Examining the Near-Infrared Properties of KH 15D with Spitzer Photometry and GNIRS Spectra

by

Nicole Annemarie Arulanantham

Faculty Advisor: Dr. William Herbst

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And when you look at the sky you know you are looking at stars which are hundreds and thousands of light-years away from you. And some of the stars don’t even exist anymore because their light has taken so long to get to us that they are already dead, or they have exploded and collapsed... And that makes you seem very small, and if you have difficult things in your life it is nice to think that they are what is called negligible, which means they are so small you don’t have to take them into account when you are calculating something.

—Mark Haddon

The Curious Incident of the Dog in the Night-Time
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# Contents

1 Introduction ........................................... 1
   1.1 Early Observations & Models ....................... 1
   1.2 Arriving at the Current Model ..................... 4
   1.3 A New Era of Observations ......................... 8
   1.4 What We Still Want to Know ....................... 12

2 Data & Methods ........................................ 15
   2.1 ANDICAM Photometry ............................... 16
   2.2 Spitzer Photometry ................................ 19
       2.2.1 Observations ................................ 19
       2.2.2 Data Reduction .............................. 20
   2.3 GNIRS Spectra ...................................... 28
       2.3.1 Observations & Preliminary Reductions .... 28

3 Results ............................................... 31
   3.1 ANDICAM Photometry ............................... 31
       3.1.1 Long-Term $I$ Band Evolution: Star B Emerges 31
       3.1.2 Cycle-to-Cycle Variations ................... 34
       3.1.3 Color Evolution ................................ 38
       3.1.4 $K$ Band Photometry and Color Evolution ..... 40
3.2 Spitzer Photometry ......................................... 44
   3.2.1 Light Curves ......................................... 44
   3.2.2 Color Evolution ...................................... 46
3.3 GNIRS Spectra ............................................. 48
   3.3.1 Faint Phase Emission Lines ....................... 48
   3.3.2 Reflectance Spectra from Forward Scattered Light . 55
   3.3.3 Potential to Detect Giant Planet Signatures ....... 57

4 Analysis ....................................................... 63
   4.1 Preparing CMDs at Spitzer Wavelengths .......... 63
      4.1.1 Interpolation of Phase-Folded I Band Photometry ... 64
   4.2 Modeling Reddening at Spitzer Wavelengths ........ 66
      4.2.1 Application of Spitzer Extinction Model to I-K Colors ... 72
   4.3 H2 and He I Emission as Outflow Signatures ........ 74
      4.3.1 Deriving an Excitation Temperature for Shocked H2 ... 74
      4.3.2 He I Chromospheric Emission ...................... 80
   4.4 Evidence for Solar System Minerals in the Ring ..... 81
      4.4.1 Identification of Mineral Features ............... 82

5 Summary & Conclusions ..................................... 87
   5.1 Summary ................................................. 87
   5.2 Future Work ........................................... 90
      5.2.1 Why study a protoplanetary environment in the near-IR? ... 90
      5.2.2 Could there be stronger emission near periastron? .... 91
      5.2.3 Can we identify signatures of a planet? ............ 92

Bibliography .................................................. 94
Chapter 1

Introduction

KH 15D is a T Tauri binary system located in the 3 Myr open cluster NGC 2264 ($d \sim 760$ pc). The two stars are embedded in a circumbinary ring that is observed to be optically thick at optical and into the near-infrared. The ring is slightly inclined with respect to the orbital plane of the stars and acts as a natural coronagraph by causing a decrease in brightness when the reflex motion of the stars carries them behind it. When the system is faint, we can extract detailed information about its behavior at wavelengths that are normally dominated by starlight. While such systems are likely quite common, KH 15D is the only known object with such an orientation along our line of sight. Its observational history will be presented in this chapter along with a description of the currently accepted model of the system and an outline of the questions that will be answered in this thesis.

