Multi-Wavelength Photometry of the T Tauri Binary KH 15D: A New Epoch of Occultations

by

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I know the stars
as wild as dust
and wait for no man’s discipline
but as they wheel
from sky to sky they rake
our lives with pins of light.

— Leonard Cohen, Another Night with Telescope (1964)
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Chapter 1

Introduction

KH 15D is an eclipsing pre-main sequence (PMS) binary system whose flux output has evolved dramatically since $\sim 1960$. Also known as V582 Mon, the object is situated northwest of the Cone Nebula in NGC 2264, a young open cluster in the constellation Monoceros, 760 parsecs away. Although first discovered by Badalian & Erastova (1970) as a variable star, the eclipsing nature of the system was not made apparent until nearly three decades later, when Kearns & Herbst (1998) attributed the depth, width, and central rebrightening of the eclipse to a nonstellar object orbiting the primary every $\sim 48$ days. Detailed monitoring since then has revealed further photometric and spectroscopic peculiarities of the system, such as a gradual increase in eclipse depth and duration, a steady decrease in maximum light, a disappearance of brightness reversals during mid-eclipse, double-peaked neutral oxygen profiles, and dramatic changes in the H-alpha emission profiles (Kearns & Herbst 1998, Hamilton et al. 2005, 2003, Mundt et al. 2010, Hamilton et al. 2012).

These phenomena have led to a working understanding of KH 15D as a close, eccentric young binary system situated in a non-coplanar, warped annulus of chondrule-sized grains that is precessing and decoupled from the surrounding gaseous accretion disk (Chiang & Murray-Clay 2004). A slight misalignment between the ring plane and the binary orbital plane, viewed nearly edge-on, al-
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lows the warped halo of solids to periodically obscure the embedded stars as it
precesses along the observer’s line of sight. As the ring eclipses the stellar com-
ponents, it produces spectroscopic and photometric signatures of the system’s
physical characteristics and furthermore entices astronomers as a natural corona-
graph (Hamilton et al. 2003).

1.1 Early Investigations

After Kearns & Herbst (1998) presented the initial intrigue of KH 15D, cit-
ing it as a young star being eclipsed every 48 days by a protostar, protoplanet,
or feature in its circumstellar (CS) disk, detailed studies culminating in an in-
ternational campaign were performed to better understand this unusual system.
Hamilton et al. (2001) and Herbst et al. (2002) both observed that while the
system’s period remained constant at 48.36 days, the depth and duration of the
eclipse had increased with time, from $\sim 3$ mag and $\sim 16$ days in 1996/1997 to $\sim 3.5$
mag and $\sim 20$ days in 2001/2002. They attributed the remarkably sharp drop in
brightness during ingress and egress to the steady passage of a knife-edge across
a limb darkened star. The lack of detectable reddening at optical wavelengths
during eclipse suggested that the disk feature was optically thick, lending further
credence to the knife-edge model. In addition, for such a sharp-edged feature to
transit the star in the time dictated by ingress and egress durations ($\sim 2 – 2.5$
days), it must be tilted with respect to its orbital direction. Furthermore, the sud-
den surge of brightness above out-of-eclipse level at mid-eclipse in 1995/1996 that
had puzzled researchers continued to confound as the peak of the central reversals
grew dimmer. At the time, spectral typing of the visible starlight determined KH
15D as a K7 V star, with MgH and strong TiO features. Moreover, the presence
of Li I lines and absence of significant Hα emission were strong evidence for a weak-lined T Tauri star (WTTS), i.e., a still contracting PMS star whose core temperature is not yet high enough to burn hydrogen. Isochronal extrapolation from the observed stellar luminosity (0.5 L⊙) and radius (1.3 R⊙) implied a mass of ~0.5 – 1.0 M⊙ and an age of ~2 – 10 Myr, confirming the youthfulness of the system (Hamilton et al. 2001).

Although the equivalent width (EW) of Hα emission was ~2 Å out of eclipse, it increased significantly to ~30 – 50 Å out of eclipse, consistent with active gas accretion. This apparent fluctuation was a result of natural coronagraphic effects by the occulting disk, which increased the observational value of this enigmatic system.

Additionally, polarimetric observations from Agol et al. (2004) showed that the system’s polarization in the optical spectrum changed from 0% outside eclipse to 2% during eclipse while the spectral type remained roughly constant throughout. The authors attributed the polarization to scattering from an uneclipsed portion of the disk. They argued that during minima, all observed flux emanates from the nearly achromatic scattered light, which is due to large dust grains ~10 μm in size, similar to those that produce zodiacal light.

The plot thickened when Winn et al. (2003) reported that historic data obtained during 1913–1951 demonstrated no eclipses at all. Fascinatingly, a follow-up archival mining project revealed that during 1967–1982, the eclipses – though present – had significantly different properties. The bright state of KH 15D was shifted by nearly 180° and appeared 0.9 mag brighter than more modern values, while the eclipse depth ΔI was 0.7 mag shallower than nominal values of ΔI ~3.5 mag at the turn of the 21st century (Johnson & Winn 2004). This curious discovery precipitated the interpretation that the system contained a second star, whose
flux was partially visible previously but completely obscured in the modern era.

These developments prompted continued monitoring and models to address fundamental questions such as: is KH 15D a single or binary system, and what is the nature of the apparent secular evolution of the system’s surrounding disk?

The first wave of models attributed the observed light curve behavior to some feature of a circumstellar disk. Barge & Viton (2003) interpreted KH 15D as a single star, periodically occulted by a large concentration of solid particles trapped inside a gaseous vortex within a nearly edge-on CS disk orbiting every \( \sim 48.4 \) days. Their dusty vortex model is built upon a surge of magnetohydrodynamics (MHD) simulations of protoplanetary disks at the turn of the millennium, which demonstrated that turbulence and instabilities may produce and sustain large-scale and long-lasting vortices (Barge & Sommeria 1995; Li et al. 2001; Klahr & Bodenheimer 2003). Numerical simulations show that these rotating shear flows can survive for many rotation periods and become elongated such that the greatest elongations reside in the inner regions of the accretion disk (Godon & Livio 2000; Tagger & Pellat 1998). Whereas turbulence dominates in gas dynamics, dust, or small solid grains, are mostly affected by (stellar) gravity and (gas) drag. An anticyclonic vortex, i.e., one spinning against the direction of disk rotation, regulates the distribution of grain sizes in the disk such that light particles diffuse to the core, while heavier ones feel optimal drag and plunge directly into the vortex core. In the KH 15D scenario, the trapped particles are “pebbles,” 1 – 11 centimeters large, which produce gray scattering and whose shell-like distribution in size cause fluctuations in opacity, perhaps resulting in the observed central rebrightening events.

While Barge & Viton (2003) proposed a large, dusty vortex as the cause of the observed eclipses, Agol et al. (2004) treated the occulting object as a warped disk.
with an extended dusty atmosphere. The material is a collection of tilted circular annuli which are aligned at the nodes. The approximately spherical dust envelope scatters light from the central star at all times. However, the equatorial plane is inclined such that as the disk rotates as a solid body every 48 days, projection of the warp periodically blocks out the K7 star, leaving scattered light as the dominant flux source during eclipse.

The observed achromatic flux and nearly grey polarization are reminiscent of zodiacal light behavior in our own solar system, which effectively reflects the solar spectrum. Consequently, Agol et al. (2004) employed a Mie scattering model, which implied μm sized particles. However, their best-fit model was not a strong fit, with a $\chi^2_r$ of 2.2. Moreover, it raised further questions such as 1) what mechanism(s) drive the short warp period? and 2) what other scatterers are present? Lastly, the scattering model did not address the “secular” light curve variations from historic archives (although at the time it had not yet been established beyond a reasonable doubt that KH 15D is a binary system).

Johnson et al. (2004) put speculations of the system’s fundamental nature to rest when they established observationally that KH 15D was a single-line spectroscopic binary; that is, a binary stellar system in which only lines from one star can be seen. They used a nonlinear least-squares model to produce best-fit parameters with orbital period $P = 48.38$ days, in agreement with photometric findings, as well as eccentricity $0.68 \leq e \leq 0.80$, and velocity semi-amplitude $K \geq 8.15 \text{ km s}^{-1}$. The lack of data during periapse introduced many orbital parameter degeneracies in the radial velocity fit, especially for eccentricity and argument of pericenter. Despite this, however, the combination of Keck/HIRES, Magellan/MIKE, and McDonald/CE radial velocity data provided enough phase coverage out of eclipse to better constrain working models, which are highlighted
in the following section.

1.2 Modern Models

Models which address the anatomy of KH 15D fall under two major schemes corresponding to differing proposed sources for its clockwork photometric variability (Johnson et al. 2004): 1) a feature of the circumstellar disk or 2) a star’s reflex orbital motion. Prior to establishing the system as a binary, those who cite the former as the reason behind the observed light curves (e.g. Agol et al. 2004; Barge & Viton 2003) present a single star surrounded by a CS disk with density inhomogeneities periodically blocking the starlight along our line of sight as the whole disk orbits every 48 days. After Johnson et al. (2004)’s discovery, proponents of the latter source (e.g. Winn et al. 2004; Chiang & Murray-Clay 2004) posit a binary system of star A and B, also surrounded by a CS disk or ring, where the reflex motion of A above or below the disk plane can reproduce the “winking” light curves (see Figure 3.11).

1.2.1 Chiang & Murray-Clay

Chiang & Murray-Clay (2004) produced a powerful physical model of KH 15D which unified all of the system’s observed properties at the time. Consider an eccentric orbit of two PMS K stars, A and B, with similar masses, where B is slightly more luminous than A. The binary is embedded in a circumbinary ring of gas and dust which is 1) inclined with respect to the orbital plane, 2) vertically warped, 3) radially thin, and 4) precessing as a rigid body. The orbital period of 48.4 days establishes the eclipse period (short-term variability) while solid-body precession, i.e., uniform nodal regression of the ring, modulates the “secular”
changes in flux (long-term variability) as it advances across the binary orbit.

In particular, rigid-body precession requires a misalignment between ring and binary planes, which can only be sustained if the ring is warped and thin, and its material can communicate efficiently across the disk. Depending on the density and constituents of the ring, thermal pressure gradients (gas) or self-gravity (solids) or a combination of both may compensate for differential nodal precession. If gas pressure is the mechanism for maintaining uniform nodal precession, the warp is such that the inclination of the inner ring with respect to the binary orbit is greater than that of the outer ring. The warp geometry is inverted, i.e., larger inclination at the outer ring, in the case of self-gravity.

One means of truncating the outer annulus is to introduce the presence of a planet, analogous to shepherd moons which confine narrow planetary rings. With the discovery of circumbinary planets by Kepler, the possibility of a planet residing in KH 15D is not unfeasible. Since the warped disk provides a natural “coronograph,” it may even be possible to tease out the signatures of a sufficiently bright (i.e., massive) young planet.

Furthermore, this model is attractive in that it provides many predictions, which may be refuted or confirmed in further studies of the young system. For instance, Chiang & Murray-Clay (2004) predict a mid-infrared excess with flux densities of $F_\nu \sim 3 \text{ mJy}$ between $10 - 100 \mu\text{m}$. They also expected the then invisible star B to resurface around 2030.

