Dynamical Masses for the Pleiades Binary System HII-2147

Guillermo Torres, Carl Melis, Adam L. Kraus, Trent J. Dupuy, Jeffrey K. Chilcote, and Justin R. Crepp

1 Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA; gtorres@cfa.harvard.edu
2 Center for Astrophysics and Space Sciences, University of California at San Diego, La Jolla, CA 92093, USA
3 Department of Astronomy, The University of Texas at Austin, Austin, TX 78712, USA
4 Gemini Observatory, Northern Operations Center, Hilo, HI 96720, USA
5 Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA

Received 2020 May 14; revised 2020 June 8; accepted 2020 June 10; published 2020 July 16

Abstract

We report our long-term spectroscopic monitoring of the Pleiades member HII-2147, which was previously spatially resolved at radio wavelengths in very long baseline interferometry (VLBI) observations. It has also been claimed to be a (presumably short-period) double-lined spectroscopic binary with relatively sharp lines, although no orbit has ever been published. Examination of our new spectroscopic material and the historical radial velocities shows that the current and previous spectra are best interpreted as featuring only a single set of lines of a moderately rapidly rotating star with slowly variable radial velocity, which is one of the sources detected by VLBI. We combine our own and other velocities with the VLBI measurements and new adaptive optics observations to derive the first astrometric-spectroscopic orbit of the G5 + G9 pair, with a period of 18.18 ± 0.11 yr. We infer dynamical masses of 0.897 ± 0.022 $M_{\odot}$ for the spectroscopically visible star and 0.978 ± 0.024 $M_{\odot}$ for the other, along with a distance of 136.78 ± 0.46 pc. The lack of detection of the lines of the more massive component in our spectra can be adequately explained if it is rotating much more rapidly than the star we see. This is consistent with the observation that the lines of the secondary are shallower than expected for a star of its spectral type.

Unified Astronomy Thesaurus concepts: Binary stars (154); Astrometric binary stars (79); Open star clusters (1160); Radial velocity (1332); Fundamental parameters of stars (555); Spectroscopic binary stars (1557)

1. Introduction

The Pleiades cluster has served as a valuable laboratory for stellar astrophysics for decades. Astrometric and spectroscopic surveys have found many binary and multiple systems among its ∼1500 members (e.g., Mermilliod et al. 1992, 1997; Rosvick et al. 1992; Bouvier et al. 1997; Hillenbrand et al. 2018), and yet very few have had their component masses—the most basic stellar property—determined reliably. To our knowledge, there are only three examples: the interferometric-spectroscopic binary Atlas (27 Tau, HD 23850; Zwahlen et al. 2004), the eclipsing system HD 23642 (V1229 Tau; Torres 2003; Munari et al. 2004; Southworth et al. 2005; Groenewegen et al. 2007; David et al. 2016), and, more recently, HCG 76 (V612 Tau; David et al. 2016), also an eclipsing binary with low-mass components.

Two other eclipsing systems have been found in the Pleiades in recent years that may also eventually lead to accurate dynamical mass determinations. One is HII-2407 (V1283 Tau; David et al. 2015, 2016), which is so far only a single-lined spectroscopic binary and must therefore await detection of the secondary lines before the masses can be determined without assumptions. The other is MHO 9 (EPIC 211075914; David et al. 2016), a long-period (42.8 days), low-mass, and very faint system ($V = 19.02$) that is double-lined but for which the available data are still insufficient to obtain meaningful estimates of its properties.

In this paper, we report our long-term spectroscopic monitoring of the Pleiades member HII-2147 (V1282 Tau, 2MASS J03490610+2346525, $V = 10.80, B − V = +0.83$). The second data release (DR2) of the Gaia catalog (Gaia Collaboration et al. 2018) reports a trigonometric parallax of 7.209 ± 0.051 mas, corresponding to a distance of 138.7 ± 1.0 pc. The object has been spatially resolved at radio wavelengths into an ∼60 mas binary with the technique of very long baseline interferometry (VLBI; Melis et al. 2014) in the course of a program prior to Gaia to determine trigonometric parallaxes in the cluster. As is the case for many stars in the Pleiades, HII-2147 is chromospherically active and displays photometric variability likely caused by spots on its surface, and on this basis, it has been listed as a member of the RS CVn class. It is also an X-ray source (Voges et al. 1999; Freund et al. 2018) with flaring activity (Gagné et al. 1995). By combining our spectroscopy with new imaging observations and other existing radial-velocity measurements from the literature, we are able to determine the masses of the components, making it the fourth system in the cluster with such empirical measurements.

We have organized the paper as follows. Section 2 discusses the historical radial-velocity measurements of HII-2147, on the basis of which it was claimed to be a double-lined spectroscopic binary, but for which an orbit was mysteriously never derived. After showing that interpretation of the system to be incorrect, we present in the same section our own spectroscopic monitoring spanning more than 37 yr. The VLBI observations are described in Section 3, and measurements from new adaptive optics (AO) imaging that resolve the pair are presented in Section 4. Then, in Section 5 we analyze all of the observations together, including brightness measurements, to derive the first orbital solution for HII-2147 and infer the component masses. Alternate scenarios are presented here as well to explain the lack of detection of the lines of the primary star in our spectra. In Section 6 we review the measurements of the rotation period and discuss their implications. We conclude in Section 7 with a discussion of the results.
properties in their Table 11 give the scatter in the velocities of HII-2147 as published, unless the value refers to only one component, or the primary and secondary velocity separation seems to always be about 20 km s$^{-1}$, whereas for a (presumably short-period) double-lined binary observed at random times, one would expect to see some range. The only measurements that depart from this pattern are ones in which only a single velocity was measured, and those happen to fall very nearly at the average of the long-term trends followed by the primary and secondary measurements. (ii) Experiments with our own observations, described below, where we treated the single broad cross-correlation peak as if it were due to two stars, also gave a nearly constant velocity separation of 20 km s$^{-1}$ and no convincing evidence of orbital motion. (iii) As a more direct indication of the same effect, the measured width of the cross-correlation profiles of our own spectra show no significant change with time, which one would expect to see if the broadened profile were the result of two narrower ones moving relative to one another. (iv) The Mermilliod et al. (1992) argument that a single broad correlation profile implies an excessive spin rate was likely based on a typical rotational period for a K star in the Pleiades (roughly 6 days) that has slowed down and settled on the rotational sequence. However, there is in fact a subsample of much more rapidly rotating cluster members of the same spectral type (e.g., Hartman et al. 2010; Rebull et al. 2016), known as ultrafast rotators (UFRs), whose origin is still being debated (see Butler et al. 1987; Barnes & Sofia 1996; Brown 2014; Garraffo et al. 2018). As mentioned earlier, HII-2147 is an active and spotted star. Several direct measurements of its rotation period from the spot modulations now place it at well under a day (see Section 6), making it a member of the class of UFRs. (v) The excess brightness of HII-2147 in the color–magnitude diagram can be adequately explained by the companion in the long-term orbit, as we will show later.

We therefore proceed under the assumption that the CORAVEL observations recorded a single, broad set of lines corresponding to a rapidly rotating star, and for the purposes of the orbital analysis below, we will approximate the centroid of those broad correlation profiles by the straight average of the primary and secondary velocities as reported by Mermilliod et al. (2009). We will also adopt provisional uncertainties given by the quadrature sum of the individual primary and secondary velocity errors as published.