1.1 Early Observations & Models

V582 Mon, also known as KH 15D, was first noted to have unusual properties when it was included in a survey of variable stars in the open cluster NGC 2264 (Kearns & Herbst 1998). It was previously classified as an irregular variable because it underwent $\sim$1 mag fluctuations, which are standard for young objects (Badalian & Erastova 1970; Hamilton et al. 2005). However, KH 15D stood out
1. Introduction

from the other survey objects because of the $\sim 3$ mag brightness variations it exhibited in strictly periodic fashion (Kearns & Herbst 1998). In addition to undergoing periodic variability, the system was unusual because it remained in its faint state for a very long time ($\sim 15$ days). The extended duration of minimum light indicated that the variations were eclipses caused by a circumstellar feature rather than intrinsic stellar variability. A second star was ruled out as a possible occulting body by the long duration of the eclipses and a mid-eclipse increase in flux that occurred during all of the cycles observed (Kearns & Herbst 1998).

Additional observations of KH 15D were required to identify the source of the eclipses and come up with a model that accounted for all the unusual properties of its light curve. The object was monitored from 1995-2001 in the Cousins $I$ band using the Perkin telescope at Van Vleck Observatory (Hamilton et al. 2001). The phase-folded light curves showed that the amount of rebrightening at mid-eclipse decreased over that five-year span and that the duration of minimum light lengthened over the years. The object was classified as a weak-lined T Tauri star (WTTS) with spectral type K7 V from low resolution spectra, but higher resolution data were required to derive a radial velocity measurement for the star. Subsequently, echelle spectra ($R \sim 40,000$) were obtained in 2003 with the UV-Visual Echelle Spectrograph on the VLT (Hamilton et al. 2003). The spectrum acquired at ingress returned a radial velocity of $+9.0 \pm 0.2$ km s$^{-1}$ for the K7 star. During egress, this increased by $+3.3 \pm 0.6$ km s$^{-1}$ to a radial velocity of $+12.3 \pm 0.6$ km s$^{-1}$ (Hamilton et al. 2003). It was suggested that the system could be a spectroscopic binary, with a higher mass companion hidden by the circumstellar material. The orbital motion of the K7 star would then be responsible for the eclipses as opposed to an orbiting body (Herbst et al. 2002). However, the high resolution spectra still weren’t sufficient to confirm the presence of a second star.
Continued photometric monitoring revealed that the eclipse depth had increased to \( \sim 3.5 \) mag and its duration to about 20 days by 2003 (Hamilton et al. 2003). The properties of the light curve were attributed to occultations by an extended circumstellar dust feature whose microscopic constituents were too large to produce reddening. The mid-eclipse rebrightening events would then occur because of density minima within the feature that would briefly allow starlight to pass through. The large depth of the eclipses eliminated a transiting protoplanet as a possible occulting body, but the presence of a planet within the circumstellar material was not ruled out. Mass estimates of the K7 star placed it between 0.5 and 1.0 \( M_\odot \) (Hamilton et al. 2001), and its age was determined to be 2-4 Myr on the basis of its membership in NGC 2264. The object’s youth and similarity to the Sun continued to make it an appealing candidate for detailed study of the earliest stages of planet formation, in spite of its distance of 760 pc (Sung et al. 1997).