1.2.2 Advancing Opaque Screen

Whereas Chiang & Murray-Clay (2004) provided a physical approach to understanding KH 15D, Winn et al. (2004) proposed a semi-empirical model which
also accounts for both large-scale modern and archival light curves. An updated version two years later (Winn et al. 2006) furthermore reconciles small-scale light variations, as well as new (2003–2005) photometry and radial velocity observations. In this updated scenario, a sharp-edged, semi-infinite opaque screen gradually advances across our line of sight and occults an eccentric PMS binary, whose stellar components A and B each possesses a faint blue halo. The screen represents the sky projection of a circumbinary disk and is treated as semi-infinite because at the time, star B’s orbit was completely blocked, i.e., the trailing edge could not be located.

Figure 1.1: Diagram from Winn et al. (2006) of KH 15D during 2001-2002 observing season.
Figure 1.1 illustrates the model’s interpretation of KH 15D during the 2001–2002 season, i.e., an epoch when the sky-projected precessing disk or “screen” is precisely at the point in the binary orbit such that star B is completely hidden and star A undergoes periodic occultations. In panel (a), star A (slightly less luminous) has passed apastron and the integrated flux is at the maximum or continuum level. As star A moves further along in its orbit toward periastron, it becomes more and more obscured, as shown in panels (b) and (c), when the flux levels begin to drop smoothly. At position (d), star A is far enough along in its orbit that only a portion of its blue halo is visible, imprinting a “kink” in the light curve. Since the halo flux has different properties from the central starlight, the slope of ingress between panels (d) and (e) has decreased significantly from that between panels (b) and (c). As star A closes in on its closest approach, a portion of its blue halo leaks out behind the opaque screen and the I-mag flux begins to increase near mid-eclipse, which coincides closely with periapse. After panel (f), when the maximum halo light is exposed at periastron, the light curve behavior KH 15D is a mirror image of panels (a) – (f) as star A goes into egress and finally passes apastron again.

One can rewind the scenario, pulling the “screen” back across the orbit of the binary to earlier epochs. Before 1960, both star A and B were fully exposed at all times. Between 1960–1980, star A was always visible and star B became periodically occulted. Then, around 1995, the “era of dominant central rebrightenings” occurred when star A was periodically eclipsed and star B remained hidden except during periastron when it peeked out. Finally, in the 2000s, when star A underwent periodic eclipses, the stellar disc of star B was obscured at all times and its blue halo would become increasingly invisible at periastron. Like Chiang & Murray-Clay (2004), the model successfully predicted the disappearance of both
stars and the eventual re-emergence of star B.

Three physical interpretations exist for the nature of the blue halos introduced in the updated model: 1) partially attenuated starlight, 2) self-luminosity from an accretion stream or a hot corona or 3) scattered starlight by material near the star (corona or accretion flow) or from the disk. Since the system's color is nearly constant or, indeed, slightly bluer during eclipse than out, the blue halo is most likely due to either scattered light by a hot corona or forward and/or backward scattering from the circumstellar ring.

1.2.3 Forward-Scattering Curved Edge Model

Silvia & Agol (2008) interpreted the “blue halos” (Winn et al. 2006) as forward scattering of starlight by a “fuzzy” dust ring edge. They argued that density fluctuations, either due to intrinsic edge effects or to vertical structure of the warp, would likely be present in the system. Therefore, they treated the occulting screen as a convolution of the canonical “knife-edge” and a power-law distribution of optical depth. They found using a curved edge (a succession of sharp edges at variable inclination corresponding to a warped disk), as opposed to a linear edge, greatly reduced the $\chi^2$ values.

As a star sets behind or rises above this dusty edge, the circumstellar material simultaneously extinguishes and diffracts the starlight such that a faint halo forms around the central star. This effect is readily seen on Earth during hazy nights, when a cloud of water droplets passes in front of the moon and scatters its light into a fuzzy halo around the dimmed moon (Silvia & Agol 2008).
1.3 From Single- to Double-Line Spectroscopic Binary

Between the years 2006–2009, the maximum light level of KH 15D steadily decreased from $I = 14.6$ to 15.6 mag (see Figure 3.11). Then, eluding modeled timing predictions (Chiang & Murray-Clay 2004; Winn et al. 2006), the system plunged into faintness in 2010. Despite both stars being occulted by the circumbinary ring at this time, photometric variability at the level of more than 2 magnitudes continued on the 48.37 day period. This supported a scenario where reflected or backscattered starlight by the background ring dominated the system when direct starlight was obscured by the foreground ring.

Without proper observational constraints, models could not precisely predict the eventual (re-)emergence of star B from the other side of the circumbinary ring. Observers were unsure if the coveted epoch would come in the next decades or if it would take centuries (Herbst et al. 2010).

Then, quite unexpectedly in 2012, the system’s light curve exhibited a dramatic rise in flux as star B, previously hidden for over a decade, rose from the trailing edge of the ring (Capelo et al. 2012). The maximum flux of the system reached only $I = 15$ mag, fainter than either star unobscured, and so was believed to be a partially concealed star. Capelo et al. (2012) compared the system’s $V - I$ color in 2012 to that of 2008 (when star B was entirely hidden and star A was periodically occulted), which demonstrated that a bluer object, characteristic of a hotter star, was now responsible for the system’s flux. Their spectral analysis of Gemini spectra obtained in January 2011, when both stars were near apastron but obscured, indicated the presence of a K1 III star. A KECK HIRES radial
velocity measurement near maximum brightness on UT 2012 March 13 yielded a center of mass velocity of $+21.3 \pm 1$ km s$^{-1}$, dramatically different from the predicted star A value of $-18.7 \pm 1$ km s$^{-1}$. This unambiguously confirmed that a hotter star (B) was the agent of system brightening.

1.4 Additional System Characteristics

1.4.1 Rotation Period

Hamilton et al. (2005) derived from 2001 – 2004 out-of-eclipse photometric observations a rotation period of the then visible star A to be 9.6 days, longer than typical values for TTSs of star A’s mass. They attributed this phenomenon to tidal pseudosynchronization between stellar orbit and rotation. As shown by Herbst & Moran (2005), the measured orbital and rotation periods satisfy tidal pseudosynchronization for $e = 0.65$, in agreement with the eccentricity values from radial velocities. The timescale for pseudosynchronization is furthermore consistent with the inferred age of the system at $\sim 3$ Myr.

1.4.2 Mass outflow

The occultation of stellar light bestows astronomers a rare treat: natural coronagraphic observations. The binary exhibits many features associated with young TTS, but regular occultations provide unique ways to study them. Observations and modeling suggest that material is collected onto the binary stars via stable accretion streams and expelled in the disk-driven bipolar jets, which produce H$_2$ filaments by means of collisional shocks (Hamilton et al. 2003, 2012; Mundt et al. 2010; Tokunaga et al. 2004).
In particular, the presence of [O I] is strong evidence for outflow launching in the binary system \cite{Hamilton2003,Mundt2010}. The double-peaked forbidden line profile and its equivalent width do not vary with phase, suggesting an axially aligned bipolar jet, approximately perpendicular to the line of sight, and whose emission zone is extended enough to elude occultations. Indeed, forbidden-line emission zones typically extend to distances of 30 AU from classical TTS binaries.

More recently, \cite{Hamilton2012} documented 2001/2002 to 2005/2006 $H\alpha$ observations for KH 15D, which showed an inverse P-Cygni profile (redshifted $H\alpha$ absorption – sometimes below the stellar continuum – on top of blueshifted emission) during ingress and a narrow double-peaked profile accompanied by broad extended wings during egress. The changing velocity of the absorption component can be understood as a co-rotational accretion stream feeding the binary that is moving along the line of sight \cite{deVal-Borro2011}. The observed high-velocity emission shoulders are stronger during egress, i.e., following periastron passage when material exchange is most intense. Such a phenomenon can be interpreted as emission by the accretion stream, enhanced after rendezvous at periapse, as it rotates away from the observer.

Furthermore, broad- and narrowband infrared observations via the adaptive optics system of the Subaru Telescope revealed filamentary $H_2$ emission structures near KH 15D \cite{Tokunaga2004}. The K-band and narrowband $H_2$ images show a curved nebulous strand containing two knots, A and B, extending 6" to the north and 7.5" to the east. The authors argue that the $H_2$ emission filament is thermally excited by (collisional) shocks within co-moving gas outflows at slightly differently velocities. Given the extent of the feature, distance to KH 15D, and nominal outflow speeds ($\sim 100$ km s$^{-1}$), the filament formed over 500 yr ago. A
counterjet, if it exists, is extremely faint in comparison with the observed northeast filament.

1.4.3 X-ray Emission

Observational studies demonstrate elevated levels of magnetic activity during the T Tauri phases of low-mass stars which manifest as flares seen in the X-ray (Feigelson & Montmerle 1999). True to form, KH 15D eludes this archetype as an intrinsically weak source of X-ray emission. Herbst & Moran (2005) showed that the system’s X-ray luminosity is an order of magnitude weaker than typical values for cluster members in NGC 2264 with similar effective temperatures and color. While the mechanism behind KH 15D’s underluminous X-ray state is not well constrained (due to poor understanding concerning general TTS flare phenomena), it is likely associated with the binary’s eccentricity and close periastron passage.

1.5 Overview of KH 15D & Emphasis of Thesis

Over the past decade or so, observers and modelers have slowly painted the following portrait of the enigmatic KH 15D: a pair of PMS stars, approximately 3 Myr of age, revolving in a close, eccentric ($a = 0.13$ AU, $P = 48.37$ d, $e = 0.6$) orbit. Upon further inspection, the binary members, designated A and B, have mass $0.6 \, M_\odot$ and $0.7 \, M_\odot$ (Hamilton et al. 2001; Johnson et al. 2004; Winn et al. 2006) and $I$-band flux 14.5 mag and 14 mag, respectively. Photometric, color-magnitude, and spectral analyses indicate A is characteristic of a K6/K7 star (Hamilton et al. 2001) while B belongs to a slightly earlier-type class (K1, Capelo et al. (2012)).

The binary is surrounded by a ring of solids (micron- or millimeter-sized
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grains), which has precipitated and settled from the more extended and gaseous circumstellar disk reservoir. This ring must be misaligned, warped, and radially thin to precess as a rigid body on timescales of $\sim 1000$ years. The nodal precession induces a sky-projected sharp-edged “screen” to advance across the orbit. While tidal interactions with the non-coplanar binary orbit confine the inner edge ($a_{in} \sim 1$ AU), truncation at outer radii ($a_{out} \sim 5$ AU) can be achieved by a shepherding body, possibly a protoplanet (Chiang & Murray-Clay 2004).

This thesis focuses on the study of the periodic and secular photometric variabilities of KH 15D. Specifically, multi-wavelength photometry in optical and near-infrared bands was reduced, adding to the wealth of information in both time and wavelength domains. A refinement of the differential photometry process was required to ensure reliability and precision of data. Analysis of the most recent observations is conducted in concert with long-term trends to address changes in color, eclipse duration and timing, and other observational properties. In particular, this research seeks to investigate the extinction behavior of the system to probe properties of the ring, as well as look for observational evidence for the presence of the putative giant planet.
Chapter 2

Data & Methods

The science presented here relies on data from the Small & Moderate Aperture Research Telescope System (SMARTS). This chapter describes the acquisition, organization, and reduction of SMARTS photometry on KH 15D. The new data obtained during the 2012/13 season contain observations in Johnson-Cousins $V/R/I/J/H/K$ bands ($\lambda_{\text{eff}} = 0.551, 0.658, 0.806, 1.22, 1.63, 2.19 \, \mu m$), taken in simultaneous optical and near-infrared (O/NIR) pairs. The reduction process is built upon IRAF scripts created by SMARTS staff and previous generations of data reduction on KH 15D. It seeks to streamline O/NIR image processing while allowing user interaction for optimizing quality control.

