ORBITAL PARAMETERS FOR THE TWO YOUNG BINARIES VSB 111 AND VSB 126

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ABSTRACT

We report orbital parameters for two low-mass, pre-main-sequence, double-lined spectroscopic binaries: VSB 111 and VSB 126. These systems were originally identified as single-lined on the basis of visible-light observations. We obtained high-resolution infrared spectra with the 10 m Keck II telescope, detected absorption lines of the secondary stars, and measured radial velocities of both components in the systems. The visible-light spectra were obtained with the 1.5 m Wyeth reflector at the Oak Ridge Observatory, the 1.5 m Tillinghast reflector at the F. L. Whipple Observatory, and the 4.5 m equivalent Multiple Mirror Telescope. The combination of our visible and infrared observations of VSB 111 leads to a period of 902.1 ± 0.9 days, an eccentricity of 0.788 ± 0.008, and a mass ratio of 0.52 ± 0.05. VSB 126 has a period of 12.9244 ± 0.0002 days, an eccentricity of 0.18 ± 0.02, and a mass ratio of 0.29 ± 0.02. Visible-light photometry, using the 0.8 m telescope at Lowell Observatory, provided rotation periods for the primary stars in both systems: 3.74 ± 0.02 days for VSB 111 and 5.71 ± 0.07 days for VSB 126. Both binaries are located in the young, active star-forming cluster NGC 2264 at a distance of ~800 pc. The difference in the center-of-mass velocities of the two systems is consistent with the radial velocity gradient seen across NGC 2264. To test the evolutionary models for accuracy and consistency, we compare the stellar properties derived from several sets of theoretical calculations for pre-main-sequence evolution with our dynamical results.

Key words: binaries: spectroscopic – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

A binary star provides one of the few ways to directly measure stellar masses. The mass is the most important property of a star and determines its basic structure and properties, as well as the duration of stages of evolution throughout its lifetime. A double-lined spectroscopic binary (SB2) enables the orbit to be solved from spectroscopically determined radial velocities (RVs), yielding the orbital elements (except i) and mass ratio, \( q \), for the component stars. Component masses may be found if the inclination of an SB2 can be measured in the case of an eclipsing binary system (i = 90°) or a resolved visual binary.

The work presented here is part of a long-term program to measure young SB2 mass ratios and eventually component masses, \( M_1 \) and \( M_2 \) (Prato et al. 2002; Schaefer et al. 2012). Such results will be facilitated with the advent of high-precision astrometric missions such as Gaia. Ultimately, a large sample of precise, dynamical masses will help to anchor models of pre-main-sequence (PMS) evolution to a solid observational basis, particularly for systems with stellar mass <1 \( M_\odot \) (e.g., Hillenbrand & White 2004; Simon 2008). Furthermore, precise measurements of the mass-ratio distribution provide critical input for theories of binary star formation (Bate 2009). Our present goal is to build up a large sample of young-star mass ratios.

Vasilevskis et al. (1965) included VSB 111 (V810 Mon) and VSB 126 (2MASS J06410777+0944030) in their study. Since then, several papers adopted the VSB acronym; therefore, we use those names throughout the paper. VSB 111 and VSB 126 are located in the young cluster NGC 2264. This cluster is an active region of star formation, with subclusters of suspected members spread across several parsecs. Dahm (2008) published a summary of the papers on NGC 2264. There are numerous estimates of the distance to NGC 2264, ranging from 700 pc (Feldbrugge & van Genderen 1991) to 950 pc (Pérez et al. 1987). We adopted a distance of 800 pc from Walker (1956) because it was a median value within the estimated distances published in Dahm (2008). We adopted an uncertainty of ±100 pc to account for the large spread of published distances. Additionally, there is a large age range cited in the literature. Estimates for the age of the cluster range from 0.1 Myr (Flaccomio et al. 1999; Rebull et al. 2002) to 10.0 Myr (Flaccomio et al. 1999), but ~3.0 Myr is common (Walker 1956; Mendoza & Gómez 1980; Feldbrugge & van Genderen 1991; Sung et al. 2004; Ramirez et al. 2004; Flaccomio et al. 2006). This is not particularly surprising, however, as the ages of stars in young clusters typically appear to span a range of millions and even tens of millions of years (e.g., Hillenbrand 1997).

Haisch et al. (2001) observed that about half of the stars within clusters lose their disks in approximately 3 Myr. Mathieu (1994) lists the Hα equivalent widths for VSB 111 as −0.3 Å and VSB 126 as −1.9 Å, indicating a lack of any appreciable gas accretion in these systems. Wide-field Infrared Survey Explorer and Spitzer data show no indication of warm dust in VSB 111 and VSB 126. We therefore believe they are diskless. The basic properties of the systems are listed in Table 1.

Mathieu (1994) originally derived single-lined spectroscopic (SB1) orbital solutions for VSB 111 and VSB 126. Given his mass functions for the systems, we knew a priori that the minimum mass ratios were both likely to be small. When a low-mass-ratio binary system is observed in visible light, the primary star’s spectrum dominates the faint secondary signal...
because of the low flux ratio. Observing in the infrared (IR) allows for detection of the secondary component and thus the solution of the system as an SB2 because the flux ratio is more favorable in the long-wavelength Rayleigh–Jeans regime. This approach was demonstrated in Prato (1998), Mazeh et al. (2002, 2003), and Prato et al. (2002). Observing PMS binaries in the IR can also be advantageous for young stars obscured in dusty star-forming regions.