Optical observations of KH 15D were extended back in time when Winn et al. (2003) identified the system in archival plates from the Harvard College Observatory collection spanning the years 1913-1951. The variability did not exceed \( \sim 1 \) mag during this time period, casting doubt on the idea that the system contained a second, higher mass companion to the K7 star. The findings gave new life to the idea that an embedded protoplanet was periodically occulting the K7 star. Interactions between the protoplanet and the disk could produce density perturbations, which would form an optically thick ridge large enough to cover the entire star. The protoplanet would form a depression around itself as it moved through the ridge. Starlight would be able to pass through the material in the depression, causing the mid-eclipse rebrightenings (Winn et al. 2003).
Cycle-to-cycle variations in the properties of the system during eclipse introduced another level of complexity to understanding its components. Hamilton et al. (2003) examined the Hα and Hβ emission features and found that the equivalent width of the Hα line during the faint phase was more indicative of a classical T Tauri star (CTTS) than a WTTS. Furthermore, the presence of the [O I] λ6300 line implied that the system was undergoing larger amounts of accretion than a typical WTTS and, in fact, driving a bipolar jet (Hamilton et al. 2003). Another unexpected property that was noted during eclipse was the slight bluing of the system during ingress. Agol et al. (2004) proposed scattering as an explanation and tested this by comparing the polarization of starlight when the K7 star was unobscured to its polarization during minimum light. The light was essentially unpolarized out of eclipse but increased to 2% polarization near mid-eclipse, while the shape of the optical spectrum did not change detectably from the bright to the faint phase. This implied that the polarization, and therefore the scattering, is only weakly dependent on wavelength. Mie scattering by relatively large dust grains (∼6-8 μm in diameter) was the most likely explanation. These grains were confirmed to be circumstellar material, since the increase in polarization during the faint phase showed that the scattering region was not becoming obscured during eclipse. A model approximating the circumstellar material as a warped disk was able to successfully reproduce the light curve (Agol et al. 2004).

1.2 Arriving at the Current Model

In 2004, two independent groups developed similar quantitative models to describe the behavior of KH 15D (Winn et al. 2004; Chiang & Murray-Clay 2004). A key success of both models was their ability to account for the various unusual
properties of the system’s light curve, including its evolution over time. The system didn’t undergo deep eclipses between 1913 and 1950, although it did exhibit $\sim 1$ mag fluctuations. Eclipses over the 48 day period observed today were seen between 1967 and 1982, but the phase of minimum light was shifted by 180°, making today’s faint phases the bright phases during that epoch. The eclipse depth was shallower then, and the peak magnitude of the system was brighter. Since 1997, the duration of the eclipses had been increasing by $\sim 1$ day/year (Johnson et al. 2004).

To account for this evolution, Winn et al. (2004) proposed that KH 15D was a binary system with a slightly more massive and luminous companion to the K7 star. The orbital path of the stars was being covered by an opaque, sharp-edged screen migrating across the orbit at a roughly constant speed of 13 m/s. Assuming a total stellar mass of $\sim 1 M_\odot$ for both components, material with such a slow orbital speed would need to be located at a distance of 25 pc. Since this was too distant for the material to remain bound to the system, Winn et al. (2004) proposed that the screen was a precessing circumbinary disk. Although this model was able to replicate many features of the light curve, the ingress and egress it predicted were somewhat sharper than what was observed. At the time, the discrepancy was attributed to the assumption that the screen edge was perfectly sharp and straight. The model was not able to predict the long-term behavior of the system, since the trailing edge of the screen had not yet been located and it was unclear from the archival photometry when exactly the eclipses had begun (Winn et al. 2004).

Chiang & Murray-Clay (2004) also put forth a similar model of KH 15D. They modeled the system as an eccentric binary undergoing eclipses when the reflex motion of the stars carried them behind an opaque screen, which was the
1. INTRODUCTION

projection of a circumbinary ring on the plane of the binary orbit. This model required the ring to be relatively thin (both radially and vertically) and warped in order for thermal pressure or self-gravity to act in a direction normal to the ring plane and maintain a rigid ring that could undergo precession. Thermal pressure and ring self-gravity were modeled individually, and both were considered viable possibilities. Tidal forces from the binary could maintain the inner radius of the ring, producing an inner hole that would explain the absence of detectable near-infrared excess. However, a third body such as a planet or small star would be required to shepherd the outer edge. Such a ring could be detected between 10-100 µm, and a flux density of 3 mJy was predicted at these wavelengths (Chiang & Murray-Clay 2004). Although it was noted from observations that the binary companion is \( \sim 20\% \) brighter than the K7 star, both components were modeled as 0.5 \( M_\odot \) objects. Neither of the two models included a contribution from scattered light, but it was expected to set the level of minimum flux in each of the model light curves. The Chiang & Murray-Clay (2004) model correctly predicted that the system would cycle backwards as the line of nodes continued to precess over a timescale of \( \sim 1000 \) years but expected the system to remain in a faint, fully occulted state for decades.

