KH 15D: A Spectroscopic Binary [1]

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ABSTRACT

We present the results of a high-resolution spectroscopic monitoring program of the eclipsing pre–main-sequence star KH 15D that reveal it to be a single-line spectroscopic binary. We find that the radial velocity is variable with an observed range of 10.7 km s^{-1}. The best-fitting Keplerian model has an orbital period $P = 48.38$ days, which is nearly identical to the photometric period. Thus, we find the best explanation for the periodic dimming of KH 15D is that the binary motion carries the visible star alternately above and below the plane of a circumbinary disk, as recently proposed by Winn et al. (2004) and Chiang & Murray-Clay (2004). We show that the mass ratio expected from models of PMS evolution, together with the mass constraints for the visible star, restrict the orbital eccentricity to $0.68 \leq e \leq 0.80$ and the mass function to $0.125 \leq F_M/\sin^3 i \leq 0.5$ $M_\odot$.

1. Introduction

KH 15D is a K6-K7 pre–main-sequence star that exhibits dramatic photometric variability (Kearns & Herbst 1998). Every 48.35 days, the star's brightness dims by 3.5 magnitudes

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[1]Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the University of California and the California Institute of Technology; Las Campanas Observatory of the Carnegie Institution with the Magellan II Clay telescope ; and McDonald Observatory of the University of Texas at Austin.

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and remains in this faint state for nearly half of the photometric period. These deep brightness minima are accompanied by a slight blueing of the star's color indices (Herbst et al. 2002, hereafter He02), little or no change in spectral type (Hamilton et al. 2001) and an increase in linear polarization (Agol et al. 2004). This implies that the star is completely eclipsed by an optically thick, extended collection of dust grains, possibly in the form of a circumstellar disk. If this is the case, the serendipitous alignment of the KH 15D star/disk system may provide insights into the evolution of young stars and their interactions with their circumstellar environments.

While KH 15D has periodic eclipses, it cannot be an ordinary eclipsing binary because of the long duration of minimum light. Recent theories postulate that the eclipses are nonetheless due to an unseen binary companion. He02 first suggested the possibility of a binary companion and in a study of archival photographic plates, Johnson & Winn (2004, hereafter JW04) discovered that the historical lightcurve of KH 15D is similar to the modern light curve but appears to be diluted by light from a second star. Motivated by these findings, Winn et al. (2004, hereafter W04) constructed a model composed of a binary system with the orbital plane inclined with respect to the edge of an optically thick screen. As the two stars orbit one another, the reflex motion carries one star above and below the edge of the screen, causing the eclipses. The long-term evolution of the light curve is reproduced by allowing the screen to move slowly across the binary orbit. A similar model was proposed by Chiang & Murray-Clay (2004, hereafter CM04) who envision the opaque screen as an inclined, nodally-precessing, circumbinary ring. Both models provide explanations of the unique features of KH 15D's light curve. The W04 model makes quantitative predictions about the orbital parameters of the binary system, while the CM04 model provides a physical description of the circumbinary ring.

A fundamental question that has not yet been answered is whether or not KH 15D is a single or multiple stellar system. He02 (see also Hamilton et al. 2003, hereafter Ha03) first searched for evidence of orbital companions using high-resolution VLT spectra and reported a radial velocity change of $+3.3 \pm 0.6$ km s^{-1} over two widely spaced epochs. However, one of the measurements was during egress when there was the strong possibility of contamination from scattered light or intrinsic variability in the line profiles. The authors were therefore hesitant to attribute the modest velocity variation to the presence of a stellar companion.

Over the past two years we have conducted a high-resolution, multi-site spectroscopic monitoring campaign to determine whether or not KH 15D exhibits orbital motion indicative of a multiple system. Here we present the results of our study that show that KH 15D undergoes significant radial velocity variations. The variations are consistent with a binary companion with an orbital period equal to the 48-day photometric period. In §2 we summarize our observations and reduction procedures. The radial velocity measurements and best-fit Keplerian orbital parameters are presented in §3. We conclude in §4 with a discussion of our findings and implications for existing models of the KH 15D eclipse mechanism.