In this paper we contribute dynamical mass-ratio measurements for two young binaries, one short period (several days) and one long period (few years), to the as yet relatively small sample of ~50 PMS SB2s. Furthermore, our results provide improved orbital parameters for both binaries. Based on the stellar characteristics and light curves measured as part of this program, we also estimated the inclinations of the binary orbital planes and the stellar rotation axes. In Section 2 we describe our observations and data reduction. In Section 3 we provide our analysis and results. Section 4 contains a discussion and Section 5 summarizes our findings.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Visible-light Spectroscopy

Visible-light spectroscopic observations of VSB 111 and VSB 126 were carried out at the Harvard-Smithsonian Center for Astrophysics (CfA) using three different telescopes equipped with nearly identical echelle spectrographs: the 1.5 m Wyeth reflector at the Oak Ridge Observatory (Harvard, Massachusetts), the 1.5 m Tillinghast reflector at the F. L. Whipple Observatory (Mount Hopkins, Arizona), and the 4.5 m equivalent Multiple Mirror Telescope (also on Mount Hopkins), prior to its conversion to a monolithic 6.5 mirror. A single echelle order 45 Å wide and centered near 5190 Å (including the Mg I b triplet) was recorded with intensified photon-counting Reticon detectors at a resolving power of $\lambda/\Delta\lambda = 35,000$. We collected 69 spectra for VSB 111 between 1984 January and 1996 January, with signal-to-noise ratios between 8 and 20 per resolution element of 8.5 km s$^{-1}$. For VSB 126 we collected a total of 30 spectra from 1984 March to 1992 February, at signal-to-noise ratios of 5–11 per resolution element. These data are largely the same as those on which the results of Mathieu (1994) are based. The details of the observations are provided here for the first time. The specific dates of observation appear in the first column of Tables 2 and 3. Spectra were reduced using standard IRAF procedures for echelle data (e.g., Torres et al. 1997).
spectra by nodding the telescope 12′′ to dither the target between two positions on the slit and using an A-B-B-A pattern of observation.

Our H-band setting (echelle = 63′′/4, cross-disperser = 36′′/3) has a central wavelength of ∼1.555 μm, which corresponds to order 49 (1.545−1.567 μm) for NIRSPEC. We focused on order 49 because it is free of telluric absorption lines and contains well-spaced OH emission lines. De-excitation of the hydroxyl molecule (OH) in the Earth’s atmosphere produces these emission lines; they are distributed throughout order 49 and were used to calibrate the wavelength zero point and dispersion (Rousselot et al. 2000). Order 49 is also rich in atomic and molecular species in the stellar photospheres that allow us to identify spectral features of both warm and cool stars.

NIRSPEC’s optics optimize the throughput of photons but the resulting spectra do not fall along uniform rows; the light falls in curved swaths. Therefore, we needed to rectify the data spatially and spectrally. For all data reductions we used the REDSPEC software package, written at UCLA by S. Kim, L. Prato, and I. McLean, and created specifically for the analysis of NIRSPEC data. The lack of terrestrial absorption lines in order 49 eliminates the need to divide by telluric standard star spectra. Median images of 10 flat and 10 dark files were used to create a master flat and dark in order to correct for effects from the detector.

The REDSPEC module spatmap was used to remap the raw images onto a uniform interval coordinate system in the spatial (cross-dispersion) direction by adding two nodded frames together and fitting a third-order polynomial to each spectral trace. The specmap module was used to remap the raw images onto a uniform interval coordinate system in the dispersion direction. A second-order polynomial was fit to each OH line to identify the approximately vertical trace. Then, a second-order polynomial fit in the dispersion direction was made to these wavelength locations for each row around the spectral trace. The final step of REDSPEC was to divide by the dark-subtracted master flat, remove any bad pixels and fringing, and clip out and sum the rows containing the rectified spectra. All spectra were corrected for heliocentric motion and the Earth’s rotation using JSkyCalc and are shown in Figures 1 and 2 for VSB 111 and VSB 126, respectively.

The photometric data were taken on 12 nights between 2012 September 14 and October 11 using the Lowell 0.8 m telescope in robotic mode. A total of 45 images were obtained for VSB 111 and 44 images for VSB 126. The CCD camera houses an e2v 2 k × 2 k chip providing a 15′ × 15′ field. The image scale is 0′.91 pixel−1 when binned 2 × 2, as here. A median bias frame

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2.2. Infrared Spectroscopy

VSB 111 and VSB 126 were observed in the IR with the Keck II 10 m telescope on Mauna Kea. The observations for VSB 111 and VSB 126 were made between 2001 December and 2012 January (Tables 4 and 5). The Keck facility near-IR spectrograph, NIRSPEC, was used to obtain H-band data at a central wavelength of ∼1.555 μm (McLean et al. 1998, 2000). NIRSPEC employs a 1024 × 1024 ALADDIN InSb array detector. The 0′.288 (2 pixel) ×24′′ slit yielded a resolution of R = 30, 000. The slit viewing camera, SCAM, which uses a 256 × 256 HgCdTe detector with 0′.18 pixels, facilitated source acquisition and guiding. For VSB 111, integration times for the individual frames were 240 s or 300 s; two to eight frames were taken on each observing date. For VSB 126, integration times for the individual frames were 300 s or 360 s; 6–14 frames were taken on each visit. For both systems, the signal-to-noise ratio was always >100 and typically 200 or higher. Background subtraction was achieved between consecutive