While Figure 1 clearly demonstrates that the star is participating in a long-period binary orbit, neither the CORAVEL observations nor our own (see below) show direct evidence of the spectral lines of the companion. In principle, it is therefore possible that the broad profile we see is the result of the blending (flux-weighted average) of the lines of those two objects, especially given that the long orbital period would imply relatively small radial-velocity amplitudes that could prevent the detection of two separate sets of lines. In that case, one would expect changes in the width of the correlation profile with time as the velocity separation widens and narrows throughout the orbit. However, no such changes are seen, as mentioned above, which argues that the correlation profile is dominated by the lines of only one object.

2.2. New Spectroscopy

Spectroscopic monitoring of HII-2147 at the Center for Astrophysics (CfA) began in 1982 and continued until 2020...
with several different instruments and telescopes, as follows. The initial observation was made with the CIA Digital Speedometer (DS; Latham 1992) on the 4.5 m equivalent Multiple Mirror Telescope (Mount Hopkins, Arizona, USA) before its conversion to a monolithic 6.5 m telescope. Five additional observations through 2003 December were made with copies of this instrument on the 1.5 m Tillinghast Reflector at the Fred L. Whipple Observatory (also on Mount Hopkins) and on the (now closed) 1.5 m Wyeth reflector at the Oak Ridge Observatory (Harvard, Massachusetts, USA). These instruments were equipped with intensified photon-counting Reticon detectors and recorded a single echelle order 45 Å wide centered at a wavelength near 5187 Å containing the MgIb triplet at a resolving power of \( R \approx 35,000 \). Reductions were performed with a custom pipeline, and the wavelength calibration was based on exposures of a thorium–argon (ThAr) lamp before and after each science exposure. Twilight observations were obtained regularly at dusk and dawn to maintain the velocity zero-point (see Latham 1992) by applying small run-to-run corrections generally smaller than 2 km s\(^{-1}\). The signal-to-noise ratios of these six observations range between about 10 and 24 per resolution element of 8.5 km s\(^{-1}\).

Beginning in 2011, the observations were continued with the Tillinghast Reflector Echelle Spectrograph (TRES; Szentygyorgyi & Fürész 2007; Fürész 2008), a bench-mounted fiber-fed instrument providing a resolving power of \( R \approx 44,000 \) and covering the wavelength region 3800–9100 Å in 51 orders. For the order centered at ∼5187 Å that we used for the velocity determinations, the signal-to-noise ratios range from about 15 to 48 per resolution element of 6.8 km s\(^{-1}\). A total of 35 spectra of HII-2147 were collected with this instrument through 2020 March. Wavelength calibrations relied on ThAr exposures preceding and following the science frames, as above, and the reductions were carried out with a separate dedicated pipeline. The velocity zero-point was monitored by taking exposures of several IAU radial-velocity standard stars and typically varies by less than 50 m s\(^{-1}\), which is more than sufficient for this work. Spectra of the same standard stars from the DS were used to place both sets of observations on a common velocity system, which is within about 0.14 km s\(^{-1}\) of the reference frame defined by observations of minor planets in the solar system (see Stefanik et al. 1999; Latham et al. 2002).

All of our spectra appear single-lined and show significant rotational broadening. Radial velocities were measured by cross-correlation using the IRAF task \texttt{xcsao}.\(^7\) The template was selected from a precomputed library of synthetic spectra based on model atmospheres by R. L. Kurucz and a line list tuned to better match the spectra of real stars (see Nordström et al. 1994; Latham et al. 2002). The wavelength region covered by these templates is limited to ∼300 Å centered at 5187 Å, and the two most important parameters for velocity determinations are the effective temperature \( (T_{\text{eff}}) \) and rotational broadening \((v \sin i)\). The optimal values of these parameters were determined by running a grid of cross-correlations over broad ranges for a fixed surface gravity of \( \log g = 4.5 \) and solar metallicity and adopting the \( T_{\text{eff}} \) and \( v \sin i \) values giving the highest correlation averaged over all exposures, following Torres et al. (2002). For this analysis, we used the more numerous and higher-quality TRES spectra. The result may be visualized in Figure 2 and yielded a best temperature of 5390 ± 100 K and \( v \sin i = 31 \pm 2 \) km s\(^{-1}\).

Figure 2. Determination of the temperature and rotational broadening of HII-2147. The contours correspond to equal values of the cross-correlation function averaged over all exposures, and the points mark the results for individual spectra.

\(^7\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
earlier by Mermilliod et al. (1992) for the CORAVEL measurements. We therefore take this as evidence that our spectroscopic observations are best interpreted as featuring a single broad cross-correlation profile.

Additional spectroscopic observations were secured at the Lick Observatory with the Shane 3 m telescope. Light was fed into the coude focus that houses the Hamilton echelle spectrograph (Vogt 1987), and all observations used Dewar #4 with the detector windowed to record light from 3850 to 9250 Å. With the exception of the 2012 November epoch (HJD 2,456,257.87), a 640 µm wide slit was employed yielding a spectral resolving power of ∼62,000, as measured from the FWHM of single titanium–argon (TiAr) arc lines in comparison spectra. For the 2012 November epoch, an 800 µm wide slit was used, resulting in $R \approx 40,000$. Data reduction for the Hamilton echelle spectrograph with IRAF tasks is outlined in detail in Lick Technical Report No. 74.8 Briefly, the data were bias-subtracted, flat-fielded, extracted, and finally wavelength-calibrated with TiAr arc lamp spectra (see Pakhomov & Zhao 2013). Signal-to-noise ratios for these observations range from 65 to 100 pixel$^{-1}$ at a mean wavelength of 6000 Å. A stable radial-velocity standard star (usually HR 124 or HD 4203; Nidever et al. 2002) was observed each night along with HII-2147 and used as the template for the cross-correlations, with adopted absolute velocities as reported by Nidever et al. (2002). The nine Lick radial-velocity measurements and uncertainties, based typically on the five best spectral orders, are given in Table 2 in the heliocentric frame.

### 2.3. Archival Radial Velocities

Aside from the CORAVEL and our own observations, only a few isolated measurements of the radial velocity of HII-2147 have appeared in the literature. Soderblom et al. (1993) published a single measurement from 1988, and White et al. (2007) published another from 2002. The latter happens to fall at a time near a radial-velocity minimum (see below), when few other observations are available, making it potentially constraining. In order to place those two measurements on the same reference frame as ours, we compared the velocities of other Pleiades stars measured by these authors with observations of the same stars from our own survey of the cluster. Based on seven stars in common with Soderblom et al. (1993), we established a correction of +0.10 km s$^{-1}$ to bring their measurement of HII-2147 onto the CfA zero-point. Similarly, from 10 stars, we determined a correction of −0.60 km s$^{-1}$ for the White et al. (2007) measurement. The adjusted velocities from these two literature sources are included at the end of Table 1. Additionally, HII-2147 is included in the Gaia DR2 catalog (Gaia Collaboration et al. 2018) with the identifier number 66503449709270400. The average radial velocity reported there is 6.1 ± 6.2 km s$^{-1}$, obtained from seven transits over a period of 22 months. The large uncertainty is due perhaps to real changes or to reduced precision because of the rotational broadening of the spectral lines. However, as it is only an average and the velocity is changing, we have chosen not to make use of that value.