2. Data

During the 2002-2003 and 2003-2004 observing seasons we made 16 observations of KH 15D at maximum light including 11 spectra with the Keck 10-meter telescope and HIRES echelle spectrometer; 2 spectra with the 6.5-meter Magellan II (Clay) telescope and the MIKE echelle spectrometer; and 3 spectra with the 2.1-meter Otto Struve Telescope at McDonald Observatory with the Sandiford Cassegrain Echelle Spectrometer (CE). The observations are summarized in Table 1. Five additional Keck/HIRES spectra were obtained during minimum light. However, since it is unlikely that the star's photosphere is visible through the obscuring material, we decided to exclude from our analysis spectra that were obtained within 10 days of mid-eclipse. In addition to our own measurements, we also include the out-of-eclipse radial velocity measurement, $v_r = 9.0 \pm 0.2$ km s^{-1}, reported by (Ha03) based on their VLT/UVES spectra.

Most of the Keck/HIRES observations were made as part of the California & Carnegie Planet Search.[6] For these observations, the relatively faint apparent magnitude of KH 15D ($V = 16$) at maximum light precluded the the use of the iodine cell to establish a wavelength scale. The cell was therefore removed from the light path during observations of KH 15D to increase the throughput of the spectrometer. The raw CCD frames from all telescopes were reduced using reduction packages written in IDL. The details of the reduction procedures are fundamentally identical to the algorithm presented by Valenti (1994). After bias-subtraction, each echelle frame is divided by a normalized median flat-field image. Order definition is performed using a bright star or flat-field exposure, and scattered light is removed by fitting a two-dimensional B-spline to the interorder regions and interpolating across each spectral order. After the scattered-light is subtracted, each order is rectified, sky-subtracted and summed in the cross-dispersion direction to form the final one-dimensional spectrum. Instead of a summation in the cross-dispersion direction, the rectified orders of the McDonald spectra were reduced to one-dimensional spectra using the optimal extraction algorithm described by Hinkle et al. (2000). In the case of the MIKE reductions, the standard code was modified to correct for the tilt of the spectrometer entrance slit with respect to the CCD columns. The correction of the slit tilt is necessary because the sky subtraction algorithm we employed

[6] `http://www.exoplanets.org`

requires that the projected slit image lie parallel to the detector columns.

The radial velocity of KH 15D relative to the Solar System barycenter is measured from each spectral observation by means of a cross-correlation analysis. For the spectra of KH 15D obtained as part of the Planet Search observing program, the program stars observed on each night provided an extensive selection of reference stars with known barycentric radial velocities listed in Nidever et al. (2002). We selected reference stars that were observed within 30 minutes of KH 15D and with spectral types ranging from M0 to G5. Since the Planet Search target stars are observed through an iodine cell, orders containing iodine absorption lines were avoided in the analysis. For KH 15D observations obtained as part of programs other than the Planet Search, HD 36003 (spectral type K5V) was used as the reference star.

The cross-correlation of each KH 15D spectrum with respect to the reference spectra was performed using routines written in IDL. The procedure involves first rebinning each one-dimensional spectral order onto a new wavelength scale that is linear in $\log\lambda$. This ensures that each pixel in the rebinned spectrum represents a velocity interval that is uniform over the entire spectral order (Tonry & Davis 1979). Regions containing telluric lines, strong emission features and CCD defects are masked out and each spectral order is cross-correlated with respect to the corresponding order of the reference spectrum. Each spectral order thus yields an independent measurement of the radial velocity of KH 15D relative to the reference star. The average of the ensemble set of velocities from all orders is then adopted as the relative radial velocity of KH 15D for a given epoch.

The relative radial velocities from each night are converted into absolute barycentric radial velocities using the relation

$$v_{rad} = \Delta v + (BC_{kh} - BC_{ref}) + v_{ref}. \tag{1}$$

In Eqn. (1), Δv is the relative velocity from the cross-correlation analysis; BC_{kh} and BC_{ref} are the barycentric corrections for KH 15D and reference star, respectively; and v_{ref} is the absolute barycentric radial velocity of the reference star as listed in Nidever et al. (2002). The measured velocities are listed in Table 1.

For nights when only one reference spectrum was available, the uncertainty was estimated using the standard deviation of the mean radial velocity measured from all echelle orders. For nights with multiple reference spectra, the standard deviation of the velocities computed from each target-reference pair was adopted as the uncertainty. Typical uncertainties fall within the range $200 \leq \sigma_v \leq 600$ m s^{-1}.