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### Table 3

| HJD      | HJD | \(v_1 \pm \sigma\) | \(v_2 \pm \sigma\) | Phase |
|----------|-----|---------------------|---------------------|-------|
| 2445783.6412 | 9.0 ± 1.0 | 0.1224 |
| 2446077.7737 | 5.2 ± 0.9 | 0.8804 |
| 2447075.9909 | 3.1 ± 0.7 | 0.9038 |
| 2447078.9952 | 7.2 ± 0.9 | 0.1159 |
| 2447127.9675 | 25.9 ± 1.1 | 0.3483 |
| 2447128.8485 | 11.5 ± 1.0 | 0.1374 |
| 2447138.8614 | 19.2 ± 1.0 | 0.2056 |
| 2447157.9395 | 0.7 ± 1.0 | 0.9803 |
| 2447158.9427 | 28.5 ± 1.3 | 0.3868 |
| 2447199.7030 | 22.8 ± 1.3 | 0.6788 |
| 2447200.7497 | 14.6 ± 1.1 | 0.7688 |
| 2447220.6977 | 26.8 ± 0.8 | 0.3122 |
| 2447222.7006 | 28.5 ± 1.5 | 0.4672 |
| 2447224.6626 | 22.6 ± 2.1 | 0.6190 |
| 2447229.6414 | 31.1 ± 1.0 | 0.0043 |
| 2447230.6267 | 5.0 ± 0.9 | 0.0085 |
| 2447250.7040 | 24.5 ± 0.7 | 0.6339 |
| 2447427.9928 | 26.4 ± 0.9 | 0.3514 |
| 2447428.9520 | 29.2 ± 1.0 | 0.4256 |
| 2447429.9625 | 28.9 ± 0.9 | 0.5038 |
| 2447489.8436 | 12.6 ± 0.8 | 0.1370 |
| 2447493.8731 | 29.0 ± 0.8 | 0.4487 |
| 2447524.9283 | 6.5 ± 0.9 | 0.8516 |
| 2447549.9192 | 14.4 ± 0.6 | 0.7852 |
| 2447845.9554 | 21.8 ± 0.9 | 0.6905 |
| 2448669.7216 | 30.3 ± 1.3 | 0.4280 |

### Table 4

| UT Date of Observations | HJD | \(v_1 \pm \sigma\) | \(v_2 \pm \sigma\) | Phase |
|-------------------------|-----|---------------------|---------------------|-------|
| 2001 Dec 31             | 2452274.9427 | 25.6 ± 1.0 | 24.4 ± 0.5 | 0.6967 |
| 2002 Feb 6              | 2452311.8627 | 27.1 ± 1.0 | 23.5 ± 2.0 | 0.5106 |
| 2002 Dec 14             | 2452623.0425 | 32.7 ± 1.0 | 14.4 ± 2.0 | 0.8556 |
| 2004 Jan 28             | 2453032.8246 | 23.6 ± 1.0 | 28.5 ± 2.0 | 0.0990 |
| 2004 Dec 26             | 2453366.0427 | 27.7 ± 1.0 | 20.5 ± 2.0 | 0.6793 |
| 2010 Dec 10             | 2455534.1187 | 15.7 ± 1.0 | 43.3 ± 2.0 | 0.0927 |
| 2012 Jan 11             | 2455937.9446 | 26.3 ± 1.0 | 23.4 ± 2.0 | 0.5304 |

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2.3. Visible-light Photometry

The photometric data were taken on 12 nights between 2012 September 14 and October 11 using the Lowell 0.8 m telescope in robotic mode. A total of 45 images were obtained for VSB 111 and 44 images for VSB 126. The CCD camera houses an e2v 2 k × 2 k chip providing a 15′ × 15′ field. The image scale is 0′.91 pixel−1 when binned 2 × 2, as here. A median bias frame

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http://www.dartmouth.edu/~physics/faculty/skyscale/flyer.html
was produced every night from several dozen zero-integration time exposures. Twilight flats are scripted for each filter in use on a rotating schedule and taken when obtainable. Further details about the telescope and its conversion to robotic use can be found in Buie (2010). Pairs of 150 s exposures using a Johnson $V$ filter were taken at each visit to NGC 2264. These were observed among roughly a dozen other targets in the queue schedule whenever the field was at less than 2.0 airmasses. Since the observing was done near the beginning of the season, typically four visits (up to eight) were made to the field each night roughly a half-hour to a full hour apart. The images were reduced with the commercial photometry package Canopus (Warner 2011). The software includes a photometric catalog with BVRI data derived from Two Micron All Sky Survey (2MASS) JHK, photometry (Warner 2007), as well as more traditional published BVRI photometry, and Sloan griz catalogs. These provide photometric zero points and color indices ($\sim$0.03 mag) for the entire sky via on-chip differential photometry without the need to observe primary standards. Canopus plots the run of instrumental magnitudes versus its internal photometric catalog of all stars in the image. The averaged photometry from the two frames at each visit to the field was used for analysis.

In the NGC 2264 region, the majority of the brighter stars are identified or suspected variables. All five of the comparison stars we selected appear in the New Suspected Variable (NSV) catalog or its supplements (Samus et al. 2012), and have hitherto suspected to be variable with ranges of up to a half-magnitude. Table 6 lists the coordinates and aliases of the comparison stars. The five comparison stars were chosen to be similar in color to the two binaries, which helps minimize errors in the photometry resulting from color terms and differential extinction. All five comparison stars are demonstrably constant at the half-percent level on a timescale of weeks. The reduced data for VSB 111 and VSB 126 are shown in Tables 7 and 8, respectively. The light curves for the primary star in each system are shown in Figures 3 and 4 for VSB 111 and VSB 126, respectively.
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Figure 3. Magnitude vs. phase for the primary component of VSB 111. The rotation period was determined to be $3.74 \pm 0.02$ days. The magnitudes are binned in JD date to minimize the errors, shown as vertical bars. The red line is a weighted sinusoidal fit. The first image taken was used to phase the light curve and represents phase zero.

(A color version of this figure is available in the online journal.)