2.1 SMARTS

Simultaneous near-infrared and optical observations were obtained in queue mode with A Novel Duel Imaging CAmera (ANDICAM) 1.3 m instrument operated by the SMARTS consortium at the Cerro Tololo Inter-American Observatory (CTIO) in Chile. The dual-channel ANDICAM imager uses a dichroic filter to split the beam into two spectrally distinct components, which are then measured by a Fairchild 447 2048 $\times$ 2048 optical CCD and a Rockwell 1024 $\times$ 1024 HgCdTe “Hawaii” near-IR array. An internal, moveable mirror allows dithering with the NIR component while a single optical exposure integrates [DePoy et al., 2003].
High-cadence (∼1 − 3 d) ground-based V/R/I/J/H/K photometry was obtained from October 1, 2012 to April 12, 2013 (JD 2456202.8 - JD 2456395.5), which supplements existing longterm V/I/J/H monitoring of KH 15D extending back to the 2010/11 SMARTS season. K- (and R-) band observations were added to this year’s campaign, allowing us to better probe system properties during optical minimum. In particular, these data should help illuminate the nature of the circumbinary ring and search for light from a possible gas giant member.

The optical photometry consist of four 150 s exposures per observation. They arrive pre-processed, i.e., bias-subtracted, overscan-subtracted, and flat-fielded, by SMARTS staff using the IRAF task \texttt{ccdproc}. NIR data are taken in sets of 15 dithered exposures, each 30 s in duration. This is employed to avoid saturation and contamination by IR-bright companion sources. Unlike their optical counterparts, NIR images were not fully calibrated and thus required additional data reduction. In previous seasons, IR dome flats for each filter were available on a 3-day rotation; however, due to understaffing, the difference between target observations and flats may now be as large as 20 days. Nonetheless, since dome flats are generally stable on multi-week timescales, the larger temporal incongruinity should introduce relatively small errors. All data products from SMARTS were uploaded to an ftp server at Yale, where they were retrieved to perform data reduction and aperture photometry.

2.2 Reduction Pipeline

To automate the data collection and organization process, I created a bash shell script \texttt{smarts_red.sh}. The user can specify the type of data, i.e., a particular date range or filter, to retrieve via ftp. Once executed, the script will unzip the ftp
data, sort the uncompressed files into correct filter directories, and, in the case of IR, sort dithered exposures into correct date directories, matching flat-field images to the closest science images within a 20 day tolerance. Below, I first describe separately the steps to prepare optical and IR images for aperture photometry, then discuss the reduction and extraction processes common to both channels.

2.2.1 Optical Preparation

Using the IRAF task \texttt{imexam}, bad images (i.e., cosmic ray streaks, poor focus and/or framing, poor PSF, etc.) were flagged and removed. The rest of the images are then aligned to a common pixel coordinate frame via an IDL script \texttt{fieldshift\_V.pro} written by Eric C. Williams in 1999, which prompts the user for a reference image and a list of science images to be shifted and produces shifted fits files marked by a pre-fix \texttt{Sh}. An example reference image in the \textit{V}-band is given in Figure 2.1. Because images with $\Delta x, \Delta y$ greater than 60 pix do not shift properly, I updated the IDL program to output a list of \texttt{badFiles}. The flagged images remain unshifted and necessitate another run-through with the IDL program. A second shifting routine requires a new reference image and file list, and typically occurs when images span a large range of dates, likely due to a change of staff and image framing technique.

To determine the quality of the images, I automated an IRAF script \texttt{getfwhm.cl} to record the full width at half max (FWHM) of each reference star for every night’s photometry. The routine requires a coordinate file \texttt{fwhm\_coord} containing $(x, y)$ pixel values for each point source in the reference image employed for shifting. Since an aperture radius of 7 pix had been previously determined for optical aperture photometry, images with FWHM $> 7$ pix for multiple comparison stars
were subsequently removed.

2.2.2 Infrared Preparation

The IR data products are separated by date into different directories. Each set of dithered exposures is prepared for further reduction with an IRAF script developed by SMARTS personnel, \texttt{ircombbin}. The program flat fields, sky-subtracts, and prompts the user to interactively select standard stars in each exposure to shift the image to a pixel frame common to a particular observing night. Simultaneously, the interactive nature of the script allows the user to search for bad exposures and remove them from the final, combined image, denoted by the suffix \texttt{ADDED}.

Each nightly \texttt{ADDED} image is then shifted to a common reference image frame (see Figure 2.2) using an IDL program \texttt{fieldshift.H.pro}. This allowed for automated FWHM extraction on all comparison stars using the IRAF script \texttt{getfwhm.cl}, analogous to the method described for optical image preparation. \texttt{J}, \texttt{H}, \texttt{K} images with FWHM > 10 pix for multiple point sources were rejected.

2.3 Aperture Photometry

Photometry is extracted from the prepared images via the IRAF task \texttt{phot} found in the \texttt{noao > digiphot > apphot} package. The task takes in a list of images with a shared origin and the coordinates of targets of interest. The CCD and IR array characteristics on the SMARTS 1.3 m telescope are such that \{readout noise, gain\} are \{6.5 e-, 2.3 e-/DN\} and \{\sim 20 e-, 7.2 e-/DN\}, respectively. The sky inner radius and width are 13 pix and 5 pix, respectively, for both optical and IR data. Photometry is performed on the optical and IR images with several
Figure 2.1: Sample optical image (V-band) with cardinal directions, reference stars 1–3, and KH 15D labeled. Line segment on the lower right corner indicates the 1' scale on the pixel image. The CCD field of view is \( \sim 6' \times 6' \).
Figure 2.2: Sample co-added IR image (H-band) with cardinal directions, reference stars 1–7, and KH 15D labeled. Line segment near the center of the image indicates the 1' scale. The IR field of view is $\sim 2.4' \times 2.4'$. 
2. Data & Methods

aperture sizes at 7, 8, 9, and 10 pix. This range of values was chosen to maximize signal-to-noise (S/N), that is, to include as much possible flux from the stellar sources while excluding stray radiation from the crowded Cone Nebula field of view.

The output from phot is an ascii file containing detailed information concerning data identification, transformation, and rejection, such as date of observation, filter ID, instrumental magnitude, and associated Poisson error for each comparison star and each aperture size. The quality of phot’s performance may be evaluated by examining the shifting and rejection algorithm outputs. For example, aperture photometry with large shifts in centering or low rejection values for an especially bright patch of sky is rejected. The ascii tables are combined to a single file; a script collect.phot.V.awk (or collect.phot.H.awk for IR filters) then extracts from the concatenated table the Julian Date, magnitude, and error for a desired aperture size and prints to a file filterID.phot.

2.4 Quality Control

2.4.1 Instrumental Artifacts & Seeing Variability

Non-ideal seeing conditions and poor focus or pointing manifested in an increase in the FWHM of the stellar PSF. Sometimes, they conspired to distort the stars such that they were no longer circular, i.e., point sources, but resembled “tear-drops” in shape (see reference stars circled in Figure 2.2). This effect is especially prevalent in the infrared observations, and requires phot to be exercised with caution. Because the tear-drop stars are nonaxisymmetric, i.e., misaligned with the $x$-$y$ pixel image plane, substantial light may persist beyond the FWHM quoted by imexamine and an inadequately sized aperture may exclude significant
flux. The FWHM of infrared images was generally 2 – 3 pix larger than that in the optical. For this reason, the 7 pixel aperture was adopted for the optical light curves and the 10 pixel aperture for $J/H$ in the infrared. The $K$-band images contained issues that prompted a separate aperture evaluation strategy, and a 10 pixel aperture was ultimately used to evaluate stellar magnitudes (see following subsection for detailed discussion). However, information pertaining to all aperture sizes were kept for consistency and future reference.

The ANDICAM instrument imprinted large and small scale artifacts in the images. The reduced optical images exhibited a rectangular vignetting effect, and observations were omitted if comparison stars and KH 15D fall across significantly different background levels. Moreover, large horizontal or diagonal bands sometimes permeated O/NIR images. The optical images were excluded if banding coincided with reference stars or KH 15D. The IR reduction and dither-combining process usually produced combined images devoid of these banding artifacts, despite the presence of contrast strips in input raw exposures. When the banding structures persisted in the combined image, the aberrant raw exposures were identified and removed before the task `ircombin` was performed again.

Furthermore, the IR channel array reads out in four quadrants. When the exposures are “stitched” together, the process can introduce seams and/or uneven background levels. This particular image quality issue was especially persistent in $J$. As with the banding effect, the reduction process of background-subtraction, bias-framing, and dither-combining often remedied the blemishes in the final data product.
2.4.2 $K$-band Issues

While the dithering mode in the infrared treated mildly uneven backgrounds and excised cosmetic defects such as hot pixels, it also left residual flat-field errors in the images. This is likely because light travels through different parts of the filter at different mirror (dithering) positions, creating interference and diffraction patterns. Indeed, even after dome-flat corrections, significant “ripples” remained in the reduced $K$-band observations. Large arcs tended to be strongest in the upper right quadrant of the images and weakest in the image center, near where KH 15D was located. Smaller annular patterns persisted throughout the entire image, however, and those ripples introduced greater uncertainties in the photometry. In particular, during minimum light, the dithering artifacts dominated the image region where the system was located, giving false signals. This set the $K$-band detection limit at $\sim 16$ mag. Furthermore, $1.5'$ north of KH 15D was a bright source which periodically underwent flaring, and some of its flux leaked into the 10 pix aperture during aperture photometry. This resulted in IRAF magnitudes brighter than 15 mag during minimum when the source was clearly not visible above the noise in the images. The amount of light contamination was greatly reduced for an aperture of 7 pix, and a comparison between aperture 7 vs. 10 pix light curves showed minimal magnitude differences outside of minimum. As a result, aperture 7 was adopted for $K$-band data.

2.5 Differential Photometry

The motivation behind monitoring KH 15D is to observe its light variability and determine how the changes in flux may be related to physical changes in the system. Therefore, to extract those signatures, ground-based photometry must be
2. Data & Methods

2.1 VRI Magnitudes for Optical Comparison Stars

<table>
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<tr>
<th>Star (ID)</th>
<th>V</th>
<th>ΔV</th>
<th>R</th>
<th>ΔR</th>
<th>I</th>
<th>ΔI</th>
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</thead>
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<td>12.902</td>
<td>0.021</td>
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<td>2 (C)</td>
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<td>12.617</td>
<td>0.020</td>
<td>12.240</td>
<td>0.021</td>
</tr>
<tr>
<td>3 (D)</td>
<td>15.013</td>
<td>0.020</td>
<td>14.328</td>
<td>0.021</td>
<td>13.645</td>
<td>0.021</td>
</tr>
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</table>

2.2 JHK Magnitudes for Infrared Comparison Stars

<table>
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<th>Star</th>
<th>J</th>
<th>ΔJ</th>
<th>H</th>
<th>ΔH</th>
<th>K</th>
<th>ΔK</th>
<th>SIMBAD Identifier</th>
</tr>
</thead>
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<td>14.564</td>
<td>0.045</td>
<td>14.285</td>
<td>0.073</td>
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</tr>
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<td>0.030</td>
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<td>0.023</td>
<td>12.549</td>
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</tr>
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<td>03</td>
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<td>0.024</td>
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<td>0.024</td>
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</tr>
<tr>
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<td>0.024</td>
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</tr>
<tr>
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<td>13.839</td>
<td>0.100</td>
<td>Cl* NGC 2264 FMS 2-1347</td>
</tr>
</tbody>
</table>

carefully calibrated to remove temporal changes in the instrument’s performance and in the seeing conditions. Differential photometry entails observing comparison stars in the same field as the target of interest and provides a means of transforming instrumental magnitudes to standard magnitudes without having to perform various measurements on extinction, zero-point, and transform coefficients.