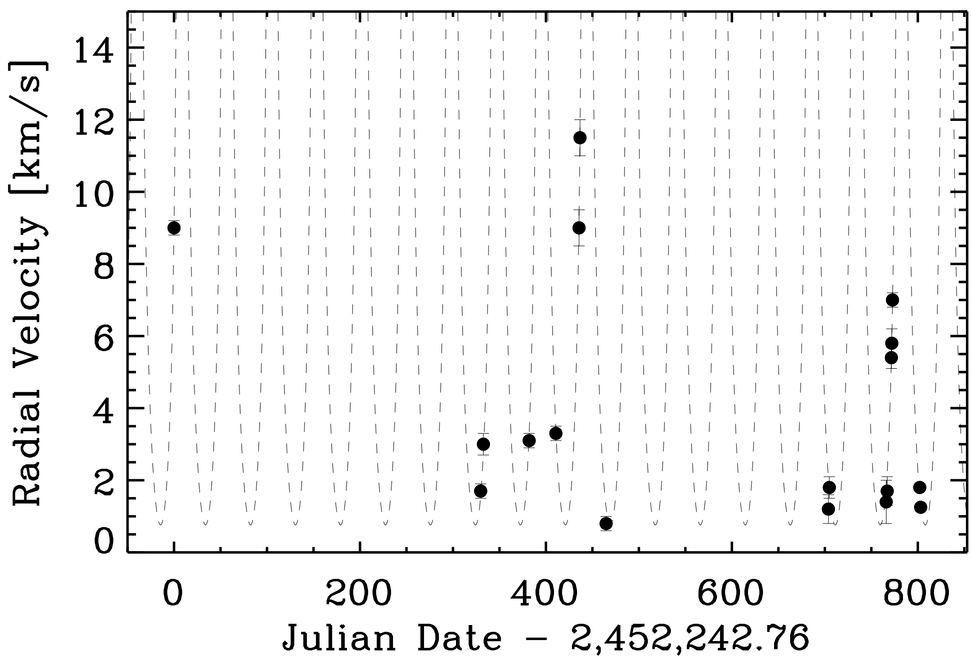

Fig. 1.— The radial velocity of KH 15D as a function of time. The dashed line is the best-fit Keplerian orbit (see §3.1).

3. Results

Figure 1 illustrates how the radial velocity of KH 15D varies temporally out of eclipse over a range of 10.7 km s^{-1}. These data indicate that there must be an unseen star in the system, as had previously been inferred from the analysis of the historical light curve (JW04). Hereafter we will adopt the naming convention of W04 and refer to the currently visible star as A and the hidden companion as B.

3.1. Orbit Solution

Using a nonlinear least-squares algorithm, we found a best-fit model orbit with a period $P = 48.38$ days, eccentricity $e \geq 0.27$, time of periastron passage 2452251.1, argument of pericenter $\omega = -2°$, velocity semiamplitude $K \geq 8.15$ km $s^{-1}$and mass function $F_M/\sin^3 i \geq 2.4 \times 10^{-3} M_\odot$. These parameters are also listed in Table 2 with uncertainties. The uncertainties in the fit parameters were estimated using a Monte Carlo simulation. We generated 10^3

statistical realizations of the velocity time series assuming the errors are normally distributed with standard deviations equal to the measurement uncertainties.

Figure 2 shows a plot of radial velocity versus orbital phase for $P = 48.38$ days. The rms scatter of the fit residuals is 0.37 km s^{-1}and the reduced $\sqrt{\chi^2_\nu} = 1.3$. The vertical lines at $\phi = 0.36$ and $\phi = 0.76$ denote the approximate phases of ingress and egress, respectively, based on the He02 ephemeris. We have no radial velocity measurements between these phases because of the eclipse of star A.

We find that the eccentricity is not well constrained due to the lack of data near periapse, which allows the velocity semi-amplitude of the orbit solution to compensate for changes in the eccentricity. As such, we were able to obtain reasonable fits by fixing the eccentricity at values ranging from $e = 0.27$ to $e = 0.85$, with each solution yielding a different value of the velocity semi-amplitude K and values of $\sqrt{\chi^2_\nu}$ that are equivalent at the 97% confidence level. While the radial velocity data provide poor constraints for the orbital eccentricity, the implied mass ratio from other observations, together with the known mass limits of star A, can be used to place limits on the value of e, as we now show.