Winn et al. (2006) subsequently updated their model of KH 15D. The properties of star A were fixed at an effective temperature of 4000 K, a luminosity of 0.4 \( L_\odot \), a radius of 1.3 ± 0.1 \( R_\odot \) and a mass 0.6 ± 0.1 \( M_\odot \), similar to the 2004 model. The archival photometry showed that star B is more luminous than star A, and the ratios \( M_B/M_A = 1.2 \) and \( R_B/R_A = 1.05 \) were derived. The mass of star B was left as a free parameter; the previous model had returned \( M_B < M_A \), even though star B was the more luminous of the two. This was attributed to the earlier assumption that the screen migrated across the plane of the binary orbit at a
1. Introduction

constant velocity. A better fit was obtained when the screen was allowed to rotate or move with constant acceleration. However, the model was unable to distinguish which scenario (or combination of the two) was closest to reality. Another addition to the model accounted for the measured rotation period of star A, which, at 9.6 days, was noticeably slower than other WTTS in NGC 2264 (Hamilton et al. 2005). It was suggested that star B had slowed the rotation of star A through pseudosynchronization of the binary components, which forces the stellar spins to reach an equilibrium with the orbits in tight systems. This was supported by the system’s low x-ray luminosity \( L_X/L_{bol} = 7.5 \times 10^{-5} \), which was attributed to low production of high energy photons due to tidal interactions at periastron (Herbst & Moran 2005). Accordingly, an upper limit of 0.66 was placed on the eccentricity (Winn et al. 2006), in agreement with the value obtained by Herbst & Moran (2005).

To account for the model’s deviation in the slope of ingress and egress, Winn et al. (2006) surrounded each star with an asymmetric, extended “halo” of light. The idea of the halo was challenged in 2008, when forward scattering off of particles at the edge of the circumbinary ring was proposed as a more likely mechanism for the gradual slope of ingress and egress as well as the mid-eclipse rebrightenings (Silvia & Agol 2008). Around optical depths \( \tau \sim 1 \), dust grains in the ring scatter the starlight. This allows us to see the star even after it is completely covered by the screen and causes the slopes of ingress and egress to become less sharp. The grains responsible for the forward scattering are expected to follow the relation \( a \sim 6(D/3\text{AU})\mu\text{m} \), where \( a \) is the diameter of the grain and \( D \) is the distance in AU between the center of mass of the star and the edge of the ring (Silvia & Agol 2008). In addition, introducing “fuzziness” to the edge of the ring as opposed to maintaining a sharp knife-edge led to a much better match between the model
and the data. The mass ratio $M_B/M_A = 1.2$ (Winn et al. 2006) was used, but the mass of star B was fixed at $M_B = 0.72 \pm 0.1 M_\odot$ rather than being left as a free parameter. The forward scattering model returned an eccentricity of $e = 0.51$ (Silvia & Agol 2008), which was well below the previously established upper limit of $e = 0.66$ (Winn et al. 2006).

### 1.3 A New Era of Observations

Observational confirmation of the existence of star B came after studying 16 high resolution spectra collected between October 2002 and February 2004 using HIRES/Keck I, MIKE/Magellan II, and the CE spectrometer on the 2.1 m telescope at McDonald Observatory (Johnson et al. 2004). All 16 spectra were obtained during the bright phase, when the entire surface of star A was directly visible. The radial velocities measured for star A varied by up to 10.7 km s$^{-1}$. The magnitude of these variations confirmed the presence of a second star in the system. An orbital solution was fit to the radial velocity measurements and returned an orbital period of $48.38 \pm 0.01$ days, consistent with the observed period of the eclipses. This provided support to a model in which the eclipses were caused by the orbital motion of star A as opposed to a dust feature orbiting a single star, but emission from a circumbinary ring had yet to be detected.