Therefore, differential photometry was performed on the reduced images. Optical comparison stars were selected from Hamilton et al. (2005). Due to the ANDICAM instrument’s smaller FOV, only three out of the seven local reference stars overlapped with Hamilton et al. (2005). They are identified in Table 2.1. Seven neighboring comparison stars were chosen in the IR; their coordinates were cross-checked in the SIMBAD database, from which standard J/H/K magnitudes were acquired (see Table 2.2).
2. Data & Methods

2.5.1 Stability of Comparison Stars

To determine their photometric stability, differences in instrumental magnitudes were examined between different comparison stars as a function of observation time. Figure 2.3 is a plot of $m_i - m_j$ vs. JD in $I$, and it clearly shows that reference star 3 (see finder chart) exhibits variability, such that $m_1 - m_3$ and $m_2 - m_3$ vary with an amplitude of $\sim 0.15$ mag. Figures 2.4 and 2.5 show similar star 3 behavior in other optical filters, where $\Delta(m_{1,2} - m_3)$ is roughly 0.25 mag in $V$ and 0.2 mag in $R$. The $\sim 0.2$ mag variability in the optical filters would contribute significantly to the error propagation in determining the standard magnitude of KH 15D. Therefore, comparison star 3 was omitted in calculating KH 15D’s standard $V$, $R$, and $I$ magnitudes.

The same photometric stability test was performed on the set of infrared comparison stars. Although the IR observations contained more reference stars in the field of view, many of them were not useable as standard magnitude calibrators because they exhibited large variability resolved under our observing cadence. Figures 2.6, 2.7, and 2.8 illustrate the relative fluxes of various pairs of comparison stars as a function of observation time in $H$, $J$ and $K$, respectively. As is the case for optical filters, deviations from constant $m_i - m_j$ with time indicated that at least one of the $i, j$ comparison pairs exhibited variability, and the identity of the variable star was determined by plotting multiple combination pairs. Due to intrinsically lower S/N in the infrared, the condition for instability was relaxed from $\Delta m_{\text{opt}} \gtrsim 0.1$ mag to $\Delta m_{\text{IR}} \gtrsim 0.2$ mag.

The relative fluxes of reference pairs containing stars 5 and 6 in $H$ and $J$ (see Figures 2.6 and 2.7) have large scatter, where $m_i - m_5$ show variability of up to 0.5 mag and $m_i - m_6$, 0.3 mag. Stars 1, 5, 6, and 7 appear to vary dramatically in
2. Data & Methods

2.5 Instrumental to Standard Magnitude

To convert KH 15D’s IRAF $z$ magnitude to standard $V/R/I/J/H/K$ magnitudes, I calculated the difference in $z$ and standard magnitude $s$, $\Delta m_i = m_{i,s} - m_{i,z}$ for $N$ comparison stars which passed the stability test described above. Then I averaged the magnitude differences such that

$$\Delta m = \frac{\sum_{i=1}^{N} \Delta m_i}{N}.$$  

Each mean differential magnitude had an associated error $\delta m$:

$$\delta m = \frac{\sum_{i=1}^{N} \sqrt{(\delta m_{i,s}^2 + \delta m_{i,z}^2)}}{N},$$

where $\delta m_{i,s}$ represents the reported uncertainty for each standard star (see Tables 2.1 and 2.2) and $\delta m_{i,z}$ is the Poisson error for each reference star from IRAF.

The averaged transform magnitude $\Delta m$ was added to the $z$-magnitude of the target star (KH 15D) $m_{0,z}$ to determine its standard magnitude $m_{0,s}$. The uncer-
Figure 2.3: $I$-band stability test for comparison stars 1, 2, and 3. (a) Top panel shows instrumental magnitude differences between reference stars as a function of JD. Star 3 clearly exhibits variability while $m_1 - m_2$ is effectively a constant as a function of time. (b) Bottom panel illustrates average instrumental magnitudes as a function of individual stellar magnitude. While stars 1 and 2 are directly proportional to the average magnitude, star 3 deviates from linearity. Note that star 3 was excluded from the average magnitude calculation for star 1 (black circle) and star 2 (blue triangle) data points.
Figure 2.4: V-band stability test for comparison stars 1, 2, and 3. As with Figure 2.3 (a) top panel shows instrumental magnitude differences between reference stars as a function of JD, and (b) bottom panel illustrates average instrumental magnitudes as a function of individual stellar magnitude. These plots demonstrate star 3’s photometric instability.
Figure 2.5: $R$-band stability test for comparison stars 1, 2, and 3. As with Figures 2.3 and 2.4, (a) top panel shows instrumental magnitude differences between reference stars as a function of JD, and (b) bottom panel illustrates average instrumental magnitudes as a function of individual stellar magnitude. Again, comparison star 3’s flux clearly varies with time, and thus must be excluded from calibration.
Figure 2.6: $H$-band stability test for comparison stars 1–7. Numbers $i - j$ in the legend refers to the magnitude difference of different combination pairs. Data points associated with stars 5 and 6 clearly exhibit variability while their pairwise counterparts show little variation when coupled with other reference stars. For example, red points in upper and lower left panels demonstrate large scatter in the relative fluxes of stars 1 to 6 and 2 to 6, respectively. That the relative flux of 1 to 2 has much smaller scatter indicates star 6 is variable.
Figure 2.7: $J$-band stability test for comparison stars 1–7. Relative fluxes associated with stars 5 and 6 clearly show large variability and/or scatter $>0.25$ mag.
Figure 2.8: $K$-band stability test for comparison stars 1–7. As stated earlier, $K$ magnitudes have larger scatter due to poorer S/N. Relative fluxes containing star 1 all exhibit light curve shapes indicating variability. Similarly, relative to other comparison sources, star 5 show dramatic variations, and stars 6 and 7 contain significant scatter. See text for a discussion on possible sources of variability (intrinsic vs. instrumental artifact).
Figure 2.9: Average $H$ magnitudes of $N$ reference stars as a function of individual magnitudes. Top panel contains the average magnitudes of $N_{\text{STAR}} = 7$ (all comparison sources), while bottom panel has $N_{\text{STAR}} = 5$ (stars 1, 2, 3, 4, 7) on the y axes. The linear relationships are much tighter in the bottom than top panel, especially for stars 1 and 7.
Figure 2.10: Average $J$ magnitudes of $N$ reference stars as a function of individual magnitudes. Top panel contains the average magnitudes of $N_{\text{STAR}} = 7$ (all comparison sources), while bottom panel has $N_{\text{STAR}} = 5$ (stars 1, 2, 3, 4, 7) on the y axes. Scatter from linearity is greatly reduced in reference stars 1, 2, 3, 4, and 7 in the lower panel.
Figure 2.11: Average $K$ magnitudes of $N$ reference stars as a function of individual magnitudes. Top panel contains the average magnitudes of $N_{\text{STAR}} = 7$ (all comparison sources), while bottom panel has $N_{\text{STAR}} = 3$ (stars 2, 3, 4) on the $y$ axes. Stars 2, 3, and 4 have tighter linear relationships with $N_{\text{STAR}} = 3$ than $N_{\text{STAR}} = 7$ average magnitudes, while stars 1, 5, 6, and 7 have no correlation with either averages.
tainty in $m_{0,s}$ was propagated as $\delta m_{0,s} = (\delta m_{0,z}^2 + \delta m^2)^{1/2}$.

For infrared observations, the dithered exposures were combined to a single image, from which the $z$-magnitudes and associated uncertainties of a single star, $(m_{i,z}, \delta m_{i,z})$, were extracted. Recall that for optical observations, however, the set of $M = 4$ images were not added in IRAF. Instead, phot magnitudes and Poisson errors were extracted for each image of the nightly set and averaged post IRAF. The $z$-magnitude for star $i$ in a single night of observation is then the sum of each $j$ exposure divided by the number of exposures $M$, i.e.,

$$
m_{i,z} = \frac{\sum_{j=1}^{M} m_{i,z,j}}{M}.
$$

(2.3)

Its associated error was propagated as the standard error of the mean (SEM):

$$
\delta m_{i,z} = \sqrt{\frac{\sum_{j=1}^{M} (m_{i,z,j} - m_{i,z})^2}{M(M - 1)}}.
$$

(2.4)

For most observations, $M = 4$, but on rare occasions $M$ may be as low as 2 if one or more of the exposures taken were of insufficient quality.

These procedures were implemented in the IDL scripts I developed for this work, ccd_mags.pro and ir_mags.pro, which output tables of JD, standard magnitude, and standard magnitude error for optical and IR filters, respectively. See Table 2.3 for sample observations and magnitude information.
Table 2.3. Sample 2012/13 Observations of KH 15D

<table>
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<tr>
<th>Julian Date</th>
<th>$I$ (mag)</th>
<th>$\Delta I$ (mag)</th>
<th>$V - I$ (mag)</th>
<th>$\Delta(V - I)$ (mag)</th>
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Chapter 3

Results

Photometry from the most recent SMARTS season comprises over 130 nightly sets of observations in each of the $V/R/I/J/H/K$ filters. This multi-wavelength monitoring constitutes the most recent effort in a continuing campaign on KH 15D, and thus the results presented here span both time and wavelength domains. Below I provide an object description of the photometric behavior of the system during the 2012/13 observing season as well as in terms of the “secular” trends most easily seen in long-term $I$-band data. A quantitative and qualitative analysis will follow in the next chapter. For readability, I organize the long-term observations of the system into three epochs: 1995–2009, 2009–11, and 2011–13. These are distinguished in accordance with the modern model of KH 15D, where the dominant source of light variability is due to periodic eclipses of star A (K7; Hamilton et al. (2005)) between 1995–2009, to scattered light from the completely obscured binary between 2009–11, and now, to regular occultations of star B (K1; Capelo et al. (2012)).

3.1 Light Curves

Figures 3.1 and 3.2 display O/NIR light curves as a function of Julian date and phase, respectively. Data points with photometric errors exceeding 0.3 mag were flagged and removed, except in the case of $K$, where the uncertainties are inher-
ently larger, as discussed in the previous chapter. The latest season of SMARTS photometry shows a small but significant increase in maximum light from previous observations.

This season’s unfolded light curves (Figure 3.1) include ~ 4 cycles, characterized by 1) a relatively flat top when the star is (partially) unobscured near, presumably, apastron, 2) a bi-linear decline in flux during ingress, 3) a short, rounded minimum, and 4) a similar bi-linear rise in flux during egress. Indeed, the ingress and egress are best described by two regimes: shallower, strictly linear slopes bounding minimum light and steeper, more arched lines neighboring maxima. It is also apparent that the linear regime in near-IR (J/H) late ingress and early egress is shallower than that in the optical. The unfolded light curves show cycle-to-cycle variations, indicating that the eclipsing material is nonuniform and/or that the eclipsed stellar source has inherent variability.