3.2. Orbit Parameter Constraints

JW04 determined from photometric measurements of archival plates that the out-of-eclipse magnitude of KH 15D was 0.9 mag brighter (at I-band) 40 years ago compared to the modern bright state. The two most probable explanations for the brighter apparent magnitude in the past is that either both stars, or star B alone, were visible. If both stars were visible, then $L_B/L_A = 1.3$. If only star B were visible, then $L_B/L_A = 2.3$. In either case the, condition $L_B/L_A > 1$ must hold.

Multi-color photometric measurements obtained during minimum light show a slight blueing of the color indices (Ha03) compared to the colors at maximum light. Similarly, Agol et al. (2004) measure slightly bluer colors during eclipse from their low-resolution spectropolarimetric observations compared to their out-of-eclipse observations. One possibility for the bluer color indices during eclipse is that the scattered light is dominated by Rayleigh scattering. However, He02 show that there is no reddening of the light from star A during ingress and egress. This suggests that the opacity of the occulting material is wavelength independent and that the bluer colors are due to a bluer object. Therefore the temperature of B must be hotter than the temperature of A, assuming both stars contribute nearly equally to the scattered component of the light observed during the eclipse of star A.

For most low-mass ($M_* < 1.0$ M$_\odot$) pre–main-sequence evolutionary models stellar mass

