STARSPOT-INDUCED RADIAL VELOCITY VARIABILITY IN LkCa 19

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ABSTRACT

We describe a new radial velocity survey of T Tauri stars and present the first results. Our search is motivated by an interest in detecting massive young planets, as well as investigating the origin of the brown dwarf desert. As part of this survey, we discovered large-amplitude, periodic, radial velocity variations in the spectrum of the weak-line T Tauri star LkCa 19. Using line bisector analysis and a new simulation of the effect of starspots on the photometric and radial velocity variability of T Tauri stars, we show that our measured radial velocities for LkCa 19 are fully consistent with variations caused by the presence of large starspots on this rapidly rotating young star. These results illustrate the level of activity-induced radial velocity noise associated with at least some very young stars. This activity-induced noise will set lower limits on the mass of a companion detectable around LkCa 19 and similarly active young stars.

Subject headings: planetary systems: formation — stars: activity — stars: individual (LkCa 19) — stars: pre–main-sequence

1. INTRODUCTION

The first successful detection produced by radial velocity surveys of a planet orbiting a star occurred in 1995 when a near-Jupiter-mass planet was found around the main-sequence star 51 Pegasus (Mayor & Queloz 1995). Subsequent observations verified the existence of the companion and refined its orbital parameters (Marcy & Butler 1995; Marcy et al. 1997). By 2007, over 200 planetary systems had been discovered via the radial velocity method, and the statistics of various properties of the planets had been cataloged (Butler et al. 2006).

Most radial velocity surveys have been conducted on main-sequence stars typically older than 1 Gyr. The use of the radial velocity method on younger stars is challenging because of increased activity, specifically in the form of signals caused by starspots. Spots on the surface of the star rotate in and out of view of the observer, potentially creating spurious radial velocity signatures.

Paulson et al. (2004) looked for planetary companions to stars in the Hyades (\( \sim \)790 Myr). They found activity-induced jitter consistent with the empirical relationship between activity and radial velocity described in Saar & Donahue (1997). Paulson et al. (2004) also found one binary (\( K = 1152 \text{ m s}^{-1} \)) and two candidate binaries with linear velocity trends, but no planetary companions. More recently, Paulson & Yelda (2006) examined 61 stars in the \( \beta \) Pic moving group (\( \sim \)12 Myr) and the Ursa Majoris association (\( \sim \)300 Myr) and found no Jupiter-mass planets in short-period orbits. The authors found these results unsurprising, as planetary companions are rare around main-sequence stars with the small orbital separations (\(<0.1 \text{ AU}) these surveys were able to probe. They measured maximum radial velocity amplitudes of 30–100 m s\(^{-1}\) for targets in Ursa Majoris and 250–600 m s\(^{-1}\) for targets in \( \beta \) Pic.

These searches were motivated, as is ours, by an interest in understanding the formation of both stellar and planetary systems. By probing the youngest stars for planetary companions, we can learn at what stage planets form. Since the timescale for the core accretion model (Pollack et al. 1996) is longer than formation due to disk instability (Boss 1997), a detection of a young planet around a T Tauri star should also provide clues to the formation mechanism itself. We can also explore the level of stellar activity in young stars and how this can affect our ability to measure radial velocity variations and therefore detect planets. Recently, Setiawan et al. (2007) reported the detection of a planet around the 100 Myr star HD 70573.

An additional motivation to search for companions around young stars is to understand the origin of the so-called brown dwarf desert. As more planetary companions were discovered in the last decade and the completeness of the surveys increased, Marcy & Butler (2000) noted the dearth of substellar objects with masses greater than 20 \( M_{\text{Jup}} \) in close orbits (\( \leq 3 \text{ AU} \)). This “brown dwarf desert” was further quantified by Grether & Lineweaver (2006), who analyzed an unbiased sample of nearby Sun-like stars to measure the rate of stellar, brown dwarf, and planetary companions. They found that \( \sim 16\% \) of their sample stars had close (\( P < 5 \text{ yr} \)) companions with masses greater than that of Jupiter. Of these, 11\% \( \pm \) 3\% were stellar, 1\% were brown dwarfs, and 5\% \( \pm \) 2\% were giant planets, where a brown dwarf is defined as an object in the mass range between 13 and 80 \( M_{\text{Jup}} \).