Note. The last two measurements are from Soderblom et al. (1993) and White et al. (2007), adjusted by +0.10 and −0.60 km s$^{-1}$, respectively, to place them on the same zero-point as the CfA velocities (see text).
with the DS and TRES instruments, we estimate that if the companion is more massive than the star we see. This raises the question of why we do not detect the lines associated with HII-2147 based on photo-

2.4. Evidence for the Companion

The combination of all available radial velocities reveals a periodicity of about 18 yr that is shown in Figure 3. If we assume, based on its temperature, that the star with visible lines is somewhat less massive than the Sun, a preliminary spectroscopic orbital solution then yields the unexpected result that the companion is more massive than the star we see. This raises the question of why we do not detect the lines of this companion in our spectra. One possible explanation might be very rapid rotation. Based on previous experience with similar spectroscopic material obtained for other objects with the DS and TRES instruments, we estimate that if the companion were rotating at a projected velocity of ~100 km s\(^{-1}\) or more, its lines would be very broad and difficult to distinguish, particularly since they would be heavily blended with those of the visible star. This possibility seems consistent with the evidence mentioned earlier of a very short rotation period (<1 day) associated with HII-2147 based on photometric modulation due to spots, provided that periodic signal comes from the companion. Alternatively, the companion may itself be a close binary, which could make its detection more challenging.

While the spectral lines of the companion are not seen directly, there is indirect evidence of its presence from the fact that the features of the visible star appear shallower than expected for a star of its spectral type. To illustrate this, we selected TRES spectra of eight sharp-lined stars from our ongoing spectroscopic survey of the Pleiades that are within 50 K of the measured temperature of HII-2147 (determined in the same way as described in Section 2.2) and are not known to be binaries. We convolved these spectra with the rotational kernel of Gray (1992) to match the rotational broadening of HII-2147 and shifted them to a common wavelength scale. These eight stars are compared in Figure 4 against an exposure of HII-2147, clearly showing the veiling effect attributable to star A. For reference, we overplot the synthetic template used earlier to derive the velocities (blue dotted line), which is seen to be a good representation of the single stars. A more quantitative discussion of the line dilution will be presented below in Section 7. We note, finally, that a veiling effect for HII-2147 was also reported by Kounkel et al. (2019) based on a near-infrared (NIR) spectrum in the H band.

3. VLBI Observations

Melis et al. (2014) observed HII-2147 between 2011 and 2013 as part of a program to determine trigonometric parallaxes of several Pleiades members using VLBI at radio frequencies (a continuum frequency of 8.4 GHz, corresponding to ~3.6 cm). The original goal was to address the disagreement between the Hipparcos measurement of the distance to the cluster and determinations by other methods. It was found that HII-2147 is a double source with a separation around 60 mas, and accurate positions for the equinox J2000 referenced to the background quasar J0347+2339 were reported for both components, oriented NW and SE at the time. In deriving a parallax for HII-2147, the authors included acceleration terms in R.A. and decl. in order to model the slow motion in an unknown orbit over the 2 yr observing period. Orbital motion was in fact evident from the opposite signs of the acceleration terms for the two components. This astrometric motion corresponds to the same orbit suggested by the radial velocities, although the portion covered by the astrometry is small (only ~10% of a cycle). Nevertheless, the VLBI observations do help to constrain that orbit by providing the angular scale, and we use them below for that purpose under the assumption that the source of the radio emission is coincident with the center of each stellar disk. These observations also constrain the parallax of the system. However, they do not identify which of the components is the one we observed spectroscopically.

4. AO Imaging

There are no observations of HII-2147 in the literature that resolve the pair, although several attempts have been made at both optical and NIR wavelengths (Bouvier et al. 1997; Bouvier et al. 1997;
Metchev & Hillenbrand (2009; Mason et al. 2009), including a lunar occultation observation by Richichi et al. (2012).

Due to the limited phase coverage of the VLBI observations, and in order to supplement the astrometry, AO imaging observations were carried out for this work with the Maunakea Observatory Keck AO system (Wizinowich et al. 2000; Wizinowich 2013) on UT 2013 February 3 and 5, as well as on UT 2019 November 3. The Keck AO system was fed into NIRC2, a camera with a 1024 × 1024 InSb Aladdin-3 array. All NIRC2 observations were performed in the “narrow” camera mode, with a plate scale of ~0\(^{\circ}\)01 pixel\(^{-1}\), and HII-2147 served as its own guide star for the AO system.

The observations on the first 2 nights consisted of a five-point dither pattern sequence. On UT 2013 February 3, short exposures (≤2 s) in which the binary system was not saturated in each frame were obtained in each of the \(J\) (1.248 \(\mu\)m), \(H\) (1.633 \(\mu\)m), and \(K_S\) (2.146 \(\mu\)m) bands. High-quality AO corrections were obtained with average Strehl ratios of ~0.6 in the \(K_S\) band, ~0.35 in \(H\), and ~0.2 in \(J\). On UT 2013 February 5, longer exposures (50 s) were obtained in the \(K_S\) band to search for faint companions to the binary system (no such companions were seen).

Unsaturated observations on UT 2019 November 3 were obtained through the \(J\), \(H\), and \(K\) (2.124 \(\mu\)m) filters and taken with a 0.2 s integration time using 10 coadds and the CDS sampling mode. The NIRC2 subarray was set to 512 × 512 pixels. Observations were gathered in a three-point dither pattern of five exposures at each location, with each leg being 1\(^{\circ}\)5, for a total of 15 observations in each filter. The average differential image motion monitor (DIMM) measure of the seeing during the observations was 0\(''\)38. Observations of V1090 Tau were made as a point-spread function (PSF) reference calibrator star. Those exposures were taken with an identical subarray, integration time, and coadd as the HII-2147 observations.

The data were analyzed using custom scripts that perform the standard tasks of nonlinearity correction, dark subtraction, and flat-fielding. These scripts also perform “destriping,” a rectification of spatially correlated detector noise that is mirrored across the quadrants of the NIRC2 detector and dominates the photometric noise budget in the read noise-limited regime. Finally, the scripts use bilinear interpolation to estimate values for pixels impacted by cosmic rays, as well as for the hot and dead pixels that were identified in superstacks of darks and flats, as described by Kraus et al. (2016).

Each science frame was then iteratively analyzed with PSF-fitting photometry to find the best-fit template that minimized the residuals after PSF subtraction, as described by Kraus et al. (2016). The first stage found the best-fit binary model (separation \(\rho\), position angle (P.A.) \(\theta\), and magnitude difference \(\Delta m\)) given an empirical template of a single star. The second stage then measured the \(\chi^2\) goodness of fit for the 1000 archival frames of single stars that were taken closest in time and in the same filter, doubling each potential template with the same binary parameters and then scaling and subtracting it from the science frame. The two steps were then repeated until the same empirical template PSF was found to yield the lowest \(\chi^2\) value in two consecutive iterations, and that PSF was adopted as the template for that science frame.