Table 8
VSB 126 Photometry

| BJD       | $V$ mag ±σ | Phase |
|-----------|------------|-------|
| 2456204.87406 | 13.505 ± 0.008 | 0.022 |
| 2456204.89336 | 13.506 ± 0.008 | 0.025 |
| 2456204.93308 | 13.504 ± 0.006 | 0.032 |
| 2456204.95158 | 13.503 ± 0.006 | 0.035 |
| 2456204.96819 | 13.508 ± 0.006 | 0.041 |
| 2456204.98598 | 13.504 ± 0.005 | 0.046 |
| 2456205.01121 | 13.503 ± 0.005 | 0.047 |
| 2456205.01694 | 13.504 ± 0.006 | 0.198 |
| 2456205.98655 | 13.508 ± 0.006 | 0.273 |
| 2456206.01396 | 13.515 ± 0.006 | 0.278 |
| 2456206.01763 | 13.518 ± 0.006 | 0.543 |
| 2456206.92283 | 13.540 ± 0.008 | 0.572 |
| 2456207.95936 | 13.542 ± 0.008 | 0.723 |
| 2456207.98904 | 13.545 ± 0.007 | 0.735 |
| 2456208.88059 | 13.572 ± 0.006 | 0.740 |
| 2456208.94489 | 13.572 ± 0.005 | 0.898 |
| 2456208.97615 | 13.518 ± 0.005 | 0.909 |
| 2456209.87799 | 13.511 ± 0.005 | 0.915 |
| 2456209.94233 | 13.506 ± 0.006 | 0.972 |
| 2456209.97354 | 13.519 ± 0.011 | 0.803 |
| 2456210.87131 | 13.503 ± 0.005 | 0.909 |
| 2456210.93555 | 13.499 ± 0.005 | 0.247 |
| 2456210.96680 | 13.305 ± 0.005 | 0.258 |
| 2456211.01759 | 13.302 ± 0.005 | 0.264 |
| 2456211.87116 | 13.520 ± 0.005 | 0.273 |

3. ANALYSIS

3.1. Radial and Rotational Velocities

All of our visible-light CfA spectra appear single-lined. The templates that best match the spectra implicitly provide an estimate of the spectroscopic parameters of the primary stars. RVs were obtained by cross-correlation using the IRAF task XCSAO, with templates chosen from a large library of calculated spectra based on model atmospheres by R. L. Kurucz (Nordström et al. 1994; Latham et al. 2002). Of the four main parameters of these templates (effective temperature $T_{\text{eff}}$, rotational velocity $v \sin i$, metallicity [Fe/H], and surface gravity log $g$), the ones affecting the velocities the most are $T_{\text{eff}}$ and $v \sin i$. Consequently, we held log $g$ fixed at a value of 3.75 for both stars and assumed solar metallicity. The optimum $T_{\text{eff}}$ and $v \sin i$ values were determined by running grids of cross-correlations seeking the maximum of the correlation coefficient, averaged over all exposures (Torres et al. 2002). We obtained $T_{\text{eff}} = 5300 \pm 100 \, K$ and $v \sin i = 31 \pm 2 \, \text{km s}^{-1}$ for VSB 111, and $T_{\text{eff}} = 5460 \pm 100 \, K$ and $v \sin i = 13 \pm 2 \, \text{km s}^{-1}$ for VSB 126.

The stability of the zero point of the velocity system (e.g., Latham 1992) was monitored by taking exposures of the dusk and dawn sky, and applying small run-to-run corrections as described by Latham (1992). The final heliocentric RVs including these corrections are listed in Tables 2 and 3. The RVs are plotted in Figures 5 and 6.

The individual RVs for the stars based on the IR data were determined by using a two-dimensional cross-correlation algorithm developed at Lowell Observatory following Zucker &
visible-light observations (Mathieu1994). To begin the process primary and secondary components. Approximate spectral types target spectrum against two templates chosen to best match the Figure 6.

Subsequently, the average flux ratios, 0.39 ± 0.08 for VSB 126 were estimated by first using the internal errors of the RVs uncertainties in the visible-light RVs for VSB 111 and VSB 126 were estimated by first using the internal errors of the RVs as initial guesses. After finding the best orbital fit (Section3.2) for the single-lined data, we used theractions μ and σ, respectively. VSB 126 was best fit with a K0 template (BS 7368) with a v sin i of 15 km s⁻¹ for the primary and secondary components, respectively. VSB 126 was best fit with a K0 template (BS 7368) with a v sin i of 15 km s⁻¹, and an M4 template (GL 402) with a v sin i of 8 km s⁻¹ for the primary and secondary components, respectively. These spectral types, the equivalent values of T_eff from Luhman et al. (2003), and the v sin i values are all given in Table 9. Results from analysis of visible-light data are included for comparison. Conservative uncertainties of 5 km s⁻¹ are estimated for the IR v sin i values based on visual inspection of the spectra and comparison with standard star spectra convolved with different rotation kernels.

The uncertainties in the IR RVs for both VSB 111 and VSB 126 were initially set at 1.0 km s⁻¹ for the primary and 2.0 km s⁻¹ for the secondary (Prato et al. 2002). The uncertainties in the visible-light RVs for VSB 111 and VSB 126 were estimated by first using the internal errors of the RVs as initial guesses. After finding the best orbital fit (Section 3.2) for the single-lined data, we used the χ² per degree of freedom as a guide to determine whether these initial values were over- or underestimated. The uncertainties were then scaled by a multiplicative constant and the process repeated until we attained a χ² per degree of freedom of ~1.0. We then included the primary star IR RVs and repeated the iterative process, multiplying the initial estimate of 1.0 km s⁻¹ by a constant until we again attained a χ² per degree of freedom of 1.0. Finally, we included the secondary star IR RVs and determined a full double-lined solution, again multiplying the initial secondary uncertainties of 2.0 km s⁻¹ by a constant until the solution converged on a χ² per degree of freedom near unity. The final uncertainties determined in visible light and in the IR are reported, respectively, in Tables 2 and 4 for VSB 111 and in Tables 3 and 5 for VSB 126.