Figure 3.2 contains the same O/NIR data but phased to KH 15D’s spectroscopically established period of 48.37 days (Johnson et al. 2004; Winn et al. 2004) and overlaid with available 2009–12 data. The system was expected to become brighter than $I \sim 14.5$ mag, the maximum out-of-eclipse flux prior to 2009, when the slightly later-type and presumably cooler/fainter K7 star was the source of eclipse. Remarkably, the system only reached $I \sim 14.8$ mag during maxima, brightening from 2011/12 by ~ 0.4 mag in $V$ and ~ 0.5 mag in $J$ and $H$. In addition, the most recent light curves exhibit broader maxima, lasting ~ 0.05 – 0.1 longer in phase from the 2011/12 season. This lengthening in duration of maxima is slightly longer toward the ingress (phase > 0.5) side than egress (phase < 0.5) in the optical, suggesting that visible light remains in bright phase (i.e., less obscured) longer as the star goes into eclipse than as it goes out of eclipse.

Figure 3.3 plots the system’s true $V/R/I/J/H/K$ magnitude during the 2012/13
3. Results

season against phase, where no $y$-offset is given and vertical line segments denote visually identified beginnings and ends of minima and maxima at each wavelength. Table 3.1 summarizes the measured eclipse properties. Indeed, the O/NIR observations indicate dramatically different eclipse shapes with wavelength. At near-IR wavelengths, the eclipse is boxier and the duration of nearly constant minimum light appears longer ($\sim 0.3$ in phase). At optical wavelengths, the eclipse is highly cusped and minimum light is shorter ($\sim 0.2$ in phase). Conversely, the duration of maxima appears to shorten slightly with increasing effective wavelength of observation. Due to uncertainty in assessing the beginning and end of ingress and egress, however, this result is not as significant. A more apt description concerning maxima is that their shape becomes more round with increasing wavelength.

Another notable feature in the phase-folded light curves is the slight rebrightening during minima, near phase 0. This effect is most prominent in $V$ and $I$, where the rebrightening reaches $\Delta \text{mag} \sim 0.5$. In $J$, there is a hint of brightness reversal at minimum; in the other filters, the minima are better characterized as large scatter. Moreover, the shape of central rebrightenings is not symmetric about phase = 0. This is most salient in $V$ (see Figure 3.3), where the rise in central rebrightening is shallower than decline from brightness reversal. As noted previously, gradual cycle to cycle variations persist in the O/NIR data, resulting in thicker phase folded light curves at maxima and minima. More abrupt changes are also evident in the data, and I defer interpretation to the following chapter.
3. Results

Figure 3.1: 2012/13 Johnson-Cousins VRIJHK magnitude as a function of Julian date.
Figure 3.2: Johnson-Cousins VRIJHK magnitude as a function of phase. Red represents observations during the most recent season (2012/13) while black represents previous observing seasons (2009–12).
Figure 3.3: 2012/13 O/NIR differential magnitude as a function of phase. Dotted lines through phases = 0.0, 0.5 are plotted for visual aid. Vertical line segments denote the beginning and end of minima and maxima; these are identified as apparent changes in the light curves and do not necessarily correspond to physical meaning.
### Table 3.1. 2012/13 Eclipse Properties of KH 15D

<table>
<thead>
<tr>
<th>Filter</th>
<th>Max (Mag)</th>
<th>Depth (Mag)</th>
<th>Early Egress (Mag/Phase)</th>
<th>Late Ingress (Mag/Phase)</th>
<th>$\Delta t_{\text{max}}$ (Phase)</th>
<th>$\Delta t_{\text{min}}$ (Phase)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$</td>
<td>16.1 ± 0.1</td>
<td>4.1 ± 0.2</td>
<td>-11.8 ± 0.1</td>
<td>10.9 ± 0.1</td>
<td>0.25 ± 0.3</td>
<td>0.20 ± 0.3</td>
</tr>
<tr>
<td>$R$</td>
<td>15.4 ± 0.1</td>
<td>3.6 ± 0.2</td>
<td>-10.9 ± 0.1</td>
<td>11.4 ± 0.1</td>
<td>0.24 ± 0.3</td>
<td>0.21 ± 0.3</td>
</tr>
<tr>
<td>$I$</td>
<td>14.9 ± 0.1</td>
<td>3.7 ± 0.2</td>
<td>-10.8 ± 0.1</td>
<td>10.1 ± 0.1</td>
<td>0.24 ± 0.3</td>
<td>0.21 ± 0.3</td>
</tr>
<tr>
<td>$J$</td>
<td>14.0 ± 0.1</td>
<td>3.4 ± 0.2</td>
<td>-9.2 ± 0.3</td>
<td>12.5 ± 0.3</td>
<td>0.23 ± 0.3</td>
<td>0.27 ± 0.3</td>
</tr>
<tr>
<td>$H$</td>
<td>13.2 ± 0.1</td>
<td>3.4 ± 0.2</td>
<td>-10.0 ± 0.1</td>
<td>11.7 ± 0.1</td>
<td>0.23 ± 0.3</td>
<td>0.30 ± 0.3</td>
</tr>
<tr>
<td>$K$</td>
<td>13.2 ± 0.1</td>
<td>&gt; 1.9</td>
<td>–</td>
<td>–</td>
<td>0.23 ± 0.4</td>
<td>–</td>
</tr>
</tbody>
</table>

Note. — Early ingress and late egress slopes were not calculated since they did not exhibit steady, linear behavior. $\Delta t_{\text{max}}$ and $\Delta t_{\text{min}}$ correspond to the durations of apparent maximum and of minimum, respectively, as identified in Figure 3.3. Also, due to the detection floor at $K \sim 16$ mag, the slopes of ingress and egress could not be determined accurately.
3.2 Colors

Figures 3.4 to 3.6 depict color variations as a function of observation date. It is worth noting that during dates corresponding to maxima (i.e., JD 2456235–JD 2456255, JD 2456285–JD 2456305, JD 2456330–JD 2456350), $V - R$ and $V - I$ colors are constant while $V - J$, $V - H$, $R - J$, $I - J$, and $I - H$ have “shoulders” bluer than the median color. The locations of these shoulders vary from cycle to cycle; the first shoulder occurs closer to the ascent to maximum light while the second shoulder appears just before descent from maximum light. While the colors during maxima are relatively flat, there seems to be large scatter during and near eclipse.

Color variations are plotted as functions of phase to better elucidate periodic features in Figures 3.7 and 3.8. Across $V - R$ through $V - H$, blue humps coincide with phase = 0, where the rebrightenings in $V$ and $I$ occur. The “shoulders” mentioned earlier are also noticeable in $V - J$ and $V - H$. Near the beginning and end of maxima (phases 0.25, 0.75), the color profiles are especially cusped. While the shoulders in $V - K$ are consistent with increased bluing from $V - I$ to $V - J$ to $V - H$, the severity of bluing beyond 0.25 and 0.75 phase is not a reliable measure of the system’s characteristics, since the signal hits the detection floor at $K \sim 16$ mag near those phases.

The color-phase plots of $V - I$ and $V - H$ also demonstrate asymmetry between ingress and egress, where the descent from maximum is steeper than the ascent to maximum. This effect is more prominent in the latter plot, whose color profile exhibits additional asymmetry in that the system’s bluing is more severe near descent from (phase = 0.75) than ascent to (phase = 0.25) maxima.

Figure 3.8 presents the color information plotted on the same scale for easy
visual comparison. No offset is introduced, so the data points reflect the system’s true colors. The color profiles are ubiquitously redder with increasing wavelength difference, except in the case of $V - K$ where there are large uncertainties outside of maxima. Indeed, from $V - R$ to $V - K$, the duration of constant color shortens while the cusping effect (blue shoulders) becomes more noticeable.

Figures 3.9 and 3.10 show various colors as a function of $V$ and $I$ magnitudes, respectively. The latter plot is especially useful since the most complete long-term data exist in $I$-band (see next subsection for presentation of all existing $V - I$ vs. $I$ data). In general, the behavior of color–$V$ plots can be divided into three regimes: 1) as the system’s total $V$ brightness declines to $\sim 18$ mag, the $V - R$ and $V - I$ colors remain constant while both $V - J$ and $V - H$ become slightly bluer; 2) from $V = 18$ to 19.5 mag, the system reddens by a small amount across all colors; 3) during the deepest minima ($V > 19.5$ mag), the system reddens more sharply overall. Regime 3 reddening is most extreme in $V - R$, and the degree of reddening lessens in $V - I$, more still in $V - J$, until in $V - H$ the reddening in regime 3 appears to be a continuation of regime 2 reddening. A similar trend exists for $I - J$ and $I - H$ vs. $I$, both of which exhibit slight bluing as the system dims to $\sim 17$ mag, large scatter as its brightness declines furthermore, and finally sharp reddening as it plunges into minimum light. At the faintest $I$ magnitudes, there is significant spread in the $I - H$ color, such that both reddening and bluing take place simultaneously.
Figure 3.4: Color vs. Julian date for the 2012/13 observing season.
Figure 3.5: Color vs. Julian date for the 2012/13 observing season.
Figure 3.6: Color vs. Julian date for the 2012/13 observing season.
Figure 3.7: Color vs. phase diagram for 2012/13 data.
Figure 3.8: 2012/13 color vs. phase diagram, plotted against the same scale for easier comparison.
Figure 3.9: Color-Magnitude diagram for 2012/13 observations.
Figure 3.10: Color-Magnitude diagram for 2012/13 observations.
3.3 Long-term Behavior

Figure 3.11 presents the most complete modern $I$-band photometry for KH 15D, extending from 1995 to 2013. The apparent “strips” of data – each corresponding to a compressed observing season’s photometry – comprise the long-term light curve. The system’s long timescale evolution modulates the periodic variations within each vertical band of data. The system’s peak brightness lingered at $I \sim 14.5$ mag from late 1995 until about early 2006, and steadily decreased from then until late 2009, when maximum light never reached above 16.3 mag. The system spent nearly 2 years in its faint phase and then unexpectedly rebrightened in late 2011. The last compressed strip contains data from the most recent observing season. Indeed, as Capelo et al. (2012) pointed out, the system’s ascent from and descent into its faint epoch (2009–11) show remarkable symmetry. The lower envelope of the long-term light curve steadily decreased from $\sim 17$ mag in late 1995 to nearly 19 mag in late 2005, where the system’s minimum light has remained. The system’s minima seem to have a more gradual evolution whereas its maxima drop off and rise more sharply.

The bottom panel of Figure 3.11 shows the $V - I$ color, which is most complete from 2006 until 2013. The system seems to become bluer from 2006–08, i.e., during its descent into its faint epoch. Just prior to what is believed to be complete obscuration in late 2009, the system reddens by more than 0.5 mag. Coinciding with the ascent from total obscuration in 2011–13, the system as a whole blues slightly from its 2009–11 state.

In light of the symmetry in the $I$-band upper envelope modulation, a long-term color-magnitude diagram (Figure 3.12) is constructed with different plot symbols/colors representing different observing seasons to illuminate epochal be-
havior. A general trend can be observed for nearly all epochs: at brighter magnitudes the epochal color is relatively constant, then as the system’s light declines, the scatter in $V - I$ increases dramatically, creating a fan-like shape.