Armitage & Bonnell (2002) suggested that the kinematic viscosity of a sufficiently massive circumstellar disk could cause brown dwarfs in close orbits, interacting dynamically with the
disks, to catastrophically migrate toward the host star and be lost to mergers. They predict that young stars should have an order of magnitude more brown dwarfs in close orbits than main-sequence stars, as the timescale for catastrophic migration is \( \sim 1 \) Myr. A search for substellar companions around T Tauri stars could confirm or refute this scenario, improving our understanding of the brown dwarf desert in older stars.

In this paper we summarize our spectroscopic and photometric observational techniques for our sample of T Tauri stars and report a detection of periodic radial velocity variations in the weak-line T Tauri star LkCa 19, for which we have a large number of observations. LkCa 19 has \( \varepsilon \sin i = 18.6 \pm 1 \) km s\(^{-1}\) (Hartmann et al. 1987) and spectral type K0 (Herbig & Bell 1988). LkCa 19, with its short rotation period of 2.24 days (Bouvier et al. 1993), provides an excellent example of the effects of starspots on radial velocity measurements. Using new simulations, we show that the radial velocity properties of LkCa 19 are well modeled by the presence of one large spot.

### 2. SAMPLE, OBSERVATIONS, AND DATA REDUCTION

#### 2.1. Sample

Our total sample consists of 100 young stars in the Taurus star-forming region and the Pleiades open cluster with a \( V \) magnitude range from 9 to 15. Approximately one-third of the Taurus objects are classical T Tauri stars, with the remainder being weak-line T Tauri stars. Stars in the Pleiades and a subsample of our Taurus objects were observed as part of the Space Interferometry Mission (SIM) PlanetQuest precursor science program. These observations will identify Jupiter-mass and greater spectroscopic companions; these systems will be excluded from the SIM target list.

Most targets were observed at least once per observing run, weather permitting. A subset of targets were selected for observation on each night of every observing run. Since rotation periods for T Tauri stars are typically 10 days or less, this was done to quantify the radial velocity variability of a subsample and to understand the possible sources of error and velocity jitter, such as starspots or other sources of activity (e.g., accretion).

#### 2.2. Observations: Spectroscopy

In 2004 we began a radial velocity survey to search for planets and brown dwarfs around a sample of T Tauri stars using the coudé echelle spectrograph (Tull et al. 1995) on the 2.7 m Harlan J. Smith Telescope at McDonald Observatory. The spectrograph yields \( R = \Delta \lambda / \lambda = 60,000 \) with a 1.2" slit. Observations at the 2.7 m Harlan J. Smith Telescope were taken in 2004 November, 2004 December to 2005 January, 2005 November, and 2006 February. The Julian Dates of these observations are listed in Table 1. Current high-precision radial velocity surveys routinely achieve velocity precision of \( \sim 3 \) m s\(^{-1}\) (e.g., Butler et al. 1996), usually by the use of an iodine cell to superimpose calibration absorption lines onto the stellar spectrum. However, because we expect T Tauri stars to have intrinsic radial velocity noise considerably higher than this due to photospheric activity such as spots (e.g., Paulson et al. 2004; Paulson & Yelda 2006), we did not require such high-precision measurements. We made use of thorium-argon lamps taken before and after each object. This method also avoids contaminating the spectra with iodine absorption lines.

#### 2.3. Observations: Photometry

We obtained near-simultaneous differential CCD photometric observations of LkCa 19 beginning in December of 2004. The purpose of these observations was to look for any concurrent photometric variability and to see if any signal in the photometry was also present in the radial velocity variations. Photometric variability in weak-line T Tauri stars such as LkCa 19 is believed to originate in dark starspots moving in and out of view as the star rotates. The resulting false radial velocity modulation shows a quarter-phase offset between the photometric and radial velocity light curves (Queloz et al. 2001). A substellar companion around a T Tauri star should not produce a photometric signature, assuming there is no planetary transit.

Photometry was obtained using the prime-focus corrector (Claver 1995) on the 0.8 m telescope at McDonald Observatory. Our observations were taken through Bessel \( V, B, \) and \( R \) photometric filters. The field of view for the images was \( 42.6'' \times 42.6'' \). Integration times ranged from 3 to 300 s.