We derived final \((x, y)\) coordinates and the magnitude difference of the two components using the least-squares minimization package MPFIT in IDL (Markwardt 2009). We converted NIRC2 pixel values into sky coordinates using the same methods as described in Dupuy et al. (2016) and Dupuy & Liu (2017), with the only difference being that we reversed the sign of the P.A. offset of 0\(^{\circ}\)252 in the Yelda et al. (2010) calibration, as noted by Bowler et al. (2018). We report the mean of the separation, P.A., and magnitude difference derived from the set of images taken in each of the three filters (see Table 3), and we adopt errors based on the rms of measurements from each data set, with systematic uncertainties in the astrometric calibration (e.g., 0\(^{\circ}\)009 in P.A.) added in quadrature to these rms values for the final errors. An image of HII-2147 in the J band is shown in Figure 5.

The 2013 observations clearly identify the fainter component as the one to the SE, whereas by 2019, orbital motion had moved the fainter star to the NW. The angular separations happen to be similar at both epochs. The measured magnitude differences are consistent between the two sets of observations in all three NIR bandpasses.

If both components of HII-2147 are single main-sequence stars, the less massive one should be fainter. On this basis, we tentatively identify the star whose velocities we measured (which we indicated earlier is less massive than its companion) as the one to the SE in 2013 (NW in 2019), and we refer to it

---

**Table 3**

| HJD    | \(\rho\) (mas) | \(\theta\) (deg) | \(\Delta m\) (mag) | Filter |
|--------|----------------|-----------------|-------------------|--------|
| 56,326.8063 | 55.2 ± 0.7 | 152.72 ± 0.6 | 0.36 ± 0.09 | \(J\) |
| 56,326.8040 | 55.48 ± 0.23 | 152.2 ± 0.6 | 0.28 ± 0.06 | \(H\) |
| 56,326.8017 | 55.3 ± 0.5 | 152.6 ± 0.6 | 0.310 ± 0.023 | \(K_S\) |
| 58,790.5065 | 55.7 ± 0.9 | 315.5 ± 1.6 | 0.36 ± 0.09 | \(J\) |
| 58,790.5041 | 54.9 ± 0.5 | 313.9 ± 1.1 | 0.34 ± 0.05 | \(H\) |
| 58,790.5013 | 54.8 ± 0.5 | 313.6 ± 0.4 | 0.322 ± 0.020 | \(K\) |
The radial-velocity measurements from all sources were combined with the astrometry from VLBI and our AO imaging into a global analysis to determine the orbital elements of HII-2147. The parameters we solved for are the following: the orbital period \( P \), the angular semimajor axis of the relative orbit \( a^* \), the eccentricity parameters \( e \), and CfA velocities \( \mu_\alpha^c \) and \( \mu_\delta^c \). Inclusion of the VLBI data adds the following free parameters: the parallax \( \pi \), the barycenter proper-motion components \( \mu_\alpha \) and \( \mu_\delta \), and offsets \( \Delta \alpha^* \) and \( \Delta \delta \) between the position of the barycenter at the average time of the VLBI observations \(( t_0 = 2,456,257.199 \text{ HJD} = 2012.9011) \) and a reference position taken to be the average of the measured VLBI positions \(( t_0 = 57.2755330891 \), \( t_0 = 23.8710742666 \)). Parallax factors were calculated using the position of the Earth’s center as provided by the JPL Horizons web interface. In addition, we solved for a possible zero-point offset between the CORAVEL and CfA velocities \( \Delta RV_{\text{COR}} \) and another between the CfA and Lick velocities \( \Delta RV_{\text{Lick}} \). Both of these offsets are to be added to the velocities from the corresponding data sets in order to place them on the CfA system.

A further constraint on the orbital elements is provided, in principle, by the proper motion measured by Gaia. This will in general be different from the proper motion of the center of mass because of the acceleration caused by the stars moving around each other (see, e.g., Brandt 2018). However, our attempts to incorporate this constraint resulted in significant tension with the VLBI measurements and a poorer fit. Consequently, we have elected not to use this measurement.

Our method of analysis used the emcee10 code of Foreman-Mackey et al. (2013), which is a Python implementation of the affine-invariant Markov Chain Monte Carlo (MCMC) ensemble sampler proposed by Goodman & Weare (2010). We used 100 walkers with chain lengths of 20,000 each, after discarding the burn-in. Uniform (noninformative) priors over suitable ranges were adopted for all of the above parameters, and convergence of the chains was checked visually, also requiring a Gelman–Rubin statistic of 1.05 or smaller for each parameter (Gelman & Rubin 1992).

The relative weighting between the different data sets (CORAVEL, CfA, Lick, VLBI) was handled by including additional adjustable parameters to rescale the observational errors as needed to achieve reduced \( \chi^2 \) values near unity. For the velocities, those parameters were taken to be multiplicative factors \( f_{\text{COR}}, f_{\text{CfA}}, \) and \( f_{\text{Lick}} \) with uniform priors; for the VLBI measurements, whose internal errors appeared from a preliminary analysis to be underestimated, they were “jitter” terms \( \sigma_j^c \) and \( \sigma_j \) to be added quadratically to the internal errors, with log-uniform priors. All of these terms were solved for self-consistently and simultaneously with the other orbital quantities (see Gregory 2005). Precession corrections to J2000.0 for the P.A.s of the AO measurements are very small but were nevertheless applied for completeness.

The results of the MCMC analysis are given in the second column of Table 4 (solution 1), where we report the mode of the posterior distribution for each parameter along with the 68.3% credible intervals. The orbital period corresponds to \( 18.18 \pm 0.11 \) yr. The bottom of the table presents derived quantities.

9 https://ssd.jpl.nasa.gov/horizons.cgi
10 We note that a comment associated with this Gaia DR2 entry in the Vizier catalog (Ochsenbein et al. 2000) indicates that there was a duplicate source in the original data reduction that was discarded. This may indicate observational, cross-matching, or processing problems, possibly compromising the astrometric or photometric results. We believe this may explain the difficulty we pointed out.
11 http://dfm.io/emcee/current

Table 4 Results from Our Combined MCMC Analysis for HII-2147

| Parameter | Solution 1 | Solution 2 ( Adopted) |
|-----------|------------|------------------------|
| \( P \) (days) | 6641.40 0.32 | 6641.42 0.39 |
| \( a^* \) (mas) | 63.23 0.49 | 63.22 0.49 |
| \( e \) | 0.074 0.023 | 0.074 0.023 |
| \( \mu_\alpha^c \) | 0.316 0.018 | 0.316 0.018 |
| \( \cos i \) | 0.2454 0.0077 | 0.2454 0.0077 |
| \( \Omega_{2010} \) (deg) | 141.81 0.18 | 141.81 0.18 |
| \( T \) (HJD–2,400,000) | 47288.95 0.95 | 47288.107 0.77 |
| \( \gamma \) (km s\(^{-1}\)) | 5.67 0.18 | 5.57 0.17 |
| \( K_B \) (km s\(^{-1}\)) | 7.33 0.16 | 7.102 0.081 |
| \( \pi \) (mas) | 7.312 0.027 | 7.310 0.026 |
| \( \mu_\alpha^c \) (mas yr\(^{-1}\)) | 19.01 0.17 | 18.855 0.099 |
| \( \mu_\delta^c \) (mas yr\(^{-1}\)) | -44.74 0.14 | -44.66 0.11 |
| \( \Delta \pi^c \) (mas) | -2.44 0.50 | -1.97 0.035 |
| \( \Delta \alpha^c \) (mas) | -4.09 0.89 | -3.256 0.074 |
| \( \Delta RV_{\text{COR}} \) (km s\(^{-1}\)) | -0.76 0.34 | -0.73 0.35 |
| \( \Delta RV_{\text{Lick}} \) (km s\(^{-1}\)) | -0.51 0.80 | -0.41 0.46 |
| \( \sigma_e \) (mas) | 0.017 0.015 | 0.017 0.014 |
| \( \sigma_j^c \) (mas) | 0.201 0.099 | 0.195 0.086 |

**Note.** Solution 2 incorporates a prior on the mass ratio \( \hat{q}_{AB} \) derived from the NIR magnitude differences (see text). For both solutions, the parameter values listed correspond to the mode of the respective posterior distributions, and the uncertainties represent the 68.3% credible intervals.