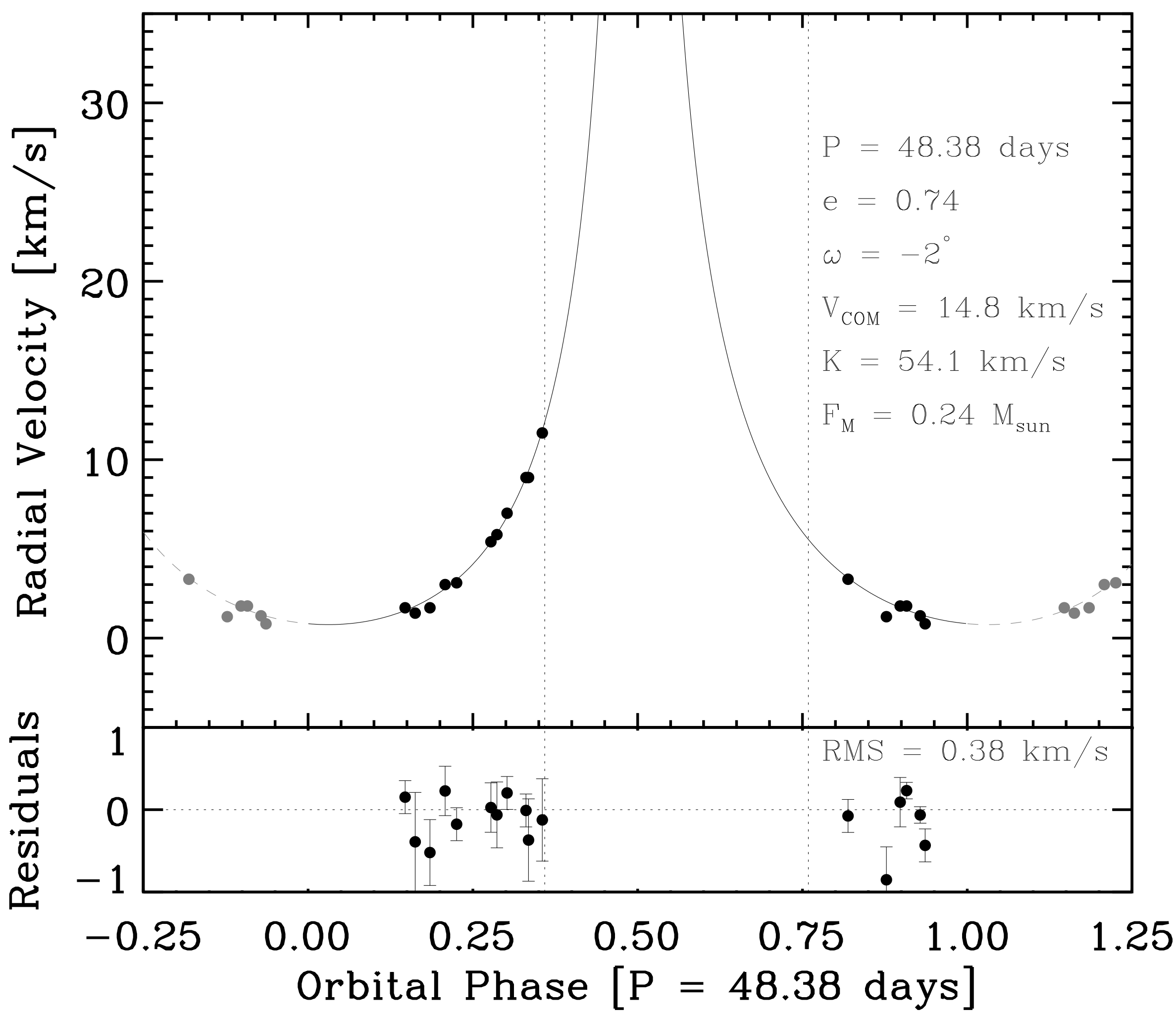

Fig. 2.— The radial velocity of KH 15D as a function of orbital phase. The solid line is the best-fit Keplerian orbit with the eccentricity fixed at $e = 0.74$—the mean value allowed by our orbit constraints (see §3.2). The fit has reduced chi-squared $\sqrt{\chi^2_\nu} = 1.3$. The vertical dotted lines represent the approximate phases of ingress (left) and egress (right) based on the He02 ephemeris.

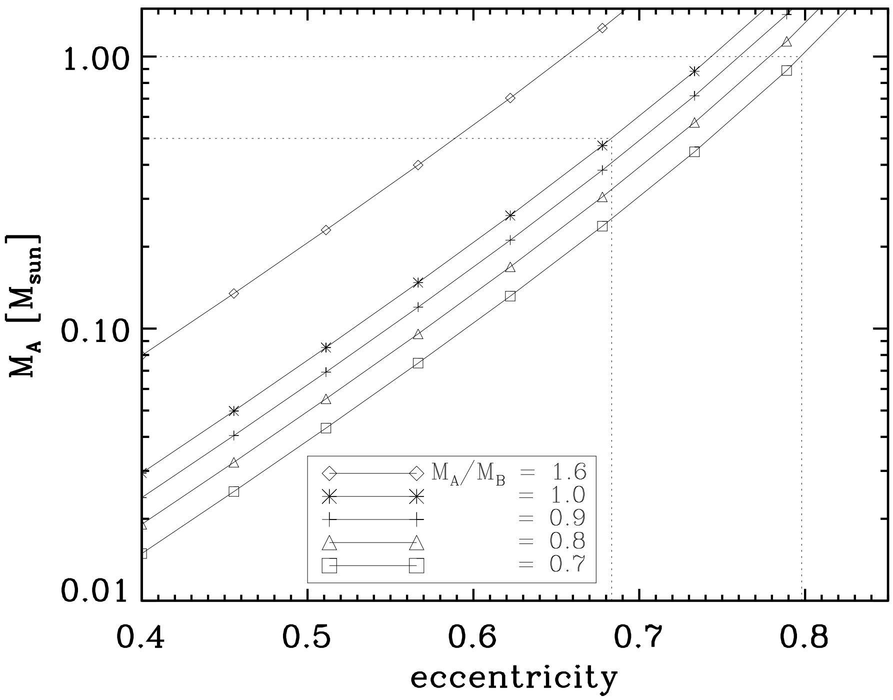

Fig. 3.— The mass of the visible component of KH 15D, M_A, versus orbital eccentricity for four choices of the mass ratio $R = M_A/M_B$. The dotted lines show for $0.5 < M_A < 1.0$ M$_\odot$, acceptable values of the eccentricity fall within the range $0.68 \leq e \leq 0.80$.

is monotonic with both luminosity and temperature (e.g Chabrier & Baraffe 1997; D'Antona & Mazzitelli 1997). For coeval stars on their Hayashi tracks, $T_B > T_A$ and $L_B/L_A > 1$ imply that $M_B \gtrsim M_A$ or, in terms of the mass ratio $M_A/M_B \lesssim 1$.