### 2.4. Data Reduction

#### 2.4.1. Spectroscopy

All data reduction, including wavelength calibration, was performed using standard echelle spectral reduction routines in IRAF. The raw spectra were bias-subtracted and flat-fielded using the normalized spectrum of an internal lamp. Optimal extraction to remove cosmic rays and improve signal-to-noise considerably higher than this due to photospheric activity was used on all targets except for the bright radial velocity standards. The dispersion solution was derived from the time-weighted average of thorium-argon lamps taken both before and after each image. Individual thorium-argon lamps had lines identified visually and calibrated using the NOAO spectral atlas database. We used 7–10 hand-chosen lines per order across \( \sim 15 \) orders of the total spectrum for the dispersion solution. The final fit was done in both the dispersion and cross-dispersion axis and had a typical rms value of about 0.002 pixels, or \( 4 \) m s\(^{-1}\), which is a negligible source of error for this program.

The RVSAO package in IRAF was used to determine the radial velocities. IDL was used to further analyze and visualize the radial

| JD         | Radial Velocity \((\text{m s}^{-1})\) | Error \((\text{m s}^{-1})\) | S/N |
|------------|-------------------------------------|----------------|------|
| 2,453,367.8252 | 2193.6                             | 190.5            | 81.6 |
| 2,453,369.6507 | 1995.0                             | 141.2            | 87.6 |
| 2,453,370.8191 | 540.5                              | 141.0            | 52.0 |
| 2,453,371.6180 | 1381.4                             | 147.9            | 76.1 |
| 2,453,372.6210 | 1092.6                             | 153.4            | 27.5 |
| 2,453,373.7105 | 1095.8                             | 175.4            | 77.6 |
| 2,453,374.7654 | 1213.0                             | 331.5            | 35.4 |
| 2,453,375.6835 | 684.5                              | 186.8            | 59.7 |
| 2,453,693.8006 | 1780.0                             | 168.4            | 54.2 |
| 2,453,694.8526 | 1193.0                             | 208.9            | 58.4 |
| 2,453,695.7514 | 1160.2                             | 202.6            | 71.3 |
| 2,453,696.7825 | 1555.0                             | 140.5            | 81.5 |
| 2,453,697.7609 | 451.8                              | 151.4            | 78.5 |
| 2,453,769.5967 | 309.0                              | 140.4            | 66.5 |
| 2,453,769.7395 | 803.8                              | 158.5            | 58.5 |
| 2,453,770.5880 | 2041.2                             | 195.8            | 60.8 |
| 2,453,770.7327 | 1924.2                             | 182.8            | 69.2 |
| 2,453,771.6556 | 192.6                              | 280.6            | 54.0 |
| 2,453,771.8006 | 505.7                              | 140.4            | 46.6 |
| 2,453,772.5921 | 2052.0                             | 163.2            | 57.8 |
| 2,453,773.5887 | 105.4                              | 144.7            | 64.5 |
| 2,453,773.7526 | 0.0                                | 121.0            | 57.7 |
| 2,453,775.6523 | 743.8                              | 148.4            | 57.7 |
| 2,453,775.7981 | 307.7                              | 164.7            | 63.2 |
velocity data. The xcasao task in the RVSAO package was performed on the extracted and wavelength-calibrated spectra to determine the radial velocities. This routine is a Fourier-based cross-correlation program, described in detail by Kurtz & Mink (1998). Cross-correlation is a powerful tool when coupled with large spectral ranges to determine precise radial velocities. We performed cross-correlation using several echelle orders, with each order covering approximately 100 Å. In order to avoid spectral-type mismatching, we used the target star itself as the template for the cross-correlation. Therefore, our velocities are measured relative only to one observation epoch. A spectrum with relatively high counts and minimal cosmic-ray contamination was chosen to be the template.

2.4.2. Photometry

Photometric data reduction followed standard procedures using IRAF, including bias correction, overscan correction, and flat-fielding. Stellar objects were identified with the DAOPHOT package within IRAF, and then aperture photometry was used on all stars in the field. The error in the photometry was estimated by selecting a background star (or several) and looking at the standard deviation of that star over all observations. Such stars should show no photometric variability, and any scatter in their measurements provides an easy estimate of the accuracy of the photometry. This error is ~0.01 mag.