3.2. Orbital Parameters

Because of the relatively large number of epochs, the visible-light data for the primary star dominate the orbital solutions for VSB 111 and VSB 126. However, combining our IR RVs for the primary and secondary with the visible RVs allows us to find the double-lined solutions. We used the Levenberg–Marquardt method with a standard least-squares algorithm from Press et al. (1992). A search using a genetic algorithm (Charbonneau 1995) yielded an initial single-lined binary solution based on the CfA spectra alone. The complete set of orbital parameters is listed in Table 10 for both spectroscopic binaries (SBs).

Figures 5 and 6 show the combined orbital solutions for VSB 111 and VSB 126, respectively. These RVs are plotted in Figures 5 and 6.

Table 9

| Property                        | IR VSB 111 | IR VSB 126 | Visible VSB 111 | Visible VSB 126 |
|---------------------------------|------------|------------|-----------------|-----------------|
| Primary rotation period (days)  | ···         | ···         | 3.74 ± 0.02     | 5.71 ± 0.07     |
| Primary spectral type          | K0 ± 1     | K0 ± 1     | ···             | ···             |
| Secondary spectral type        | M0 ± 1     | M4 ± 1     | ···             | ···             |
| Primary T_eff (K)              | 52.48 ± 194| 52.48 ± 194| 5300 ± 100      | 5460 ± 100      |
| Secondary T_eff (K)            | 38.46 ± 192| 32.58 ± 180| ···             | ···             |
| Primary v sin i (km s⁻¹)       | 30 ± 5     | 15 ± 5     | 31 ± 2          | 13 ± 2          |
| Secondary v sin i (km s⁻¹)      | 15 ± 5     | 8 ± 5      | ···             | ···             |
| log(L/L☉)                      | 0.87 ± 0.16| 0.47 ± 0.17| 0.87 ± 0.07     | 0.51 ± 0.08     |
| log(L/L☉)                      | 0.22 ± 0.28| -0.72 ± 0.22| ···             | ···             |
| R_i (R☉)                       | 3.29 ± 0.73| 2.09 ± 0.57| 3.25 ± 0.29     | 2.00 ± 0.19     |

VSB 111 was found to best match a K0 template (BS 7368) with a v sin i of 30 km s⁻¹, and an M0 template (GL 763) with a v sin i of 15 km s⁻¹ for the primary and secondary components, respectively. VSB 126 was best fit with a K0 template (BS 7368) with a v sin i of 15 km s⁻¹, and an M4 template (GL 402) with a v sin i of 8 km s⁻¹ for the primary and secondary components, respectively. These spectral types, the equivalent values of T_eff from Luhman et al. (2003), and the v sin i values are all given in Table 9. Results from analysis of visible-light data are included for comparison. Conservative uncertainties of 5 km s⁻¹ are estimated for the IR v sin i values based on visual inspection of the spectra and comparison with standard star spectra convolved with different rotation kernels.

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Mazeh (1994). The algorithm calculates the correlation of the target spectrum against two templates chosen to best match the primary and secondary components. Approximate spectral types for the VSB 111 and VSB 126 primary stars were known from visible-light observations (Mathieu 1994). To begin the process of estimating secondary star spectral types, we used the mass function from Mathieu (1994) to find the minimum secondary mass by assuming a primary mass of 1.0 M☉ for both VSB 111 and VSB 126. We estimated the secondary spectral type from the minimum secondary mass using model data presented in Figure 5 of Luhman et al. (2003). We then used template spectra with the corresponding spectral type for each component taken from the suite presented in Prato et al. (2002). The two templates were shifted in RV, combined, and correlated with the observed spectra for each epoch, enabling the identification of component RVs. The flux ratio, α, was determined by maximizing the cross-correlation coefficient for each epoch and taking the average. Subsequently, the average flux ratios, 0.39 ± 0.05 for VSB 111 and 0.13 ± 0.05 for VSB 126, were held fixed and the RVs were redetermined. The rotational velocity, v sin i, was measured by using a set of templates rotationally broadened to a range of v sin i values (e.g., Mace et al. 2012). We selected the v sin i that yielded the maximum correlation coefficient. Tables 4 and 5 show the UT dates and measured IR RVs of both components of VSB 111 and VSB 126, respectively. These RVs are plotted in Figures 5 and 6.
the center-of-mass velocity, $\gamma$, between the visible-light and IR RVs to be a free parameter in order to test the consistency of the zero point for the two data sets. For both systems, we found an offset: $-1.2 \text{ km s}^{-1}$ for VSB 111 and $-0.1 \text{ km s}^{-1}$ for VSB 126. In the final, merged (visible+IR), double-lined solution we corrected the IR RVs for these offsets before determining the final orbital parameters. The offsets likely arise as the result of small discrepancies in the RVs determined for the observed template library spectra.

We calculated the $O-C$ values for both SB2 systems and conducted a Scargle periodogram analysis on these residuals to search for any underlying RV signals. For both VSB 111 and VSB 126, the average $O-C$ was close to zero. No obvious periodicity was detected.

### 3.3. Stellar Rotation Periods

A Fourier fitting routine searched for periodicities in the photometric data resulting from flux variations, as the face of the rotating star carries large spots across our line of sight. For VSB 111, we recover the previously published rotation periods rather closely (Kearns & Herbst 1998; Makidon et al. 2004); our data indicate a period of 3.74 ± 0.02 days (Table 9) with range 12.577 < $V$ < 12.650 mag. Kearns & Herbst published a period of 3.77 days and Makidon et al. published a period of 3.75 days. The light curve of VSB 111 appears in Figure 3 and was fitted by a weighted, sinusoidal curve producing an rms scatter of 0.006 mag. The data in Table 7 and Figure 3 show magnitudes binned in JD to minimize errors. For VSB 126, the light curve was also fitted with a weighted sinusoid to yield a rotation period of 5.71 ± 0.07 days (Figure 4, Table 9). This is the first determined rotation period for VSB 126 in the literature. The magnitude range on the fitted light curve is 13.499 < $V$ < 13.542 and the rms scatter is 0.004 mag. Similarly, the data in Table 8 and Figure 4 represent the binned results. These rotation periods indicate the primaries are not pseudo-synchronized with the orbital motions. Given the large primary-to-secondary star flux ratios in visible light, which presumably prevented these systems from being identified as double-lined binaries on the basis of the shorter wavelength data, we interpret these rotation periods as pertaining to the primary star only.