Measurements whose internal errors appeared from a preliminary analysis to be underestimated, they were “jitter” terms \( \sigma_j^c \) and \( \sigma_j \) to be added quadratically to the internal errors, with log-uniform priors. All of these terms were solved for self-consistently and simultaneously with the other orbital quantities (see Gregory 2005). Precession corrections to J2000.0 for the P.A.s of the AO measurements are very small but were nevertheless applied for completeness.
properties including the total mass of the system, $M_{\text{tot}}$, the masses of the two components ($M_A$ and $M_B$) and their mass ratio ($q \equiv M_B/M_A$), the distance, the linear semimajor axis of the orbit ($a$), and the inferred velocity semiamplitude of the unseen primary component ($K_A$). These derived quantities were computed by directly combining the chains of the adjusted variables involved.

Appealing to a 125 Myr solar-metallicity model isochrone for the Pleiades from the PARSEC series (Chen et al. 2014), we find that a star with the mass of the secondary ($M_B = 0.865 M_\odot$) is expected to have an effective temperature of about 5220 K, which is somewhat lower than our spectroscopically measured value (5390 ± 100 K). A further check on the accuracy of our solution can be made by using the measured masses to predict the primary/secondary magnitude differences in the NIR. These can then be compared against the measured values from Table 3. Similarly, we can calculate the expected total system brightness at both optical and NIR wavelengths for comparison with the magnitudes in the Gaia DR2 and Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) catalogs. For these tests, we have preferred not to rely entirely on the model isochrone used above to predict fluxes, as we find that it does not match the empirical color–magnitude diagram of the cluster sufficiently well for our purposes. Instead, we developed semiempirical relations to predict fluxes in the Gaia and 2MASS bandpasses as a function of mass. Briefly, we fit spline relations to the empirical color–magnitude diagram of the Pleiades and then used the models to provide the connection between masses and observed bandpass magnitudes in the two photometric systems. The details of this derivation are given in the Appendix, where we also present a test of the semiempirical relations mentioned in the text (see the Appendix).

Using these semiempirical relations, we find that the expected 2MASS magnitudes from our solution 1 for the combined light of HII-2147 agree quite well with the measured $JHK_s$ values (see Table 5). The corresponding predictions for the Gaia bandpasses are also formally consistent within the uncertainties, although they are all systematically brighter than the measured magnitudes by about 0.1 mag, on average. On the other hand, the predicted $JHK$ magnitude differences between stars A and B are all larger than observed by 0.2–0.3 mag. However, the uncertainties in this case are large enough that there is again formal consistency with the measurements. The inflated uncertainties for $\Delta J$, $\Delta H$, and $\Delta K$ are a reflection of the relatively imprecise value of the mass ratio, which is what largely determines those magnitude differences.

The fact that the predicted $JHK$ magnitude differences are worse, in a systematic sense, than those for the combined light suggests the possibility of a small bias in the mass ratio $q$. The only observations used in our analysis that constrain $q$ are the VLBI measurements for the primary and secondary, which are measured separately on an absolute reference frame. The constraint is weak, however, because the VLBI observations only cover a small fraction of the orbit. The accuracy of the mass ratio will then depend critically on how well the center of mass can be located on the plane of the sky, as represented by the free parameters $\Delta \alpha^*$ and $\Delta \delta$. These two variables happen to be the ones most strongly correlated among themselves and with other free parameters, so it would not be surprising if they were affected by subtle biases. Indeed, $\Delta \alpha^*$ correlates very strongly with $\Delta \delta$ (correlation coefficient $-0.998$), $\Delta \mu_\alpha^*$ ($-0.965$), and $K_B$ ($-0.950$), whereas $\Delta \delta$ shows significant correlation with $\Delta \mu_\delta^*$ ($+0.965$) and $K_B$ ($+0.950$). This is illustrated in the top panel of Figure 6.

The availability of the NIR magnitude differences from our AO observations presents an opportunity to check or improve the accuracy of the mass ratio, as they are the measurements with the closest connection to $q$. To this end, we constructed an empirical relation that allows us to predict $q$ from a difference in brightness in the $JHK$ bandpasses. For this, we enlisted the other binaries in the Pleiades that have measured masses. As none of them have NIR brightness measurements for the individual components, we opted instead to use their total system masses along with their combined-light 2MASS magnitudes. Only two of the three available systems have reliable 2MASS magnitudes (HD 23642 and HCG 76; David et al. 2016), with the third (Atlas; $V = 3.6$) being too bright. To these we therefore added HII-2147 itself and used its total mass from solution 1 together with its combined $JHK_s$ magnitudes from the 2MASS catalog. We then calculated the ratio of the total masses of HII-2147 and HCG 76 with respect to the total mass of HD 23642 (the more massive system) and the magnitude differences in $JHK$ between each of the two lighter systems and HD 23642. A diagram of these three system mass ratios and magnitude differences is shown in Figure 7, with corresponding interpolated spline curves for each filter. Finally, with the measured values of $\Delta J$, $\Delta H$, and $\Delta K$ for HII-2147 from Table 3 (averaged between the two AO epochs), we used these curves to infer three values for the mass ratio. The mean and standard deviation are $q = 0.917 \pm 0.004$.

We then carried out another orbital solution using the same observations as before, this time applying the above result as a Gaussian prior on the mass ratio. We refer to this as solution 2. The orbital elements and derived properties we obtained are listed in the last column of Table 4. The results are all very similar to those of our initial analysis, with the anticipated exception of the parameters that were previously highly correlated with each other (see above). For those, the uncertainties are now considerably reduced, as are the mutual correlations (see Figure 6, bottom panel). The mass ratio is slightly larger in the new solution but more than an order of magnitude more precise. As a result, the individual masses are also somewhat different and considerably better determined.