3. ANALYSIS

3.1. Radial Velocity Uncertainties

In order to gain a better understanding of the accuracy of our radial velocity technique, we observed six radial velocity standard stars, selecting objects from Nidever et al. (2002), Butler et al. (1996), and Cumming et al. (1999). By measuring radial velocities of these targets each night of each observing run, we estimate the systematic errors and the accuracy of the radial velocity measurements with our instrumental setup. We observed three bright standard stars in the third to fourth V magnitude range, in addition to three fainter objects around sixth to seventh V magnitude. These standard stars were reduced and analyzed in the same way as our target stars, using one epoch of the standard star itself as the cross-correlation template. Within a given run, we obtained very low radial velocity scatter; however, there are systematic effects between runs that appear in the observations of our standard stars.

Figure 1 shows radial velocity measurements for our three bright standard stars. Each standard shows a distinct systematic offset between the several observing runs. Simple explanations do not account for this systematic error; the residuals in the dispersion solution look very similar in each run, and we accounted for the motion of the earth itself. We suspect the likely cause of the offset is the resetting of the slit plug from one observing run to the next, which could alter the position of the slit relative to the optical axis of the telescope and the thorium-argon lamp. However, even with this systematic error uncorrected, the overall scatter of the standard stars remains ~120 m s\(^{-1}\) (see Table 2), which we believe is our nominal level of precision. The final error listed in Table 1 is the sum in quadrature of this systematic error and error estimated from the order-to-order scatter in the measured radial velocities of LkCa 19.

3.2. Detection of Periodic Signals

Our T Tauri targets have considerably larger radial velocity variations, with standard deviations in the range of ~200–3000 m s\(^{-1}\), than the radial velocity standards. LkCa 19 shows radial velocity variation with a standard deviation of ~670 m s\(^{-1}\), which is about 6 times higher than our nominal radial velocity standard.

For targets with a significant number of observations, such as LkCa 19, we analyzed the data to look for any periodic variations of the radial velocity measurements. This was done with an IDL implementation of the Scargle method of power-spectrum estimation (Scargle 1982). This method is best suited for our data, as it does not require the data to be evenly spaced in time. The LkCa 19 power spectrum is shown in Figure 2.

Once the initial power spectrum was computed over a wide range of periods, the power spectrum was computed again with dense sampling in order to resolve the strongest peak and determine the best period, which we found to be 2.177 days with an uncertainty of 0.0264 days. We then used the period to phase-fold

| Table 2: Radial Velocity Standards Observed |
|---|---|---|
| Star | \(N\) | \(V\) Magnitude | Standard Deviation\(^a\) (m s\(^{-1}\)) |
| 107 Psc | 20 | 5.2 | 100 |
| HD 4628 | 20 | 5.75 | 129 |
| \(\tau\) Ceti | 19 | 3.50 | 184 |
| HD 65277 | 15 | 8.12 | 110 |
| HD 80367 | 19 | 8.16 | 107 |
| HD 88371 | 18 | 8.43 | 132 |

\(^a\) Includes systematic error seen in Fig. 1.
alarm probability (FAP) of less than 10^−5 indicates a high significance of this period detection and a false analysis than was present in the actual LkCa 19 data. This in-locity data had a peak as strong or stronger in its power-spectrum our actual observations. None of these instances of random ve-dom data sets were analyzed using the same temporal cadence as distributed random radial velocities with overall velocity scatter velocity data. For LkCa 19, 100,000 simulated sets of normally was accomplished with a Monte Carlo simulation of our radial ascertain the true significance of the detection of a period. This eval-uated (Fig. 3).

LkCa 19 shows periodic radial velocity variations with a period of 2.177 ± 0.0264 days. However, this period is very near the 2.24 day rotation period of LkCa 19 (Bouvier et al. 1993), suggest-ing that the observed signal is not the result of orbital motion. Additional periods in the power function occur near 2.238 and 2.251 days, which are near the power of the strongest peak at 2.177 days. This is an additional indication that we are observ-ing the rotation period of the star. The application of a correction for the systematic effects seen in Figure 1 produced no noticeable change in the Scargle periodogram of LkCa 19 and no change in any of the detected periods.