### 3.4. Other Derived Parameters

Luminosity was determined as described in Prato et al. (2003; Section 3.3) using $T_{\text{eff}}$, $A_V$ (determined from the near-IR colors, as per Prato et al. 2003, to be zero for both VSB systems); $r_K$; the $K$-band excess, which was zero for both our systems; a distance to NGC 2264 of 800 pc (Walker 1956); and the $J$, $H$, and $K$-band values from 2MASS. A blackbody curve appropriate to the specific $T_{\text{eff}}$ was produced, fit to the $J$, $H$, and $K$-band magnitudes, and converted to absolute flux using $d = 800$ pc. We then integrated under this curve to obtain the luminosity, $L$. Errors for $\log(L/L_\odot)$ were determined from the uncertainties in distance and total flux across the three bandpasses. To apportion the apparent magnitudes between the primary and secondary stars, we applied the $H$-band flux ratio, $\alpha$, found in the cross-correlation analysis, to the 2MASS magnitude. Once the component $H$ magnitudes were established, we used the $J-H$ and $H-K$ colors for the relevant spectral types (Tokunaga 2000) to determine the $J$ and $K$ component magnitudes. This yielded a similar result as applying the $H$-band flux ratio from the cross-correlation to all three bandpasses, $J$, $H$, and $K$. The conservative errors adopted on the flux ratios account for the largest source of error when determining the component apparent magnitudes.

We estimated the primary star radii for both systems based on $T_{\text{eff}}$ and luminosity, using $L = 4\pi\sigma R^2 T_{\text{eff}}^4$. The distance was the largest source of error in the luminosity calculations and the luminosity was the largest source of error in the radii calculations. Derived quantities for the components of VSB 111 and 126, such as $L$ and $R$, are shown in Table 9. We repeated this analysis for the primary stars in both systems based on the visible-light parameters as well (Table 9).

With values for the primary star $u \sin i$, radius, and $P_{\text{rot}}$, we used the relation $\sin i = u \sin i \times P_{\text{rot}}/(2\pi R)$ to determine the inclination of the primary star rotation axes ($i_{\text{stellar}}$) with respect to the line of sight. We found 43$^{+14}_{-12}$ for VSB 111 and 49$^{+24}_{-23}$ for VSB 126 based on IR data and 45 ± 5° and 47$^{+9}_{-8}$, respectively, based on the visible-light data. The largest source of error in the visible-light stellar inclination angle for VSB 111 stems from the uncertainty in radius and the largest source of error for VSB 126 stems from the rotation velocity, ±2 km s$^{-1}$. The largest source of error in the IR-determined stellar inclination angles stems from the adopted error on the rotation velocity, ±5 km s$^{-1}$, for both systems. Obtaining more precise values for the distance to VSB 111 and VSB 126 will help reduce the large errors in luminosity, radii, absolute magnitude, and stellar inclination.

### 4. DISCUSSION

#### 4.1. Masses and Ages

To place the components of the systems on the Hertzsprung–Russell (H-R) diagram and estimate the ages and masses of the stars, we tested four sets of PMS evolutionary tracks, by Baraffe et al. (1998), Siess et al. (2000), Dotter et al. (2008), and Tognelli et al. (2011). We used the values of $T_{\text{eff}}$ determined from the IR data, described above and given in Table 9, because the IR analysis successfully detected both SB components. For the Dotter et al. and Baraffe et al. tracks, we plotted absolute $H$ magnitude to determine the stars’ locations in the H-R diagram. For the Siess et al. and Tognelli et al. tracks, we used $\log(L/L_\odot)$. For both components in each system, we used the distance of 800 pc to convert from apparent to absolute $H$ magnitude and to calculate luminosities as described in Section 3.4 (Table 9). Tables 11 and 12 list the results for $M_1$ and $M_2$ as well as the corresponding mass ratios and approximate ages for VSB 111 and VSB 126, respectively. The Dotter et al. tracks are plotted in Figure 7.

The model results for mass are consistent with each other, which is not surprising given the large uncertainties involved in
The spectral type, however, may provide a clue. The Dotter et al. (2008) tracks we find age uncertainties of at least
in the component ages, these results are not significant; for the unrealistically low. However, given the very large uncertainties
light data yield independent values for placing the target components on the H-R diagram. The visible-
Baraffe et al. (1998) tracks (α = 1.9) do not go above 1.4 M⊙.

Table 11
Evolutionary Track Comparisons for VSB 111 (qobs = 0.52 ± 0.05)

| Tracks                      | M₁ (M⊙) | Age (Myr) | M₂ (M⊙) | Age (Myr) | q ± 1σ |
|-----------------------------|----------|-----------|----------|-----------|--------|
| Baraffe et al. (1998)       | ···       | ···       | 0.63 ± 0.10 | <1       | ···    |
| Tognelli et al. (2011)      | 2.3 ± 0.3 | 2 ± 1     | 0.45 ± 0.20 | 0.5 ± 1.0 | 0.2 ± 0.1 |
| Siess et al. (2000)         | 2.1 ± 0.3 | 3 ± 2     | 0.41 ± 0.10 | 0.3 ± 0.5 | 0.2 ± 0.1 |
| Dotter et al. (2008)        | 2.2 ± 0.3 | 2 ± 1     | 0.47 ± 0.15 | <1       | 0.2 ± 0.1 |

Note. * Baraffe et al. (1998) tracks (α = 1.9) do not go above 1.4 M⊙.