### Table 5

| Parameter | Solution 1 | Solution 2 (Adopted) | Measurements |
|-----------|------------|----------------------|--------------|
| $G$ (mag) | 10.32 ± 0.17 | 10.39 ± 0.15 | 10.421 ± 0.030 |
| $G_{\text{B}}$ (mag) | 10.72 ± 0.19 | 10.81 ± 0.17 | 10.873 ± 0.030 |
| $G_{\text{V}}$ (mag) | 9.75 ± 0.14 | 9.81 ± 0.13 | 9.832 ± 0.030 |
| $J$ (mag) | 9.10 ± 0.10 | 9.13 ± 0.10 | 9.166 ± 0.021 |
| $H$ (mag) | 8.733 ± 0.086 | 8.750 ± 0.083 | 8.719 ± 0.042 |
| $K_s$ (mag) | 8.633 ± 0.083 | 8.649 ± 0.080 | 8.603 ± 0.017 |
| $\Delta J$ (mag) | 0.68 ± 0.32 | 0.380 ± 0.019 | 0.360 ± 0.064 |
| $\Delta H$ (mag) | 0.57 ± 0.27 | 0.317 ± 0.016 | 0.310 ± 0.042 |
| $\Delta K$ (mag) | 0.55 ± 0.26 | 0.306 ± 0.015 | 0.316 ± 0.015 |

Note. Solution 2 uses a prior on the mass ratio (see text). The magnitude differences in the last three rows of the last column are averages of the values in Table 3 in each bandpass. Uncertainties for the Gaia magnitudes have been see the Appendix. For these tests, we have preferred not to rely entirely on the model isochrone used above to predict fluxes, as we find that it does not match the empirical color–magnitude diagram of the cluster sufficiently well for our purposes. Instead, we developed semiempirical relations to predict fluxes in the Gaia and 2MASS bandpasses as a function of mass. Briefly, we fit spline relations to the empirical color–magnitude diagram of the Pleiades and then used the models to provide the connection between masses and observed bandpass magnitudes in the two photometric systems. The details of this derivation are given in the Appendix, where we also present a test of the semiempirical relations mentioned in the text (see the Appendix).
whereas the total mass is essentially unchanged compared to its uncertainty. The predicted combined magnitudes in the Gaia bandpasses agree better than before with the observations, as can be seen in Table 5, while the magnitude differences now track the measured values closely, by construction.

The mass of star B in this new solution is now slightly larger than before, and the corresponding effective temperature according to the PARSEC isochrone is 5350 K, which is much closer to the value we measured spectroscopically. We conclude that this set of orbital parameters is consistent with all available observational constraints for HII-2147.

Our solution leads to a parallax for HII-2147 of $\pi = 7.310 \pm 0.026$ mas, corresponding to a linear distance of $136.78 \pm 0.46$ pc. This is twice as precise as but in good agreement with the parallax reported in the Gaia DR2 catalog, after that value is adjusted for a systematic difference compared to VLBI determinations ($+0.075 \pm 0.029$ mas) following Xu et al. (2019), giving $\pi_{\text{Gaia}} = 7.284 \pm 0.059$ mas.

A representation of the path of each star on the plane of the sky, together with the VLBI measurements, is shown in the top panel of Figure 8, with the arrow indicating the direction and magnitude of the change due to proper motion over the span of 1 yr. The bottom panel shows the parallactic ellipse for HII-2147 along with the VLBI measurements corrected for proper motion and orbital motion, following our solution 2. The measured position of each component relative to the barycenter is illustrated in the top panel of Figure 9, with the proper motion and parallactic motion removed. Motion in the relative orbit (star B relative to star A) is shown in the bottom panel, including the AO measurements. Orbital motion on the plane of the sky is counterclockwise (direct). The predicted radial-velocity curves for the primary and secondary can be seen in Figure 10 along with the observations.

As a check on our mass determinations for HII-2147, we compared the measurements with stellar evolution models from the MESA Isochrones and Stellar Tracks (MIST; Choi et al. 2016) series. Most models, including these, have difficulty matching the color–magnitude diagram of the Pleiades, as mentioned earlier, so here we have compared theory and observations via evolutionary tracks in a diagram of apparent $K_S$-band magnitude versus effective temperature. An estimate
of $T_{\text{eff}}$ for the primary was derived from the spectroscopic value for the secondary and a temperature offset $\Delta T_{\text{eff}}$ calculated using the $JHK$ magnitude differences from AO. The offset was determined by using a 125 Myr MIST isochrone for the Pleiades and recording the changes in temperature corresponding to changes in $JHK_S$ brightness from the predicted values for the secondary at its measured mass. Because the models are used here only in a differential sense, the dependence of the temperature offset (and therefore the primary temperature) on theory is weak. The average of the three $\Delta T_{\text{eff}}$ estimates is 350 K, resulting in a final primary temperature of $5740 \pm 150$ K (conservative uncertainty). Figure 11 indicates that the models are consistent with the component temperatures and brightnesses at their measured masses.

5.1. Alternate Scenarios

While solution 2 provides satisfactory agreement with all astrometric, spectroscopic, and photometric observations for HII-2147, it still requires an explanation for the lack of detection of the lines of star A in our spectra, especially given that it is the more massive component and should therefore be
calculated using the combined from our AO measurements lines more challenging, more so if one or both of its the mystery somewhat by making the detection of its spectral close binary, composed of stars Aa and Ab. This could alleviate Figure 10. Radial-velocity model from our analysis, together with the observations of HII-2147. Symbols are the same as in Figure 3. The dashed line represents the predicted velocity curve of the unseen spectroscopic companion, and the dotted line marks the center-of-mass velocity of the system.

assumed so far. This is because dividing up its mass among two smaller stars (Aa and Ab) can reduce its total brightness, depending on the mass ratio. This could have significant consequences for the orbital solution, because it would reverse the location of the star that has the measured velocities relative to the VLBI measurements, potentially changing some of the orbital elements. On the other hand, other mass ratios between Aa and Ab would allow it to remain the brighter component.

In principle, we can explore both of these possible triple-star scenarios (Aa + Ab brighter than star B, or vice versa) by adding the mass ratio \( q_A = M_{Ab}/M_{Aa} \) as a free parameter. However, the astrometric, spectroscopic, and photometric observations used up to now do not constrain this new parameter, so for this we chose to make use of the Gaia and 2MASS magnitudes of HII-2147 as measurements, with their corresponding uncertainties. We used the semiempirical mass–magnitude relations developed in the previous section to predict the individual magnitudes at each step of the iterations, adding the appropriate term to the likelihood function. As mentioned in the Appendix, we do not expect this mapping between theoretical masses and fluxes to be free from systematic error; there are many physical ingredients in the models that can affect the passband-specific flux predictions in ways that are difficult to quantify. To guard against this, we took two precautions in our new solutions: we allowed for a shift \( \Delta M \) in the mass scale of the models by adding it as one more free parameter in our MCMC analysis (solved simultaneously with the rest), and we conservatively increased the photometric uncertainties from Gaia and 2MASS by adding 0.02 mag in quadrature to the formal errors as a way of accounting for biases in the model fluxes as well as variable extinction within the Pleiades cluster. The resulting masses will therefore be model-dependent to some extent, as opposed to the ones in solution 2, which are purely empirical.

We produced two new solutions using the magnitudes and \( JHK \) magnitude differences from Table 3 as observables, along with the same astrometric and spectroscopic information used in solution 2 above. We refer to the new triple-star solution with component A being brighter than star B as solution 3 and the one with component A being fainter as solution 4. Most of the orbital elements are largely unchanged. We report the results for the masses in Table 6, with the values from solution 2 repeated for reference in the second column.