The mass function of a Keplerian orbit can be expressed as

$$F_M(e, K, P) = \frac{K^3 P (1 - e^2)^{\frac{3}{2}} \sin^3 i}{2\pi G} = \frac{M_B^3 \sin^3 i}{(M_A + M_B)^2}, \tag{2}$$

where P is the orbital period and K is the velocity semi-amplitude. Solving Eqn. (2) for M_A yields

$$M_A(e, M_A/M_B) = \frac{M_A}{M_B} \left(1 + \frac{M_A}{M_B}\right)^2 \left[\frac{F_M(e, K, P)}{\sin^3 i}\right]. \tag{3}$$

The mass function $F_M/\sin^3 i$ in Eqn. (3) is calculated from the parameters of the best-fit orbit to the radial velocity data with the value of e fixed in the fitting procedure. Figure 3 shows plots of M_A versus e for $M_A/M_B = 0.7$, 0.8, 0.9 and 1.0. Since the mass of the visible star is known to fall within the limits $0.5 \leq M_A \leq 1.0$ $\mathrm{M}_\odot$ (Flaccomio et al. 1999; Park et al. 2000), it can be seen by inspection of Figure 3 that acceptable choices of the eccentricity fall within the range $0.68 \leq e \leq 0.80$ yielding a value of the mass function $0.125 \leq F_M/\sin^3 i \leq 0.5$ $\mathrm{M}_\odot$.

3.3. Periodicity

As discussed in §3.1, we find the best-fit Keplerian has an orbital period of $P = 48.38 \pm 0.01$ days. He02 report a period of $P = 48.35 \pm 0.02$ days from their photometric monitoring and JW04 report $P = 48.42 \pm 0.02$ days from a periodogram analysis of archival photographic plates photometry. Thus, our measured orbital period differs by 1.5σ and 2σ from the modern and historical photometric periods, respectively. Since the evolving shape of the light curve may complicate the accurate determination of the photometric period, we conclude that the orbital period and photometric period of KH 15D are identical to within measurement errors.

3.4. Stellar Rotation

The cross-correlation function (CCF) of each KH 15D spectrum with respect to a reference spectrum is used to estimate the projected rotational velocity of star A. A HIRES observation of HD 31560 (K3V, $v \sin i = 1.35$ km s^{-1}; D. Fischer, private communication) obtained with the iodine cell out of the light path is used as the reference spectrum. The reference spectrum is convolved with a rotational broadening kernel (Gray 1992, eqn. 17.12), with an assumed limb-darkening coefficient $\epsilon = 0.6$. A synthetic CCF is calculated by cross-correlating the broadened spectrum with the original reference spectrum. This process is repeated using a nonlinear least-squares procedure until the synthetic CCF matches the CCF of KH 15D. From our Keck/HIRES observations of KH 15D, we measure a projected rotational velocity $v \sin i = 11.4 \pm 0.6$ km s^{-1}. We note that this is more than a factor of 2 larger than the upper limit of 5 km s^{-1} measured by Ha03. We use a radius of star A, $R_A = 1.3 \pm 0.1$ $\mathrm{R}_\odot$ estimated by Hamilton et al. (2001), to infer a stellar rotation period $P_r/\sin i = 5.8 \pm 0.5$ days.

4. Discussion

The results of our spectroscopic monitoring campaign show that the radial velocity of KH 15D varies in a manner inconsistent with the behavior of an isolated star. Instead, the observed radial velocities are consonant with a stellar companion with an orbital period equal to the photometric period. We now discuss the implications of the binarity of KH 15D for current models of the photometric variability mechanism.

Existing models of the KH 15D eclipse mechanism fall into two classes differentiated by whether it is the orbital motion of the star or the disk that causes the photometric variability. The first class of model posits the existence of a single star surrounded by a circumstellar disk containing a nonaxisymmetric density enhancement or alternatively, a warp. As the disk feature orbits the star with a 48-day period, it periodically blocks the line-of-sight to the stellar surface. Based on their spectropolarimetric observations that showed an increase in polarization during minimum light, Agol et al. (2004) developed a model a warped disk with an extended atmosphere and obtained a reasonable fit to the 2001-2002 light curve. A similar analysis was performed by Barge & Viton (2003) using a large dusty vortex.

In the second class of model proposed by W04 and CM04, there exists an unseen binary companion of comparable mass to the visible K-type star seen today. Surrounding the two stars is a circumbinary disk viewed nearly edge-on. The orbital plane of the two stars is tilted at a small angle with respect to the disk plane and the observed light curve is produced as the reflex motion of Star A carries it alternately below and above the plane of the disk.