Table 12
Evolutionary Track Comparisons for VSB 126 (qobs = 0.29 ± 0.02)

| Tracks                      | M₁ (M⊙) | Age (Myr) | M₂ (M⊙) | Age (Myr) | q ± 1σ |
|-----------------------------|----------|-----------|----------|-----------|--------|
| Baraffe et al. (1998)       | ···       | ···       | 0.28 ± 0.14 | 2 ± 5     | ···    |
| Tognelli et al. (2011)      | 1.7 ± 0.3 | 4 ± 2     | 0.25 ± 0.12 | 2 ± 3     | 0.2 ± 0.1 |
| Siess et al. (2000)         | 1.6 ± 0.3 | 5 ± 3     | 0.17 ± 0.07 | 1 ± 2     | 0.1 ± 0.1 |
| Dotter et al. (2008)        | 1.6 ± 0.4 | 5 ± 4     | 0.24 ± 0.11 | 2 ± 6     | 0.2 ± 0.1 |

Note. * Baraffe et al. (1998) tracks (α = 1.9) do not go above 1.4 M⊙.

placing the target components on the H-R diagram. The visible-
primary star in VSB 111, K0, is significantly warmer than those of the LkCa 3 primaries, which are between K7 and M2 (Torres et al.). The Dotter et al. tracks may thus provide consistent results between stars of lower masses but the higher-mass primaries in the VSB systems possibly span a range of mass tracks for which the results are less homogeneous. This underscores the necessity of testing tracks on a relatively broad sample of systems with a range of masses and mass ratios.

Far more stringent tests of evolutionary tracks would be possible with improvements in the determination of Teff and distance for the stellar components in VSB 111 and VSB 126. Currently, our procedure is to use spectral type standards for the cross-correlation and to identify the young SB components’ spectral types from maximizing the correlation coefficient. Teff is then determined from compilations of spectral type–Teff equivalence, such as those presented in Luhman (1999) and White et al. (1999). To avoid this complication, Torres et al. (2013) adopted the Teff values directly from those assigned by Rojas-Ayala et al. (2012) for several of the template stars used, or from the color/temperature calibrations of Boyajian et al. (2012). In addition to the lack of Teff values for all of our templates from Rojas-Ayala et al. and the lack of colors for the secondary stars in our sample, it is not possible to determine Teff for the primary stars in our sample in this way because they are too hot. Thus, we have followed our standard procedure. With a modest investment of observing time in the future, it would be possible to obtain low-resolution (~2000) K-band spectroscopy and to follow the methodology of Rojas-Ayala et al. and assign Teff values directly to all low-mass (Teff < 4000) stars in our library of template spectra. An alternative approach must be developed for earlier spectral type stars.

The determination of much-improved distance estimates of the target SBs in NGC 2264 is also possible. Combining the angular and physical scales of a system identified as both a visual binary and an SB2 yields an independent distance measurement.
Table 13
Properties of PMS SB2s with \( v_1 \sin i \) Twice as Large as \( v_2 \sin i \)

| System       | \( v_1 \sin i \) (km s\(^{-1}\)) | \( v_2 \sin i \) (km s\(^{-1}\)) | \( e \) | \( q \) | Period (days) |
|--------------|----------------------------------|----------------------------------|--------|------|--------------|
| VSB 111\(^a\) | 30 ± 5                           | 15 ± 5                           | 0.79   | 0.52 | 902.1        |
| VSB 126\(^b\) | 15 ± 5                           | 8 ± 5                            | 0.18   | 0.29 | 12.92        |
| RX J0539.9 + 0956\(^b\) | 80 ± 10                         | 40 ± 5                           | 0.27   | 0.7  | 1118.3       |
| RX J0513.1 + 0851\(^b\) | 60 ± 10                         | 30 ± 5                           | 0.067  | 0.44 | 4.018        |
| EK Cep\(^c\)    | 23 ± 2                           | 10.5 ± 2.0                       | 0.109  | 0.55 | 4.43         |
| Parenago 2494\(^d\) | 22.0 ± 2.5                      | 11.4 ± 2.0                       | 0.257  | 0.71 | 19.48        |
| RX J0441.0 – 0839\(^e\) | 2 ± 1                           | 1 ± 1                            | 0.216  | 0.82 | 13.56        |
| RX J0350.5 – 1355\(^e\) | 19 ± 2                          | 7 ± 1                            | 0.0    | 0.92 | 9.28         |

Notes.
\(^a\) This paper.
\(^b\) Ruíz-Rodríguez et al. (2013).
\(^c\) Landin et al. (2009).
\(^d\) Reipurth et al. (2002).
\(^e\) Covino et al. (2001).

For the 902 day period binary VSB 111, Very Long Baseline Array (VLBA) interferometry permits spatial mapping of the binary orbit and will be possible if at least one of the components is a sufficiently strong radio source (\( \gtrsim 0.5 \) mJy), which is likely given that VSB 111 has a large X-ray flux (Dahm et al. 2007). Based on the orbital period and the total binary mass determined from the Dartmouth tracks (Figure 7), and assuming a distance of 800 pc, the average stellar separation is \( \sim 3 \) mas, easily resolvable by the 0.8 mas FWHM VLBA beam at 8 GHz (4 cm). For VSB 126, Gaia is sufficiently sensitive (standard errors of 15–20 \( \mu \)as for the \( V = 13.4 \) mag of VSB 126; de Bruijne 2012) to resolve the orbit: based on the total mass estimated from the Dartmouth tracks, the period, and \( d = 800 \) pc, the average stellar separation of VSB 126 is 165 \( \mu \)as. Gaia is scheduled for a 2013 December launch.