The total mass of the system is very nearly the same in all three cases, indicating that it is robust no matter what the configuration is. This is because it is essentially constrained by the orbital period, semimajor axis, and parallax, each of which is well determined to better than 1%. We find that in order to fit the observations, solution 3 requires a shift in the scale of the model masses of \( \Delta M = -0.062 M_\odot \), which seems uncomfortably large; it amounts to almost 1/3 of the mass of star Ab. Furthermore, for a star with the mass of \( M_B \) in this solution, the PARSEC isochrone for the Pleiades predicts an effective temperature of 4970 K, which is more than 400 K cooler than the value we measured spectroscopically (5390 ± 100 K). For these reasons, we do not consider this model to be plausible. Solution 4, in which component A is fainter than star B, fares somewhat better regarding the temperature, although the predicted value of 5140 K is still 250 K cooler than we measure. Moreover, the offset required in the mass scale of the models is even larger than before, \( \Delta M = -0.113 M_\odot \), which is again about 1/3 of the mass of star Ab in this configuration.
Aside from being more contrived, we conclude that neither of the triple-star scenarios provides a description of the system as satisfactory as solution 2, given the available observational constraints. Nor do they help in explaining the lack of detection of the lines of another star in our spectra, given that in both cases, star Aa would not be too different in mass (and therefore brightness) from star B (see Table 6). The two-star scenario (solution 2) is thus favored by all available evidence.

6. Rotation

Photometric monitoring of HII-2147 by a number of authors has yielded several different estimates of the rotation period based on the modulation due to spots. All are very short, placing the object in the category of the UFRs in the Pleiades (Hartman et al. 2010; Rebull et al. 2016). Norton et al. (2007) analyzed SuperWASP photometry and reported $P_{\text{rot}} = 0.3082$ days with a peak-to-peak amplitude of about 0.04 mag in unfiltered white light. Hartman et al. (2010) used observations from the HATNet transiting planet survey and gave a period of $P_{\text{rot}} = 0.7762$ days that is 2.5 times longer, with a total amplitude of 0.031 mag in the Sloan r band. Subsequently, Kiraga (2012) measured a period $P_{\text{rot}} = 0.3083$ days that is essentially identical to that of Norton et al. (2007), with an amplitude of about 0.07 mag from the V-band ASAS photometry. More recently, Rebull et al. (2016) used observations from NASA’s K2 mission and reported a preferred rotation period of 0.7768 days with an amplitude of 0.037 mag, as well as a secondary modulation with a much shorter period of 0.1541 days that is exactly half of the value found by Norton et al. (2007) and Kiraga (2012). The various estimates therefore appear to be in the ratios 1:2:5.

If the true spin rate is the fastest one (0.1541 days), it would imply an equatorial rotational velocity of about 250 km s$^{-1}$ for a star such as component B in HII-2147. Given our spectroscopically measured projected rotational velocity of $\nu_B \sin i = 31$ km s$^{-1}$ for that star, we infer that it would have to be seen nearly pole-on ($i_{\text{rot}} \sim 7^\circ$) in order to be responsible for the photometric modulation, which we cannot rule out. For this calculation, we adopted a radius of $R_B = 0.78 R_\odot$ based on the PARSEC isochrone. The longer rotation periods would lead to less extreme inclinations relative to the line of sight of about 14$^\circ$ and 37$^\circ$, respectively. As none of these angles agree with the orbital inclination, they would imply a misalignment between the spin and orbital axes. Whether or not this is the case, star B is itself clearly a UFR, as its measured projected rotational velocity of 31 km s$^{-1}$ implies an upper limit to its rotation period of 1.3 days, much shorter than typical for a star of its spectral type in the Pleiades.

On the other hand, a possibility that seems more likely to us is that the rotational modulation signature originates from the primary star, whose lines we do not detect in our spectra. It is the brighter component by nearly a factor of 2, if we rely on the PARSEC models for stars of these masses, and very rapid rotation of the primary would in fact be a natural explanation for its nondetection. In that case, both components of HII-2147 would fall into the category of UFRs, and their spin rates would be primordial, as tidal forces are negligibly small in an orbit with such a long period. If the rotational signal comes from the primary, an assumed radius for the star of 0.86 $R_\odot$ would result in equatorial rotational velocities of about 280, 140, and 55 km s$^{-1}$ for the three reported values of $P_{\text{rot}}$. The actual line broadening would depend on the inclination angle of its spin axis projected onto the line of sight.

7. Discussion and Conclusions

HII-2147 is the fourth system in the Pleiades cluster with dynamical mass determinations. We have shown that previous claims suggesting it contains a pair of sharp-lined stars in a presumably short-period orbit are incorrect, and that based on the currently available observations, the system is best described as consisting of a moderately rotating star with visible spectral features in a slightly eccentric 18 yr orbit around a more massive companion. The masses we determine from our new spectroscopic and AO observations, other radial velocities from the literature, and previously published VLBI measurements that resolve the pair have relative uncertainties of about 2.5%. They are limited mostly by the precision of the early radial velocities (pre-1995). The masses correspond approximately to stars of spectral types G5 and G9. We also derive a parallax good to better than 0.4%, which is in excellent agreement with the (adjusted) value from Gaia DR2, though more precise.

The most puzzling aspect of our results is the lack of detection of the lines of the G5 primary star in our spectra, despite multiple attempts carried out with TODCOR using a wide range of template parameters. According to the PARSEC models, that star is expected to be roughly 0.6 mag brighter than the secondary. Circumstantial evidence that the light of star A is attenuating the lines of star B was presented in Section 2.4. We now examine this in a somewhat more quantitative fashion.

As a first step, we made an independent estimate of the brightness difference between the components using solar-metallicity synthetic spectra based on PHOENIX model atmospheres from the library of Husser et al. (2013). We adopted effective temperatures of 5750 and 5400 K, near those determined for stars A and B, and a radius ratio estimate of $R_B/R_A = 0.9$ from the PARSEC models. The resulting flux ratio as a function of wavelength is seen in Figure 12. The values for the 2MASS $JHK_\text{s}$ bandpasses ($F_B/F_A = 0.702,$
integrating over the curve using the corresponding transmission functions.

of our TRES spectra

differences of

and temperatures of 5750 and 5400 K, normalized using a radius ratio of $R_B/R_A = 0.9$. The values for the 2MASS $JHK_s$ bandpasses and the wavelength region of our TRES spectra ($\sim 5187$ Å) are indicated with squares and result from integrating over the curve using the corresponding transmission functions.

0.747, and 0.754, respectively) correspond to magnitude differences of $\Delta J = 0.38$, $\Delta H = 0.32$, and $\Delta K_s = 0.31$, which are very close to the values measured from our AO observations (see Table 3). The predicted ratio at the mean wavelength of our spectroscopic observations ($5187$ Å) is 0.56 ($\Delta m = 0.63$). We therefore expect star A to be about 1.8 times brighter than star B in this spectral region.

With this information, we then explored the effect on the strength of the lines of star B. Figure 13 (top panel) reproduces the same observed spectrum of HII-2147 from Figure 4, which was shown there to be affected by veiling. Also plotted is the synthetic template we used to derive the radial velocities, which we take to represent star B without dilution. This template provides a very good match to the line profiles of real stars of the same spectral type, as illustrated before. To represent star A, we have chosen a synthetic template from the same library with a temperature of $5750$ K and an arbitrary rotational broadening of $100$ km s$^{-1}$. The bottom panel of Figure 13 displays the result of adding together the flux of star B and 1.8 times the flux of star A after renormalization. The comparison with the real spectrum of HII-2147 shows very good agreement in the line depths, providing a satisfactory explanation of the observed degree of veiling.