Despite the mirroring in $I$-band variations symmetric about mid-2010 (the gap between the two shortest vertical bands of data), the color behavior between 2007–09 and 2011–13 are drastically different. The system’s median $V - I$ color is $\sim 1.57$ mag in 2007–09 observations (red +’s) and $\sim 1.29$ mag in 2011/12 data (blue x’s) despite reaching the same maximum brightness at $I \sim 14.85$ mag. This past season’s data (2012/13 - black Δ’s) follow closely the 2011/12 trend, with a median $V - I$ color of $\sim 1.29$ mag as well. This indicates that the source of flux during 2011–13 observing seasons is different from that of 2007–09.
Figure 3.11: Long-term $I$-band light curve of KH 15D, extending from late 1995 to early 2013. The bottom panel shows the available $V - I$ color information.
3. Results

Figure 3.12: Long-term color-magnitude diagram of KH 15D, where red triangles represent data from 2002–08, purple circles depict data from 2009–11, blue triangles represent 2011/12 observing season, and black squares correspond to data from the most recent season. The median photometric errors are roughly 0.02 mag during bright phase ($I < 16.5$ mag), 0.1 mag during intermediate phase ($16.5 < I < 18$ mag), and 0.2 mag during the faintest phases ($I > 18$ mag).
Chapter 4  
Analysis & Discussion

In this chapter I revisit the results of the multi-wavelength SMARTS campaign and discuss their implications on the properties of the system. Existing models (Chiang & Murray-Clay 2004; Winn et al. 2006) are long overdue to be updated; they anticipated the chronology of complete binary obscuration followed by eventual emergence of star B, but failed to predict the precise timing of events. I consider a simple, phenomenological model to paint a current picture of KH 15D. I then use it in concert with more physical and robust (but outdated) models to analyze the photometric variations of the system. In particular, I note the anomalous features in the 2012/13 observations and offer qualitative explanations for their presence. Then, I investigate the long-term O/NIR color evolution of the system and characterize the size of grains in the obscuring medium, in light of the recent photometry revealing the re-emergence of star B. Finally, I speculate on aspects of the system that may account for such photometric variations.

4.1 The Return of Star B

Figures 4.1, 4.2, and 4.3 show the system’s long-term optical (2002–13) and near-infrared color (2003–13) behavior as a function of $I$ magnitude. The dotted lines indicate epochal median colors above $I \sim 16.5$ mag, when the stellar photosphere nears 100% coverage by the occulting screen. Note that near-infrared
photometry when star A was being regularly occulted are from Kusakabe et al. (2005). Their data span from December 15, 2003 – March 3, 2005 (JD 2452989.42 – JD 2453433.31).

The $V - I$ color-magnitude diagram clearly demonstrates two distinct colors corresponding to star A (2002–09) and star B (2011–13). Although the system was dimmer overall in $I$ during 2007–09 than 2002–07, the median $V - I$ of the earlier epoch ($1.59 \pm 0.09$ mag) is entirely consistent with that of the later one ($1.57 \pm 0.07$ mag). This color is attributed to star A, whose photosphere was periodically eclipsed by the ring until about 2009. As noted by Capelo et al. (2012), the bright phase color has changed dramatically in the more recent data, reaching a value of $V - I = 1.26 \pm 0.03$ in 2011/12, about 0.3 mag bluer than star A. This most recent observing season shows a median $V - I$ color of $1.25 \pm 0.02$ mag, which confirms that star B is continuing to rise and set above the occulting horizon, although its peak brightness is not nearly as high as previously expected.

Indeed, perhaps the most prominent feature of this year’s light curves is the fact that maximum light never reaches brighter than $I = 14.8$ mag (see Figure 3.1). From historical archives we know that the combined light of stars A and B amounted to $I=13.57 \pm 0.03$ mag (Winn et al. 2006). Modern (CCD) photometry informs us that star A has an unobscured brightness of $I = 14.47 \pm 0.04$ mag, implying that star B has at the least $I = 14.19 \pm 0.06$ mag. This signifies that star B’s photosphere is still significantly obscured by some (projected) portion of the circumbinary ring.

To specify the covering factor of the occulting screen upon star B further, I employ a phenomenological model to fit the relative flux of the system at maxima from 2005/06 to 2012/13. Similar to Winn et al. (2004)’s model, I treat the occulting material as a screen of size $L_{\text{ring}}$, velocity $v_{\text{ring}}$, and flux $f_{\text{ring}}$. The 2009–
Figure 4.1: Long-term color-magnitude diagram of KH 15D. Dotted lines correspond to median colors out of eclipse and dashed lines indicate system colors during intermediate phases after starset ($I = 17$ to 18 mag).
Figure 4.2: Long-term color-magnitude diagram of KH 15D showing variations in $I - H$ and $I - K$ color behavior. Dotted lines correspond to median colors out of eclipse and dashed lines indicate system colors during intermediate phases after starset ($I = 17$ to 18 mag)
Figure 4.3: Long-term color-magnitude diagram of KH 15D.
11 data when both stars were completely obscured illustrate the strong dependence of the flux of the ring on the phase of the binary period (Herbst et al. 2010). However, since the purpose of the model is to fit the stellar flux at maxima (near apastron), the time is only sampled every orbital period, and the flux of the ring is treated as “constant.”

In this simple picture of KH 15D (see Figure 4.4), the binary orbit is in cartesian coordinates such that the origin coincides with the center of mass. As the screen marches along the +x direction, the leading (trailing) edge will increasingly cover (uncover) portions of star A (star B)’s disc.

For the purposes of this exercise, the binary orbit is sufficiently characterized by a set of parameters \{M_A, M_B, a_A, a_B, e, P\} describing the masses and semi-major axes of star A and star B, eccentricity, and period of the binary orbit. Photometric and radial velocity measurements (Johnson et al. 2004; Hamilton et al. 2005; Herbst & Moran 2005; Winn et al. 2006) constrain the binary masses \( (M_A = 0.6 \, M_\odot, M_B = 0.7 \, M_\odot) \), eccentricity \( (e = 0.6) \), and period \( (P = 48.37 \, \text{d}) \). These values are taken to be fixed in order to solve for the semi-major axes \( (a_A = 0.15 \, \text{AU}, a_B = 0.13 \, \text{AU}) \) and thus perihelion and aphelion distances \( d_{p, A/B} \) and \( d_{a, A/B} \), which are used to describe the position and size of the screen.

I quantify the distribution of flux across the stellar discs using a quadratic limb darkening law

\[
I(r, t) = 1 - \alpha(1 - \cos \theta) - \beta(1 - \cos \theta)^2 , \quad (4.1)
\]

where \( \alpha \) and \( \beta \) are the limb darkening coefficients and \( \theta = \sin^{-1}(r/R) \) is the angle between the line of sight and the normal to the stellar surface. \( (\alpha, \beta)_A = (0.4554, 0.2088) \) and \( (\alpha, \beta)_B = (0.2564, 0.3188) \), appropriate for K7 (star A; T
\[ f_{\text{eclipsed}}(t) = \frac{\int_0^R (1 - \alpha (1 - \cos \theta) - \beta (1 - \cos \theta)^2) \times r (\gamma - \sin \gamma) \, dr}{\int_0^R (1 - \alpha (1 - \cos \theta) - \beta (1 - \cos \theta)^2) \times 2\pi r \, dr}, \quad (4.2) \]

where \( R, \theta, \) and \( \gamma \) have implied subscripts \( A \) or \( B \), depending on which star is under consideration. \( \gamma \), the opening angle of the chord, i.e., screen edge intersecting the circular disc, is \( 2 \cos^{-1}\left(\frac{R_A - h_A(t)}{R_A}\right) \) and \( 2\pi - 2 \cos^{-1}\left(\frac{R_B - h_B(t)}{R_B}\right) \) for stars \( A \) and \( B \), respectively. \( h(t) \) is the height of the segment on the stellar disc and represents photospheric coverage such that

\[
h(t) = \begin{cases} 
E_{ad} - (d_{a,A} - R_A) & \text{if } R = R_A \\
E_{tr} + (d_{a,B} + R_B) & \text{if } R = R_B 
\end{cases} \quad (4.3)
\]

Here, \( E_{ad} \) is the location of the advancing edge, determined by initial conditions, while \( E_{tr} \) is the coordinate of the trailing edge, given by \( E_{ad} - L_{\text{ring}} \).

The normalized flux of the system near apapse at \( t \) orbits is then

\[
f_{\text{sys}}(t) = \frac{1 + f_{\text{ring}} - f_{\text{eclipsed}}(t)}{1 + f_{\text{ring}}} \quad (4.4)
\]

I use the Levenberg-Marquardt technique mpfit (Markwardt 2009) to minimize \( \chi^2 \). One difficulty with understanding flux variations in KH 15D is extricating the changes due to stellar activity and those due to obscuration by the (evolving) circumbinary ring. Because stellar activity such as spot variation and flaring...
modulates flux emission at significant levels (above photometric uncertainties and changes due to precessing ring), the photometric error bars underestimate the uncertainties and are thus inflated by a factor of 2.

The best fitting parameters are \( \{ L_{\text{ring}}, v_{\text{ring}}, f_{\text{ring}} \} = \{ 100 \, R_\odot, 0.1 \, R_\odot / P, 0.13 \} \).

Figure 4.5 plots the corresponding \( I \) magnitude (converted from \( m - m_0 = -2.5 \log(f_{\text{sys}}(t)) \)) as a function of time. The simple model predicts that in the coming 4 cycles of the next observing season, star B will reach a mean brightness of \( I \sim 14.3 \) mag; the star will not rise completely above the ring horizon until mid 2014/15 observing season.

Although the model provides an adequate numerical match to the observations \( (\chi_r^2 = 1.6) \), the parameter uncertainties are not well-defined because the parameter space is unphysical and has degeneracies. Several underlying assumptions should be relaxed for a more robust fit and better error analysis. The most unphysical assumption here is that the screen is moving at a linear velocity across the binary orbit. It has been shown rigorously that the ring is precessing rigidly, i.e., has a constant (and slow) angular velocity. The assumption of constant linear velocity breaks down for long time integrations, and this must be further explored in future work. In the same vein, the time sampling is insufficient to well constrain the stellar radii, since ingress and egress are not fitted. I suspect this is why \texttt{mpfit} yielded extremely large uncertainties for \( R_A \) and \( R_B \). Furthermore, the parallel orientation of the straight screen edges is assumed for simplicity, but one can imagine that the occulting horizons may have different orientations, and furthermore the edges may be curved or have local humps. The next sections will review the possibility of local and global irregularities further.
Figure 4.4: Cartoon of KH 15D depicting geometry of phenomenological model. Upper panel illustrates the extent of the (nearly edge-on) binary orbit in $R_\odot$ in the center of mass frame, as well as the size of the obscuring screen $L_{\text{ring}}$. Lower panel is in the frame of star B at orbit $t$. $\gamma$ denotes the opening angle of the cord (occulting edge) which changes as a function of $t$ and moderates the stellar disc coverage by the screen. Note that since limb darkening is spherically symmetric, the slant of the leading or trailing edge will not affect the fractional flux obscured under the assumption that the edges are parallel with respect to each other.
Figure 4.5: The top panel is a plot of model $I$ magnitude vs. time overlaid with observed data values (black circles with photometric error bars). The red diamonds are predicted $I$ brightnesses for the four cycles of the next observing season. The bottom panel illustrates the residuals between the fit and the data. The error bars shown here are the standard deviation of magnitudes used to calculate $I$ brightness at various maxima ($0.5 \pm 0.05$ phase). The data points which deviate significantly from zero are attributed to stellar activity rather than photospheric coverage due to the motion of the occulting screen. See text for more details.
4. Analysis & Discussion

4.2 2012/13 Photometry

4.2.1 Cycle-to-Cycle Anomalies

Having established the current configuration of the system, investigations of the temporal and wavelength variations in the most recent SMARTS photometry may now be discussed in context. One of the most intriguing results in the 2012/13 light curves is the striking cycle to cycle variations. In particular, the shape of maxima during the last cycle is dramatically different from that of the other three (see Figure 3.1). It contains an extremely well-defined but asymmetric peak that occurs before phase = 0.5, followed by a remarkably linear decline in magnitude across all bands. A closer inspection informs us that the light profile of maxima actually grows more acute, i.e., more kinked, from one cycle to the next.