Independent evidence for the binary nature of KH 15D has emerged from studies of archival photographic plates. In a study of plates obtained from Asiago Observatory, JW04 show that the apparent magnitude of KH 15D was variable from 1968 to 1983, but the light curve from this epoch was markedly different from the one observed today. The bright state was nearly a factor of 2 brighter in the past and the eclipse depth was a factor of 5 shallower. Both of these findings can be explained by invoking the presence of a second star that was visible in the past but is unseen today.

Motivated by these findings, W04 constructed a model of an eccentric binary with a fraction of the orbital plane obscured by an opaque screen and found a quantitative orbital solution by fitting simultaneously to the 2001-2002 photometry of He02, the historical photometry of JW04 and the radial velocity measurements of Ha03. Based on a preliminary investigation of the radial velocities presented here, CM04 independently used physical arguments to propose a similar model of an eccentric binary surrounded by a nodally precessing circumbinary ring. As the ring precesses, the light curve gradually changes from the one recovered from the archival plates to the shape seen today. Perhaps the greatest advantage of the two-star class of model is its ability to explain not only the present-day light curve, but also its evolution over the past half century.

In addition to explaining the photometric phenomenology of KH 15D, the two-star models make predictions about the nature of the binary orbit. Both CM04 and W04 predict that (1) periastron passage occurs during minimum light, (2) the orbital companion has a mass comparable to the primary star, and (3) the binary orbit is highly eccentric. These predictions are precisely what are seen in our orbit solution.

The W04 model makes additional, quantitative predictions about the orbital parameters of the binary. For an assumed fixed period of 48.35 days, the model produces a velocity semi-amplitude of 27.5 km s^{-1}, eccentricity $e = 0.7$, a mass ratio $M_A/M_B = 1.6$, argument of pericenter $\omega = -7^{\circ}.2$ and a center of mass radial velocity $V_{COM} = +15.5$ km s^{-1}. As can be seen in Table 2, the W04 model predictions agree well with the limits set by the orbit fit to the radial velocity data. An important parameter predicted by the W04 model which is not constrained by the radial velocities is the inclination of the binary orbital plane, $i = 84^{\circ}.6$ or $\sin i = 0.996$. Similarly, using the geometry of the circumbinary ring proposed by CM04, a lower limit on the inclination of $i < 80^{\circ}$ can be assigned to the binary orbit based on the time lag between periastron passage and mid-eclipse (Chiang, private communication).

We note that the W04 model has the peculiar feature that the less massive star is the more luminous star. Using Equation 3, the values of P, K and e produced by the W04 model lead to a mass function $F_M = 0.038$ $M_{\odot}$ and a mass $M_A = 0.41$ $M_{\odot}$. This mass is significantly less than the lower limit of 0.5 $M_{\odot}$ measured by Park et al. (2000) and the value of 0.6 $M_{\odot}$ measured by Flaccomio et al. (1999). Figure 3 shows a plot of M_A as a function of e for $M_B/M_A = 1.6$. For our best-fitting model parameters, only eccentricities between 0.58 and 0.65 yield a mass of Star A between 0.5 and 1.0 solar masses. Therefore, for a mass ratio of 1.6 the eccentricity produced by the W04 model is larger than the value allowed by our radial velocity measurements, assuming $0.5 \leq M_A \leq 1.0$ $M_{\odot}$. However, this discrepancy is not too surprising since the W04 model used only two radial velocity measurements. It is also important to note that the mass limits of Star A are derived by placing KH 15D on an HR diagram and are therefore subject to the accuracy of the PMS evolutionary model employed. In all other features of the KH 15D binary system, there is a remarkable agreement between the W04 model and the orbital solution calculated from the radial velocities.

The single star models, on the other hand, do not adequately explain the temporal changes in the observed light curve. Indeed, it is not even clear if a binary companion to KH 15D is compatible with an eclipsing disk feature. If a density enhancement in a circumstellar disk is responsible for the 48-day photometric period, the feature must orbit central star ~ 0.22 AU, assuming a Keplerian orbit. This geometry would restrict a binary companion to orbit either at distances less than 0.22 AU or greater than the extent of the circumstellar disk. However, since our best-fit orbit yields a period of 48.38 ± 0.01 days and $a \sin i \leq 0.29$ AU, neither of these scenarios seems plausible.

Thus, it does not seem possible for both an eclipsing disk feature and a stellar-mass companion to coexist with the same orbital period. Because of the strong evidence of a second star from our radial velocity measurements and the historical photometry, we find the two-star class of model to be the most compelling explanation of the KH 15D photometric variability mechanism.