We view the result of this exercise as a valuable self-consistency check on the various aspects of our analysis, including the mass determinations. It also supports the notion advanced earlier in the paper that rapid rotation is, in fact, responsible for the nondetection of the lines of star A in our spectra.

Although Gaia will not spatially resolve the 18 yr pair and can only measure the motion of its center of light, by the end of the mission, it is possible that it could provide some constraints on all of the elements of the A–B orbit (which has the same shape as the photocenter orbit) except for the semimajor axis. Direct spectroscopic detection of star A may be possible with observations of higher signal-to-noise ratio than we have available. In that case, measurement of its radial velocities would result in a better-constrained semiamplitude $K_A$, which would, in turn, improve the mass determinations further.

The spectroscopic observations of HII-2147 were gathered with the help of P. Berlind, M. Calkins, and G. Esquerdo. We thank D. Latham for scheduling those observations and J. Mink for maintaining the CfA echelle database. We also thank the anonymous referee for helpful comments. G.T. acknowledges partial support from the National Science Foundation (NSF) through award AST-1509375. C.M. acknowledges support from the NSF under award AST-1313428. Research at Lick Observatory is partially supported by a generous gift from Google. Some of the data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. The research has made use of the SIMBAD and VizieR databases, operated at the CDS, Strasbourg, France; NASA’s Astrophysics Data System Abstract Service; and the WEBDA database, operated at the Department of Theoretical Physics and Astrophysics of Masaryk University (Czech Republic). The work has also made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC; https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided.
by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. The computational resources used for this research include the Smithsonian Institution’s “Hydra” High Performance Cluster (https://doi.org/10.25572/SIHPC).

Appendix

We describe here our procedure to develop a relation to predict the magnitudes of Pleiades stars in the Gaia and 2MASS bandpasses as a function of mass, which we used in Section 5 to test the accuracy of solution 1 and explore alternate configurations for HII-2147 involving three stars.

We began by establishing purely empirical relations between color and brightness using the list of 1454 likely Pleiades members published recently by Gao (2019) based on astrometric and photometric observations from the Gaia DR2 catalog. We fitted cubic spline relations to the (single-star) main sequence in diagrams of absolute $G$, $G_{BP}$, and $G_{RP}$ magnitude as a function of the observed $G_{BP}$–$G_{RP}$ color, where the absolute magnitudes were computed using the parallax of each star to reduce scatter due to the nonnegligible depth of the cluster. Note that all of these photometric quantities are affected by extinction, although the effect is relatively small in the Pleiades ($E(B-V) \approx 0.04$ mag; Taylor 2008). Next, to provide the necessary connection with stellar mass, we adopted a mapping between mass and theoretical $G_{BP}$–$G_{RP}$ color from the 125 Myr, solar-metallicity PARSEC isochrone used in the main text. The model colors were adjusted by applying reddening in the amount of $E(G_{BP}-G_{RP}) = 1.31E(B-V)$ (Stassun et al. 2019) to make them more consistent with the observed colors (i.e., the abscissa of the empirical spline relations). Reliance on models for the mass–color mapping will of course not be perfect because of deficiencies in the model fluxes (due, e.g., to missing opacity sources), but it is unavoidable, and in the end, this two-step procedure allows us to predict the brightness and color of a star from its mass more accurately than using the models alone. We illustrate this below. In a similar fashion, we developed spline relations to predict the $J$, $H$, and $K_S$ magnitudes in the 2MASS system as a function of the observed $G_{BP}$–$G_{RP}$ color.

Figure 14 shows the predicted location of the two stars in the color–magnitude diagram of the Pleiades based on Gaia photometry, together with other cluster members from the list of Gao (2019). The observed location of HII-2147 above the single-star sequence is represented by the red cross, and the point with error bars marks the predicted location of the combined light according to the masses derived in solution 2 based on our semiempirical spline relations (red solid line). The dashed line represents the 125 Myr solar-metallicity PARSEC isochrone for the Pleiades (Chen et al. 2014), which does not provide as good a match to the observations.

As a sanity check, we tested the ability of these relations to predict the true colors of stars as a function of mass by using the few examples in the Pleiades that are in binary systems and have dynamically measured masses. One of them, Atlas, has its dynamical mass measured. One of them, Atlas, has its dynamical mass measured. The location of HII-2147 above the single-star sequence, as measured by Gaia, is indicated by the red cross. The solid red line is based on our semiempirical mass–magnitude relations, and the blue open circles on it mark the predicted locations of the binary components according to their masses of 0.978 and 0.897 $M_\odot$, as given in Table 4 (solution 2). The blue point with error bars represents the combined light of the binary inferred using the semiempirical relations, with the errors being dominated by the uncertainty in the masses (photometric errors are much smaller). The theoretical color–magnitude relation as given by the PARSEC isochrone mentioned in the text (dashed line) shows a poorer fit to the observations. All magnitudes and colors shown are affected by extinction and reddening.

validity range but near the edges of our relations (upper and lower ends, respectively). Nevertheless, with the individual masses in each of these systems, we predicted their brightness in the Gaia bandpasses and then calculated the $G_{BP}$–$G_{RP}$ color index for the combined light for comparison with the measurements from Gaia. For HD 23642, our relations predict a $G_{BP}$–$G_{RP}$ index of 0.096 mag, whereas the measured value is 0.107 mag. For HCG 76, we obtain $G_{BP}$–$G_{RP} = 2.925$ mag, and the measured value is 2.913 mag. Given that the reddening toward these two objects may be different than the mean value we have adopted for the cluster, we consider these differences (−0.011 and +0.012 mag) to be small and therefore to support the accuracy of our calibration.

**ORCID iDs**

Guillermo Torres @ https://orcid.org/0000-0002-5286-0251
Carl Melis @ https://orcid.org/0000-0001-9834-7579
Adam L. Kraus @ https://orcid.org/0000-0001-9811-568X
Trent J. Dupuy @ https://orcid.org/0000-0001-9823-1445
Justin R. Crepp @ https://orcid.org/0000-0003-0800-0593

**References**

Baranne, A., Mayor, M., & Poncelet, J. L. 1979, *VA*, 23, 279
Barnes, S., & Sofia, S. 1996, *ApJ*, 462, 746
Bouvier, J., Rigaut, F., & Nadeau, D. 1997, *A&A*, 323, 139
Bowler, B. P., Dupuy, T. J., Endl, M., et al. 2018, *AJ*, 155, 159
Brandt, T. D. 2018, *ApJS*, 239, 31
Breger, M. 1986, *ApJ*, 309, 311
Brown, T. M. 2014, *ApJ*, 789, 101
Butler, R. P., Cohen, R. D., Duncan, D. K., et al. 1987, *ApJL*, 319, L19

---

13 Reddening is not uniform across the Pleiades cluster, being smaller on the eastern side than the western side (see Breger 1986; Taylor 2008). As individual estimates are not available for all 1454 members, we have chosen to adopt here an average $E(B-V)$ of 0.04 that suffices for this work.
