are aware of. The other spectroscopic binary we have found, HD 22637 (\( P = 71.8 \) days), has log \( P = 1.86 \), and is the only one shortward of the peak. Although this sample of binaries is very small, the period distribution of the B and A stars in the Pleiades appears to also be consistent with the results of Moe & di Stefano (2017), at least qualitatively.

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