4.2. Rotational Velocities

Based on the IR analysis, VSB 111 has a primary rotational velocity of 30 km s\(^{-1}\) with a secondary rotational velocity of 15 km s\(^{-1}\) and VSB 126 has a primary rotational velocity of 15 km s\(^{-1}\) and a secondary rotational velocity of 8 km s\(^{-1}\) (Table 9). These are consistent to within 1 \( \sigma \) of the primary star \( v \sin i \) values found in the visible-light analysis (Section 3.1). We searched the literature for other \( v \sin i \) measurements in PMS SB2s (e.g., Ruiz-Rodríguez et al. 2013; Landin et al. 2009; Reipurth et al. 2002; Covino et al. 2001) and found \( \sim 35 \) systems for which the \( v \sin i \) values of both SB2 components have been measured. Half of these systems are isolated and half are in young clusters. We examined the ratio \( v_1 \sin i \) to \( v_2 \sin i \) as a function of mass ratio, orbital period, and eccentricity and found that eight systems have a primary star \( v \sin i \) value about twice as great as the secondary \( v \sin i \) value, including VSB 111 and 126 (Table 13). For the remainder of the systems examined, the ratio was close to unity. There were no obvious correlations found when comparing this ratio to \( e \), \( q \), and the orbital period. This result might suggest that rotational evolution between the \( v \sin i \) ratio of \( \approx 2 \) and a ratio of \( \approx 1 \) takes place rapidly, or it may simply be the outcome of observational bias and/or imprecise assignation of \( v \sin i \) values. A comparable sample of \( v \sin i \) values for main sequence SB2s from Goldberg et al. (2002) showed no preferential distribution in the primary to secondary \( v \sin i \) ratio. Given the large uncertainties associated with most of the young star \( v \sin i \) values from the literature, as well as with our IR results for VSB 111 and VSB 126, i.e., \( \pm 5 \) km s\(^{-1}\), the odd distribution of \( v \sin i \) ratios in young SBs is unlikely to be significant.

4.3. Additional Orbital Properties

We used the model tracks shown in Figure 7 and estimated the mass and associated uncertainties for each star in each binary (Tables 11 and 12). Given the values for \( M_1 \sin^3 i \) and \( M_2 \sin^3 i \) determined in the orbital fit for each SB2 (Table 10), we combined these to estimate \( i_{\text{orb}} \) as illustrated in Figures 8 and 9 for VSB 111 and 126, respectively (Prato et al. 2001; Mace et al. 2012). From these plots we find that for VSB 111 \( i_{\text{orb}} = 48^\circ \) and for VSB 126 \( i_{\text{orb}} \) is between 36\(^\circ\) and 39\(^\circ\).
However, with facilities such as the VLBA and the Gaia mission, due for launch late in 2013, it will be possible to map out these orbits and to determine the relative orientation of the orbital plane with respect to the stellar equatorial plane. These relative orientations are important for understanding the dynamics of star–orbit interactions, which may in turn shape the planet formation and evolution environment. By directly and accurately measuring the orbital inclination, it will also be possible to derive the model-independent absolute component masses directly.

4.4. NGC 2264

The locations of VSB 111 and 126 are separated by ~0.02 pc in right ascension and ~1.9 pc in declination, assuming an 800 pc distance to NGC 2264. VSB 111, with $\gamma = 25.31$ km s$^{-1}$ (Table 10), lies very close to the core of a $^{13}$CO cloud, as determined from visual inspection of Figure 1 from Fűrész et al. (2006). VSB 126, with $\gamma = 17.16$ km s$^{-1}$ (Table 10), does not appear to be associated with any cloud cores. If VSB 111 is actually associated with this cloud core, this location is consistent with VSB 111 being younger than VSB 126, as suggested by Figure 7.

Both $\gamma$ velocities for VSB 111 and VSB 126 fall within the cluster distribution range for membership: Fűrész et al. (2006) found that NGC 2264 is hierarchically structured with respect to the stellar equatorial plane. The Astronomical Journal

3.3. Stellar Rotation Periods

Our analysis indirectly provided additional physical properties for both stars in each SB2, such as $T_{\text{eff}}$, binary flux ratio, luminosity, and $v \sin i$. These results in turn allowed us to place both stars in each binary on an H–R diagram for comparison with model calculations of PMS evolution, effectively testing the evolutionary tracks against our dynamical results. By using the model-determined masses, we estimated the binaries’ orbital inclinations; we also found the inclination angles of the primary stars’ equatorial planes. With observations of the angularly resolved orbits of these NGC 2264 members, through VLBI and Gaia, the dynamical determination of the orbital inclination and orientation (i.e., the nodal angle) will be possible. These measurements in turn yield the absolute component masses, distance to the system, and the relative inclinations of the primary stars with respect to the orbital planes.

Determining the spectroscopic orbital solutions for these two young SB2s us closer to our immediate goal of significantly increasing the number of such systems in order to better understand and improve models of binary star formation, and to help anchor theoretical evolutionary tracks with solid dynamical data.

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5. SUMMARY

High-resolution IR spectra were obtained for the young SBs VSB 111 and VSB 126 in NGC 2264 and combined with visible-light spectra. One- and two-dimensional cross-correlation was used to obtain the RVs and orbital parameters for these systems. VSB 111 has a period of ~902 days, an eccentricity of 0.79 ± 0.01, and a mass ratio of 0.52 ± 0.05, while VSB 126 has a period of ~12.9 days, an eccentricity of 0.18 ± 0.02, and a mass ratio of 0.29 ± 0.02. The eccentricity of VSB 111 is the second highest known for a PMS SB2 measured to date (Mace et al. 2009). We determined the stellar rotation periods for the primary components of both systems, ~4 and ~6 days for VSB 111 and VSB 126, respectively.

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