3.3. Bisector Analysis

Bisector analysis of line profiles was first suggested by Gray (1976) as a means to quantify the asymmetry of a specific absorption or emission line. Bisector analysis as a means to check on the origin of radial velocity variations started with analysis of the original extrasolar planet 51 Pegasus (Hatzes et al. 1997). The method was used subsequently by Queloz et al. (2001) to look for a correlation between the slope of the bisectors of the spectrum’s cross-correlation function (CCF) and the measured radial velocity of the star. Similar analysis was done by Martı´nez Fiorenzano et al. (2005) on several potential extrasolar planets and by Bouvier et al. (2007) to test the origin of apparent radial velocity variations in the T Tauri star AA Tau. We performed bisector analysis on the CCF used to measure the radial velocity shift from one observation to another to test whether spots might be the cause of the observed radial velocity variations in LkCa 19.

3.4. Photometric Analysis

Photometric observations were obtained nearly simultaneously with our spectra of LkCa 19 to further aid the interpretation of any radial velocity variations. The photometric light curves and any periodicity can be compared to the radial velocity curves and detected periods.

A FORTRAN code provided by J. Anderson was used to analyze the multiple exposures over many nights and to create light curves for our target stars. The photometric zero point was determined using a σ-clipped average of all the stars in the field. The photometry was phase-folded using the radial velocity period found in § 3.2. Furthermore, the photometry was analyzed to look for other periodicity.

We analyzed 41 R-band photometric points for LkCa 19, which are binned into nightly averages producing 17 photometric
measurements. On any given night, the $R$-band images were taken within $\pm 20$ minutes of each other. The data points, phased to the radial velocity period of LkCa 19, are plotted in Figure 7. The photometry does not appear in phase with the radial velocity signal. A Scargle power-spectra analysis for our photometry yields a period of 2.05575 days. However, this photometric period determination does not withstand Monte Carlo test scrutiny, and the FAP for the 2.05575 day LkCa 19 photometric period is 40%. The poor strength of this period is likely due to the smaller number of measurements compared to the radial velocity data and the greater noise in the photometric measurements compared to the amplitude of the photometric variability. This period, however, is close to both the detected radial velocity period and the known 2.24 day rotation period of LkCa 19 (Bouvier et al.

**Fig. 4.** — *Left:* CCF and its bisector. The dotted line connects opposite sides of the CCF curve; the midpoint of this line represents one of the points of the bisector. *Bottom left:* Two mean velocities are computed, one in the upper region denoted by the dashed lines and another between the dotted lines. The bisector span is the difference between these two velocities. *Right:* Four bisectors for LkCa 19 at opposite phases of the radial velocity curve. The changing asymmetry of the profile is noticeable. Dotted lines indicate the CCF power ranges in which the span is measured.

**Fig. 5.** — *Left:* LkCa 19 bisector analysis. The radial velocity and bisector appear to be correlated, with a linear correlation coefficient of $-0.73$. The slope is consistent with the spot-induced radial velocity variations of Queloz et al. (2001). *Right:* HD 68988 bisector analysis. No correlation is found.
1993). The peak-to-peak amplitude in the $R$ band is 0.12 mag. We observed the same amplitude in the $V$ band; however, in the $B$ band the peak-to-peak amplitude is larger at 0.18 mag.

### 4. STARSPOT MODELS

#### 4.1. Conceptual Framework

The goal of our starspot modeling was to test the hypothesis that at least some of the radial velocity signatures observed in T Tauri stars can be attributed to the star’s rotation combined with the presence of low-temperature spots on the surface of the star. In order to test these assumptions, it is necessary to numerically replicate the effect of starspots on a synthesized stellar spectrum.

To accomplish this task, a stellar-disk integration model was constructed. The apparent stellar disk is divided into sections, allowing for portions to be at a lower temperature and therefore lower intensity than the rest of the star, with appropriately different spectral features. With the modeled stellar disk divided between a stellar spectrum at one effective temperature and one or more localized spots at a lower temperature, an integrated spotted-star spectrum can be created and analyzed in the same manner as the observed stellar data. This modeling involved integrating an artificial stellar disk, with control over the location and size of spots on the apparent disk, and was implemented in IDL.