The first, and perhaps most mundane explanation for the linear decline in magnitude is the presence of a foreground object or obscurer. This can be easily verified or refuted since ∼ one week of data remain unreduced, and the signatures of an opaque foreground source should be incoherent with phase.

Can stellar activity cause the dramatic decrease in flux near maxima during the last cycle? Keep in mind that at this phase (0.4 − 0.6), star B’s photosphere is ∼ 50% above the trailing edge and its brightness would otherwise remain constant at the 0.1 − 0.2 mag level. This means the reduction from expected flux behavior is ∼ 45%, i.e., almost half of the revealed photosphere is covered in the last cycle. If this flux reduction is due to cold spots on the star, a common feature in weak-lined TTS, then the spot (or collection of spots) must cover ∼ 20% of the stellar hemisphere. While this value is consistent with typical covering factors (10 − 40%; (Bouvier et al. 1995; Herbst et al. 1994)), such a scenario would entail either the
recent appearance of spots or the combined effect of the gradual revealing of the stellar photosphere coinciding with rotational modulation of the stellar disc. This would be an exceptional event, indeed, on top of the serendipitous alignment of this system. Furthermore, because dark spots are simply regions of temperature contrast, their effect on the stellar continuum should decrease with increasing wavelength, given that the temperatures of spots are typically $\sim 750$ K lower than photospheric values (Bouvier & Bertout 1989).

The data, however, show remarkably similar linearity in the steady brightness decline across all filters. Linear fits to the anomalous data points yield slopes of 6.0 ($V$), 6.0 ($R$), 6.1 ($I$), 6.2 ($J$), 6.2 ($H$), 6.2 ($K$) $\pm 0.1$ mag/binary period, with mean $\chi^2_r$ values of 1.7. Although this particular feature is inconsistent with rotational modulation of spots, dark blemishes on star B are not unexpected, given the spottedness of its (presumably coeval) companion (Hamilton et al. 2005; Herbst et al. 2010).

Another means of explaining the anomalous data points near maxima is the presence of a local protuberance of material or curvature of the occulting edge, which is favorable over dark spots in the following way. As mentioned previously, the early onset of flux decline is wavelength independent. This grey attenuation of flux is consistent with the behavior of the system immediately after complete photospheric obscuration (see starset analysis in the next section). If the radius of curvature of the occulting edge is strong enough, it is conceivable that the translational and rotational motion of the screen’s trailing edge with respect to the stellar rotation axis will obscure more of the stellar photosphere. I note that Silvia & Agol (2008)’s treatment of the leading edge as a curved rim provided an adequate fit to the observed data during the epoch of star A.
4.2.2 Flux Reduction at the Point of Inflection

The regular occultations of star B allow the observer to probe the obscuring medium along the line of sight. A comprehensive understanding of the physical properties and fine structure in the ring requires detailed radiative transfer modeling, which I defer to future work. For the scope of this thesis, I make simple qualitative arguments to constrain the size of particles in the ring, which will hopefully provide incentive for future observations.

Although star B has not fully risen above the occulting edge, its geometric position with respect to the screen edge is relatively well-known and the light received at maxima (phase = 0.5) is direct. Thus, it can be used as one of two baseline fluxes for comparing the wavelength dependency of flux reduction. The point of inflection (POI) – a well-defined “kink” during ingress or egress where the brightness decline becomes quasi-linear – provides the second baseline. Each minimum is bounded by two such points (one during ingress and the other during egress), which mark the onset of 100% coverage of the photosphere. The magnitude corresponding to the POI is chosen as follows. Since $I$-band observations are most representative of the stellar photosphere, I define its phase as the POI phase for a particular observing season. Because the light curve is not always well-sampled at those phases, I interpolate the POI magnitude by extending the linear slope and the sharp drop off until these lines intersect near POI phase. Figure 4.6 shows the POI phase and magnitude for 2012/13 O/NIR data.

For a comparative analysis, I utilize available literature data to map the change in magnitude behavior at different epochs. Warm Spitzer IRAC observations from the Young Stellar Object VARiability (YSOVAR) project coincided with the 2011/12 SMARTS observing season, when star B was $\sim 40\%$ revealed. Additional
Figure 4.6: Observations used to determine the maximum and point of inflection magnitude for each filter. When data coverage is insufficient to extract a direct measurement, the point of inflection magnitudes are interpolated by determining the intercept of the linear ingress or egress with respect to the dashed vertical phase line.
I/J/H/K observations from 2003–05 when star A rose and set completely behind the occulting material are from Hamilton et al. (2005) and Kusakabe et al. (2005). These data are plotted in Figure 4.7 with overlays showing the POI phase and magnitudes at those epochs.

Figure 4.8 presents the wavelength dependence of eclipse depth at starset for star A and star B. Linear fits to the data produce slopes consistent with 0 at optical and near infrared wavelengths. This clearly demonstrates that at wavelengths shorter than 2.2 \( \mu \)m, the flux reduction is grey, i.e., constant with \( \lambda \). Note that although the larger \( \Delta \text{mag} \) value in \( K \) in the 2012/13 is enticing, I hesitate to call the bump a significant detection, especially since the point of inflection nears the S/N limit at \( K \sim 16 \) mag.

Neither grey scattering nor grey transmission is compatible with the behavior of interstellar dust, which are typically sub-micron in size. That the attenuation of light for both star A and star B is grey out to \( \sim K \) indicates the line of sight material is larger than the size of the wavelength of observation, or grain size \( a > 2.2 \mu \text{m} \). If the reduction of light is due purely to absorption, then the extinction efficiency, of \( \sim \)micron sized amorphous astrosilicate grains is consistent with the observed extinction curve. In particular, the tentative “bump” in \( K \) in the 2012/13 data coincides with a broad peak in the astrosilicate extinction efficiency curve centered around the \( K \)-band effective wavelength (Draine 2011).

Furthermore, the particles in the occulting ring must be similar in size at least on angular scales of the projected binary orbit (which is physically \( \sim 0.5 \) AU across), since star A probes a different line of sight from that of star B (i.e., leading edge vs. trailing edge of the occulting screen due to ring precession). However, I stress that the exact viewing geometry for KH 15D is not known, which makes mapping of the physical locations of the lines of sight difficult.
Figure 4.7: Same as Figure 4.6, but with 2003–05 and 2011/12 data from literature.
4. Analysis & Discussion

Figure 4.8: The flux reduction of KH 15D from maxima (X% coverage) to the point of inflection, or 100% coverage. Black diamonds correspond to data pertaining to star A where X = 0% at maxima; red circles denote star B in 2011/12, when X = 60% at maxima; blue triangles are data from the 2012/13 observing season when star B was X = 50% covered at maxima. The depth of eclipse at starset is roughly constant across optical and near-infrared wavelengths. See text for more discussion.

Moreover, the plot shows that at warm IRAC channels = [3.6 µm, 4.5 µm], the change in magnitude is a factor of 1.5–2 smaller than at shorter wavelengths. This reddening indicates that the obscuring medium is no longer opaque at 3.6 microns and that we are finally seeing the transmitted component of light from star B. Based on the lower limit on the grain size $a \sim 2.2 \mu m$, and assuming uniform distribution, an upper limit on the column density along the line of sight may be derived such that $N \sim 8.5 \times 10^6$ cm$^{-2}$. 
4.2.3 Ingress & Egress

The linear regime of star B’s ingress and egress during regular occultations are slightly asymmetric. In 2012/13 $V$ and $I$, late ingress is shallower than early egress; the reverse is true for $R$, $J$, and $H$ band light curves. Below (see Figures 4.9 to 4.12), I plot the phased $V/I/J/H$ light curves during the epoch of star B and their color-phase counterparts. Circles with blue hues denote 2011/12 observations while red hues correspond to the 2012/13 data. The intensity of each color indicates different cycles, where lighter shades are earlier in the observing season and darker shades are data from later in the season.

The $V$-band color-magnitude-phase light curves show a slight $V-I$ bluing effect near phase $= 0.3$ for 2012/13 data (red circles). The $J$ dataset also exhibits some hint of $I-J$ bluing at the 0.1 mag level after periastron passage near phase $= 0.2 - 0.3$. The same bluing effect can be seen near phase $= 0.2 - 0.3$ in 2011–13 $I-H$. Since the amplitude of bluing is greater in $I-J$ and $I-H$ while $J-H$ color has more scatter than trend, it follows that $I$-band brightness is relatively brighter at those phases. This bluing in $V$- and $I$-band light post periastron passage is consistent with a phenomenon prominent in classical T Tauri stars known as veiling.

Simulations (Artymowicz & Lubow 1996; de Val-Borro et al. 2011) and observations (e.g., DQ Tau; Basri 1997) of eccentric binaries show that accretion streams funneling material from the circumstellar disk are cut off from the parent stars near periastron, allowing accretion material to fall onto the stellar surfaces. This can result in accretion shocks, flares ranging from X-ray to millimeter (Salter et al. 2010), and/or hot spots, which overwhelm the continuum intensity, either via line emission filling in photospheric absorption lines or excess continuum emission.
Figure 4.9: $V$ and $V - I$ vs. phase plot for all available data on star B.
Figure 4.10: $I$ and $I - H$ vs. phase plot for all available data on star B.
Figure 4.11: $J$ and $I - J$ vs. phase plot for all available data on star B.
Figure 4.12: $H$ and $J - H$ vs. phase plot for all available data on star B.
(Petrov et al. (2011) and references therein). This “veiling” effect may manifest itself in small amplitude variations in broadband flux densities. In the case of KH 15D, where weak accretion has been detected (Hamilton et al. 2005, 2012), such events are not unfeasible since the stars come within $\sim 25 R_\odot$ at periastron. However, claiming a detection on the $\sim$ few tenths of a magnitude level would require better signal to noise and more rigorous analysis.

Another intriguing feature of these plots is the apparent small, but sinusoidal change in color as a function of phase for the 2012/13 data (red circles). This amplitude is extremely small, perhaps a couple tenths of a magnitude, and unconfirmed. These tentative oscillations in color-phase space have a node to node duration that is $\sim 0.12$ in phase. This, as well the slight bluing present in $V$ and $I$, warrants further analysis in the future.