However, the case of the "winking star" is still far from closed. A key missing aspect of the two-star models is direct detection of a circumbinary disk around KH 15D. He02 report a lack of near-IR excess and a null detection at millimeter wavelengths. CM04 state that such findings are consistent with a circumbinary ring having an inner radius of ~ 1 AU that is tidally truncated by the central binary, and an outer radius of ~ 5 AU that is possibly shepherded by an as yet unseen planet. They predict mid-infrared fluxes that are observable with the Spitzer Space Telescope. Clearly such observations will be vital in further development of models of the KH 15D system.

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Table 1. Spectroscopic Observations of KH 15D

UT Date	Telescope/ Instrument	$\Delta\lambda$ [Å]	R	J.D.-2.4×10^6	v_r [km/s]
25 Oct 2002	Keck/HIRES	3900-6200	70,000	52572.574	1.7 ± 0.2
28 Oct 2002	HIRES	3900-6200	70,000	52575.511	3.0 ± 0.3
16 Dec 2002	Magellan/MIKE	4500-6800	45,000	52624.738	3.1 ± 0.2
14 Jan 2003	Keck/HIRES	3900-6200	70,000	52653.468	3.3 ± 0.2
8 Feb 2003	Keck/HIRES	4200-6600	70,000	52678.400	9.0 ± 0.5
9 Feb 2003	Keck/HIRES	4200-6600	70,000	52679.410	11.5 ± 0.5
9 Mar 2003	Magellan/MIKE	4900-8700	45,000	52707.511	0.8 ± 0.2
3 Nov 2003	Keck/HIRES	4200-6600	30,000	52946.584	1.2 ± 0.4
4 Nov 2003	Keck/HIRES	4200-6600	30,000	52947.594	1.8 ± 0.3
4 Jan 2004	McDonald/CE	5600-6900	30,000	53008.762	1.4 ± 0.6
5 Jan 2004	McDonald/CE	5600-6900	30,000	53009.852	1.7 ± 0.4
10 Jan 2004	Keck/HIRES	3900-6200	70,000	53014.320	5.4 ± 0.3
10 Jan 2004	McDonald/CE	5600-6900	30,000	53014.760	5.8 ± 0.4
11 Jan 2004	Keck/HIRES	3900-6200	70,000	53015.506	7.0 ± 0.2
9 Feb 2004	Keck/HIRES	3900-6200	70,000	53044.834	1.8 ± 0.2
10 Feb 2004	Keck/HIRES	3900-6200	70,000	53045.828	1.3 ± 0.2

Table 2. Optimized Model Parameters

Parameter	Best-Fit to Velocities	W04 Model 1
P [day]	48.38(0.01)	48.35 (fixed)
e	≥ 0.27	0.7
K [km s^{-1}]	≥ 8.15	27.5
ω [deg]	-2(8)	-7.2
V_{COM}[a][km s^{-1}]	$\geq +6.9$	+15.5
$a \sin i$ [AU]	≤ 0.29	0.18
$F_M/\sin^3 i$	$\geq 2.4 \times 10^{-3}$	3.8×10^{-2}
T_p[b][J.D.]	2452251.1(0.9)	–
Fit rms [km s^{-1}]	0.37	–
Reduced $\sqrt{\chi^2_\nu}$	1.3	–

[a]Radial velocity of the binary C.O.M. with respect to the Solar System barycenter

[b]Time of periastron passage

Table 3. Example Orbit Parameters for Various Mass Ratios

Parameter	$\frac{M_A}{M_B} = 1.0$ $e = 0.719$	$\frac{M_A}{M_B} = 0.9$ $e = 0.737$	$\frac{M_A}{M_B} = 0.8$ $e = 0.756$	$\frac{M_A}{M_B} = 0.7$ $e = 0.776$
V_{COM}[a]	+14.3 (0.7)	+14.8 (0.7)	+15.2 (0.7)	+15.7 (0.7)
K [km s^{-1}]	48 (2)	54 (2)	60 (2)	68 (2)
$F_M/\sin^3 i$ [$M_\odot$]	0.188	0.231	0.289	0.371
$a \sin i$ [AU]	0.23	0.21	0.20	0.19

[a]Radial velocity of the binary C.O.M. with respect to the Solar System barycenter. Positive values correspond to motion away from the Sun.