In order to construct the apparent stellar disk of a star containing spots, it was necessary to first synthesize appropriate spectra for both the star and the spot. The input spectra were produced using the Spectroscopy Made Easy (SME) code of Valenti & Piskunov (1996). We chose a 100 Å bandpass near 6300 Å, similar to one of the echelle orders in our actual data. The SME synthesis code utilized NextGen atmospheric models (Allard & Hauschildt 1995) and a line list from the Vienna Atomic Line Database (VALD). The dispersion of the artificial spectra was 0.02 Å pixel$^{-1}$, with the input and output spectra having 5000 pixels. The stellar temperature was chosen to be 4300 K and the spot temperature 2900 K, based on observations and modeling of V410 Tau (Petrov et al. 1994). This produced a brightness ratio between the spots and the stellar surface of 0.08.

Spots were defined by the colatitude and longitude of the spot center and the radius of the spot. The spot’s projected shape and location on the stellar disk were used to trigger the integration routine to use the lower temperature and intensity spot spectrum...
rather than the standard stellar spectrum when the given portion of the stellar disk is included. Each grid point of the star that was deemed to be inside the spot was assigned the cooler, dimmer spot spectrum. In addition, each grid point had the corresponding radial velocity shifts based on the rotation of the star. Therefore, Doppler broadening of the line profiles was handled within the disk integration itself. Stellar limb-darkening was handled by using the appropriate SME spectra for multiple limb angles. The disk integration’s output was tested against the disk integration output of the SME code—a star with no spots—and correctly returned a spectrum identical to the output of the original SME disk integration.

4.2. Analysis of Simulated Spectra

The simulation produced a series of spectra, which were then read into IRAF and analyzed for radial velocities in a manner identical to the actual observations. Because the relative spectral fluxes are preserved, the IRAF bandpass spectrophotometry task sbands was used on a continuum region of the spectrum to estimate the photometric variations of the star due to the spots, using a wavelength bandpass 1 Å wide centered at 6235.5 Å.

Twenty synthesized spectra were created representing 20 evenly spaced rotation steps of 18° and thus one complete stellar rotation. Each spectrum was cross-correlated against a template synthetic spectrum of the same $v \sin i$ but without any starspots. The primary difference in the model analysis was that, without multiple echelle orders, we could not estimate the radial velocity error from the order-to-order scatter. The artificial spectra were otherwise run through the same analysis as the actual data, although they were not rebinned or resampled to the resolution of the observations, nor was any noise added. The RVSAO package was used to compute the velocities of the simulated spectra, and the bisector analysis was performed in the same manner as for the actual stellar data.

The simulation code can be used with a variety of stellar spot configurations, ranging from a simple equatorial spot on an un-inclined star, to a polar spot on a star with a tilt, to a multipolar configuration, or any combination of the above. This wide range of possibilities led to the question of which scenarios to simulate and whether any of them could reproduce the magnitude of radial velocity variations seen in our program stars. We discuss three specific cases. All of the computations were done with a $v \sin i$ value of 20 km s$^{-1}$, which is near the value for LkCa 19, unless otherwise noted.

4.2.1. A Circumpolar Spot

A single equatorial spot will yield a flat radial velocity curve while the spot is on the opposite side of the star from the observer. In order to produce, with a single spot, a radial velocity curve that shows persistent amplitude modulation over time, it is necessary for the spot to always be visible to the observer. Therefore, a spot close to the pole of the star, with the star inclined toward the observer, has been chosen as a simple geometry to model. In this case, the spot has a colatitude of 40° and a radius of 15°; the stellar inclination is 35°. Several Doppler imaging surveys have found polar and near-polar spots (e.g., Strassmeier et al. 1994; Joncour et al. 1994; Johns-Krull & Hatzes 1997; Unruh et al. 2004). The circumpolar-spot rotation sequence is illustrated in Figure 8.

The photometric light curve and the radial velocity curve are shown in Figure 9. This spot configuration produces a radial
Fig. 9.—Radial velocity and photometric curves for the single circumpolar spot (left) and the corresponding bisector span vs. radial velocity plot (right).