4.3 Color Evolution

4.3.1 $V - I$

The long-term $V - I$ diagram (see Figure 4.1) shows that during recent years (2011–13), the system at intermediate faint phases ($I = 16.5$ to 18.5 mag) experiences little bluing beyond star B’s median photospheric color. By contrast, when star A was undergoing regular occultations, the system exhibited significant bluing near minima – in fact, this $\Delta(V - I) = 0.3$ mag corresponds exactly to the color of star B’s photosphere as revealed in recent data. This indicates that the blueness seen in 2002–09 observations immediately after star set is due to scattered light from (the then invisible) star B, the hotter and bluer of the pair. $V - I$ colors during faint phases from 2009–11, when both stars were completely obscured, also trace the blueness (notice the upper color envelope in Figure 4.1).
Table 4.1. Long-term System Colors

<table>
<thead>
<tr>
<th>Color (mag)</th>
<th>Observations (year)</th>
<th>Bright Phase Median (mag)</th>
<th>Faint Phase Median (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V - I$</td>
<td>2002-07</td>
<td>1.59 ± 0.05</td>
<td>1.47 ± 0.21</td>
</tr>
<tr>
<td>$V - I$</td>
<td>2007-09</td>
<td>1.57 ± 0.07</td>
<td>1.49 ± 0.26</td>
</tr>
<tr>
<td>$V - I$</td>
<td>2009-11</td>
<td>1.44 ± 0.26</td>
<td>1.44 ± 0.16</td>
</tr>
<tr>
<td>$V - I$</td>
<td>2011/12</td>
<td>1.26 ± 0.03</td>
<td>1.36 ± 0.15</td>
</tr>
<tr>
<td>$V - I$</td>
<td>2012/13</td>
<td>1.25 ± 0.02</td>
<td>1.35 ± 0.10</td>
</tr>
<tr>
<td>$I - J$</td>
<td>2003-05</td>
<td>1.04 ± 0.29</td>
<td>0.88 ± 0.18</td>
</tr>
<tr>
<td>$I - J$</td>
<td>2011/12</td>
<td>0.88 ± 0.07</td>
<td>0.75 ± 0.11</td>
</tr>
<tr>
<td>$I - J$</td>
<td>2012/13</td>
<td>0.88 ± 0.04</td>
<td>0.83 ± 0.15</td>
</tr>
<tr>
<td>$I - H$</td>
<td>2003-05</td>
<td>1.71 ± 0.29</td>
<td>1.38 ± 0.23</td>
</tr>
<tr>
<td>$I - H$</td>
<td>2011/12</td>
<td>1.56 ± 0.07</td>
<td>1.42 ± 0.14</td>
</tr>
<tr>
<td>$I - H$</td>
<td>2012/13</td>
<td>1.62 ± 0.04</td>
<td>1.55 ± 0.16</td>
</tr>
<tr>
<td>$I - K$</td>
<td>2003-05</td>
<td>1.99 ± 0.27</td>
<td>1.77 ± 0.28</td>
</tr>
<tr>
<td>$J - H$</td>
<td>2012/13</td>
<td>1.73 ± 0.07</td>
<td>1.33 ± 0.33</td>
</tr>
<tr>
<td>$J - H$</td>
<td>2011/12</td>
<td>0.68 ± 0.01</td>
<td>0.55 ± 0.03</td>
</tr>
<tr>
<td>$J - H$</td>
<td>2012/13</td>
<td>0.68 ± 0.02</td>
<td>0.65 ± 0.09</td>
</tr>
<tr>
<td>$J - K$</td>
<td>2003-05</td>
<td>0.73 ± 0.03</td>
<td>0.71 ± 0.10</td>
</tr>
<tr>
<td>$J - K$</td>
<td>2012/13</td>
<td>0.97 ± 0.03</td>
<td>0.97 ± 0.03</td>
</tr>
<tr>
<td>$I - K$</td>
<td>2012/13</td>
<td>0.86 ± 0.09</td>
<td>0.86 ± 0.08</td>
</tr>
</tbody>
</table>

set by star B.

4.3.2 System Reddening

The long-term O/NIR color plots (see Figures 4.1, 4.2, and 4.3) compare the color behavior between the epoch of star A vs. star B. It is apparent that the colors redden at the faintest phases (beyond $I \sim 18.2$ mag), especially in the most recent season (2012/13). At $I \sim 18.7$ mag, $I - J$ and $I - H$ colors reach +1.5 and +2.3 mag, respectively, which roughly correspond to colors $\sim 0.5$ mag redder than star A. In $J - H$, the system reddens to +1 mag, about 0.3 mag redder than the median color of star B before it sets completely behind the occulting screen. See Table 4.1 for list of median bright and faint phase colors.

Furthermore, the $J - H$ vs. $J$ (see Figure 4.3) plot reveals an unexpected phenomenon at bright phase. Whereas the median bright phase color of star B
is ubiquitously bluer than that of star A in $V-I, I-J, I-H, I-K, J-K$, the 2012/13 data show a redder color in $J-H$ than 2003–05 data. Theory and observationally derived intrinsic $J-H$ colors ([Ducati et al.](2001)) both indicate that the later-type star (A) should be redder (by $0.1-0.2$ mag) than the earlier-type star (B), and not the other way around. Moreover, 2011/12 data – when star B was $\sim 10\%$ more covered than now – seem to agree quite well with star A’s $J-H$ color.

Unfortunately, the $J-H$ excess of star B in 2012/13 is about $0.05 \pm 0.03$ mag, just slightly better than a 1σ detection. While this is not a robust detection, its presence, in conjunction with the severe reddening in $I-J, I-H,$ and $J-H$ at the faintest phases, invite intriguing possibilities and certainly warrant future observational attention for confirmation or refutation.

If the infrared excess is due to the presence of a third object which injected $\sim 0.05$ mag in the composite $H$-band flux, then the radiating body must have $H \sim 17$ mag. Given the distance $= 760$ pc to NGC 2264, the third body would have an absolute $M_H = +8$ mag, consistent with $\sim$Myr old “hot start” 10 $M_J$ planet ([Fortney et al.](2008) [Spiegel & Burrows](2012)). Physical models of KH 15D necessitate the presence of a truncation mechanism to maintain the finite width, warp, and precession of the circumbinary ring at $\sim 5$ AU ([Chiang & Murray-Clay](2004)). If the shepherding body is a super-Jupiter orbiting in (or near) the plane of the central binary, then every few years or so the planet would be on the far side of the ring, which may explain why $J-H$ was not as red in previous years of data. Indeed, $J-H$ colors during the epoch of star A show no hint of reddening even at faint phases. The speculative nature of this discussion must be emphasized, but continued photometric and/or spectroscopic monitoring of the system in the near-infrared should help disambiguate the possible $H$-band excess reported here.
Chapter 5

Conclusions

5.1 Summary of Results

In this work, I present multi-wavelength $V/R/1/J/H/K$ photometry of KH 15D, a close, eccentric T Tauri binary system embedded in a circumbinary ring. The most recent optical and near-infrared observations reveal the continued “secular” rise of star B above the obscuring horizon as it undergoes periodic occultations. The data show that star B’s photosphere is only $\sim 10\%$ more revealed in 2012/13 than in 2011/12. Furthermore, the light curves in this observing season have significant cycle to cycle variations, even near maxima when we are seeing direct light from the star. In particular, I attribute the wavelength independent linear decline in flux during the last maxima of the season to local protuberances in the occulting region.

As a pedagogical exercise, I employ a basic phenomenological model to fit the fractional $I$ flux of the system during maxima in the past $\sim 8$ years. The best fit model yields a $\chi^2_r = 1.6$, which is a modest fit given the simple assumptions of the model. If the historical data revealing the brightness of the uneclipsed binary are correct and model approximations still hold true, then star B will reach $I \sim 14.4$ mag in the next observing season and will not rise completely above the occulting horizon until late 2014.
5. Conclusions

The depth of eclipse at starset, i.e., the flux reduction between maxima and the point of inflection, has no dependence on $\lambda$ at optical and near-infrared wavelengths. This signifies the obscuring medium has grains of size $> 2 \mu m$, consistent with previous studies \cite{Knacke2004, Kusakabe2005, Silvia2008}. Moreover, archival observations with Spitzer IRAC channels 1 and 2 exhibit reddening, which indicate that the ring is becoming transparent at those wavelengths.

Additionally, I present the long-term color evolution of KH 15D, based on recent multi-wavelength SMARTS monitoring and $J/H/K$ data from literature. The long-term $V-I$ vs. $I$ plot clearly demonstrate dominance of star B’s scattered light within the system during faint phases of all epochs, including when star A was being regularly occulted (until $\sim 2009$) and both stellar photospheres were obscured (2009–11). I report on the deep reddening of the system across O/NIR colors during the faintest phases that is more prominent in the most recent data. Finally, I note the slight reddening reversal in $J-H$ color between star A and star B at bright phases, when we are observing direct light from the stars. Although further observations are needed to confirm or refute this tentative detection, the difference in the system’s bright phase $J-H$ color between 2011/12 and 2012/13 observations is consistent with “hot start” radiation signatures of young giant planet invoked to maintain rigid precession in the ring.

5.2 Future Work

A deeper understanding of the system’s geometry and evolution necessitates an up-to-date and robust dynamical model. This was beyond the scope of this thesis. However, simple improvements can be made to the basic phenomenological
model in the following ways. First, to better constrain the periodic and secular evolution of the system, finer time sampling is needed for a full solution of Kepler’s equation and the binary orbit with respect to the ring. Once the orbit is better specified, more physical parameterization of the ring, such as differential inclination and alignment of nodes, introducing curvature to the occulting edges, as well as providing a full treatment of precession, may be implemented. The error analysis performed here would be insufficient; a more robust means of estimating uncertainties would be to employ a more statistical approach such as the Monte Carlo method or its variants. One could potentially perform simultaneous spectral energy distribution fitting by solving the radiative transfer equation to better understand the properties of the circumbinary ring. Before delving into further modeling, however, a better understanding of error analysis and model parameter space, i.e., degeneracies, is crucial.

On the observational side, continued monitoring of the system in $J$, $H$, and $K$ may address the apparent red excess at the faintest phases as well as the nature of the reddening in $J - H$ at relatively bright phases. A Gemini near-infrared (GNIR) proposal has been put forth and spectra at three brightness phases are being obtained, with bright and intermediate phases in hand. These new spectra will hopefully provide insight into the possible excess $H$-band flux. It would be interesting to revisit the GNIR results reported in H. Capelo’s thesis, and compare the relative strengths of the spectral region around $\lambda = 1.6 \mu m$ between 2011/12 and 2012/13 to see if they match the color difference observed in the photometry.

Furthermore, in the coming seasons, most of star B’s photosphere will be revealed, lengthening the duration of maxima. This will provide an excellent means of studying stellar properties such as spot activity and distribution, since the signal to noise will increase greatly as star B nears its peak $I \sim 14$ mag.
5. Conclusions

Unless star B’s rotational axis is pole-on to the line of sight, rotationally-induced spot variations should be observationally feasible. The most direct route is to investigate out-of-eclipse variations, like was done on star A by Hamilton et al. (2005). An alternative or complementary method is to examine the color-phase information. Reddening (bluing) should be present as the star is rising above (setting behind) the occulting edge, since more of the cooler regions of the stellar disc is being revealed (obscured).

KH 15D’s membership as a weakly-accreting T Tauri star was derived from observations when star A was being regularly occulted. Determining whether star B’s activity is similar to that of its later-type companion would help inform binary star interactions and (co)evolution. In particular, Chandra observations which coincide with the warm Spitzer data already exist in the archives and may be a potential goldmine for assessing stellar activity. It would be interesting to apply the same method of study as Herbst & Moran (2005), who found that star A’s X-ray light was significantly underluminous for its WTTS and cluster identification.

Despite nearly two decades of monitoring, KH 15D continues to pose interesting astrophysical problems and challenge modern understanding. By good fortune, however, its serendipitous alignment bestows a time-limited window of opportunity for the discerning observer to probe the system in unique ways and answer those very questions it poses.
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