Fig. 10.—Rotation sequence of 15 random spots; $i = 86^\circ$. 
velocity curve that varies continuously and has an equally regular photometric curve. For this spot the photometric variation is at most 0.086 mag, and the full radial velocity amplitude is $1820 \, \text{m s}^{-1}$. We adopt a maximum flux-weighted filling factor for the spot following O’Neal et al. (1996), who define the flux-weighted filling factor as the total fractional projected area of spots on the observed hemisphere weighted by limb-darkening. This is readily computed via our disk integration code and is 9.1% compared to the predicted values of 8.7% of Saar & Donahue (1997) and 6.4% of Hatzes (2002). Both papers contain an empirical relationship between the related filling factor, radial velocity amplitude, and $v \sin i$.

4.2.1.15 Random Spots

In addition to a simple one-spot model, we performed a simulation that involves many spots, randomly distributed, with the star at a random inclination. The random spot distribution was accomplished using the randomu task in IDL to produce 15 uniformly randomly distributed colatitude and longitude pairs. The sizes of the spots were fixed, with five spots each of three different sizes (Fig. 10).

Models with multiple spots of different sizes produced very different radial velocity and photometric light curves (Fig. 11) than the simpler one-spot model. The bisector analysis demonstrates the intrinsic scatter of the bisector span–radial velocity correlation. The trend observed in this simulation is consistent with the correlation seen in LkCa 19. The most significant feature of this simulation is the amplitude of the radial velocity curve, roughly $1200 \, \text{m s}^{-1}$, and the amplitude of the photometric measurements, $\sim 0.1 \, \text{mag}$.

4.3. The Relationship between Photometric and Radial Velocity Amplitude

The results from the three example spot simulations, along with other spot geometries not described here in detail, prompted an inquiry into the relationship between the photometric amplitude...
We have also presented a new simulation of the effects of a rotating star with spots on line profiles and measured the radial velocities and photometric variations from spectra produced by the simulation. The models can reproduce the photometric and velocity amplitudes of LkCa 19. All simulations show a strong and significant bisector correlation, summarized in Table 3. Further, each spot simulation shows a 0.25 lag in phase between photometry and radial velocity, regardless of spot configuration, which is expected for cool spots.

The spot geometry with the most regular or planet-like radial velocity curve is that of a single spot near the pole of a star with a low inclination angle. A highly spotted star with the spots set randomly on the stellar surface produces much more irregular radial velocity and photometric light curves.

If the magnitude of the photospheric activity–induced radial velocity variations of LkCa 19 is typical of young stars, then our ability to find companions to these objects will be limited to the extremely massive and short-period substellar companions. LkCa 19 has an exceptionally short rotation period and relatively high $v\sin i$ value, which offers some hope that its spot-induced radial velocity variations are not necessarily typical for T Tauri stars.

We made use of IDL libraries available from the NASA Goddard Space Flight Center and the John Hopkins/Advanced Physics Lab/Space Oceanography group, as well as IRAF, originally from the National Optical Astronomy Observatory and now maintained by the volunteers at http://iraf.net/. Jay Anderson provided very helpful assistance with the photometric reduction and useful discussions regarding the spot simulation code. The authors are grateful to the anonymous referee for useful comments. This research also made use of NASA’s Astrophysics Data System. M. H. was partially supported by NSF Cooperative Agreement HRD-0450363 as a part of the Rice University Alliance for Graduate Education and the Professoriate (AGEP) Program. Additional support was provided through NASA grant 05-SSO05-0086 to Lowell Observatory (PI: L. Prato) and from the Space Interferometry Mission Key Project, A Search for Young Planetary Systems and the Evolution of Young Stars (PI: C. Beichman).

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### TABLE 3

| Object                  | Spearman $\rho^a$ | Two-Sided Significance | Linear R |
|-------------------------|-------------------|------------------------|----------|
| LkCa 19                 | -0.79             | $3 \times 10^{-5}$     | -0.73    |
| Simulation (15 spots)   | -0.94             | $1.4 \times 10^{-9}$   | -0.93    |
| Simulation (1 circumpolar spot) | -0.96         | $8.6 \times 10^{-12}$  | -0.92    |

* $^a$ Rank statistic.
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