Although the models of KH 15D as a binary provided good fits to the observational data, they could be improved by filling in gaps in the historical light curve. A set of 87 photometric plates obtained from all over the world between 1954-1997 were examined, and it was confirmed that the system had been $\sim$1 mag brighter in previous decades, presumably when the orbit of star B was not yet hidden by the occulting screen. The new photometry called into question the previous
assumption that no eclipses had occurred between 1951 and 1965. Although 0.5 mag variations were observed, the data were not sufficient to determine whether the fluctuations were irregular or periodic (Johnson & Winn 2005).

Previous studies of archival photometry had been primarily conducted in the $I$ band, and therefore it hadn’t been possible to see whether the system’s colors had evolved since photometry was first collected. The international set of plates analyzed by Johnson et al. (2005) contained a wider range of bandpasses, including 18 pairs of plates obtained simultaneously in different bands. The past behavior of the colors was similar to modern observations, with the optical colors remaining about the same through all phases except for a slight bluing during mid-eclipse. Furthermore, the system’s colors had remained constant to within about 0.2 mag over the time period that the plates spanned. However, an analysis of the system’s colors in the near-infrared later revealed color excesses of $E(I - J) = +0.6$ mag and $E(I - H) = +0.7$ mag during minimum light (Windemuth & Herbst 2014).

Photometric monitoring of KH 15D was extended to near-infrared wavelengths by observing in the $JHK_S$ bands (Kusakabe et al. 2005). The measured near-IR period was the same as the optical period, and the light curves showed that the eclipse depth and duration were also similar to the system’s behavior in the optical bands. The possibility that the observed bluing during ingress was caused by a background source was ruled out on the basis that there was no observable position shift in the system; therefore, it was unlikely that another object could appear. A model of the near-infrared photometry suggested that the scattering particles were on the order of 5 $\mu$m, but the constraint on the size of the particles causing the gray attenuation of light during eclipse was much looser at $a \gg 2$ $\mu$m (Kusakabe et al. 2005).

The discovery of KH 15D’s unusual properties had sparked a worldwide ob-
serving campaign. Between 1995 and 2004, KH 15D was observed photometrically at USNO, VVO, Tenagra Observatory, Lick Observatory, Mount Maidanak Observatory, Konkoly Observatory, Teide Observatory, European South Observatory (ESO), and CTIO. Although there were some inconsistencies in data collection, the wealth of well-sampled photometry allowed for careful measurement of long-term trends. The eclipse duration had been increasing by $\sim$1-2 days/year since 2001, so the system remained in the faint phase for nearly half the orbital period by 2004 (Hamilton et al. 2005). This was consistent with the near-infrared observations, which showed a similar duration of the faint phase (Kusakabe et al. 2005). It was also noted that the eclipse depth had been increasing by about 0.2 mag/year since 1995 while the magnitude of the rebrightening at mid-eclipse became fainter (Hamilton et al. 2005). These observations were all consistent with the models of KH 15D as a binary system (Winn et al. 2004, 2006; Chiang & Murray-Clay 2004; Silvia & Agol 2008).

The long-term light curve displayed one data point from the first set of photometry obtained at VVO in which the system was much brighter than in any subsequent observations. Since the phase of the data point corresponds to mid-eclipse, this was later understood to be an observation of star B when it was at periastron. Although the orbit of star B was completely occulted by the screen soon after the point was collected, it was estimated to have an $I$ band magnitude of $14.01 \pm 0.01$ (Hamilton et al. 2005).

The color evolution of KH 15D has now been examined in some detail. The CTIO and USNO observations were used to compare colors over several phases and, again, showed a bluing effect after ingress and a significant change in the slope of the light curve at a phase of $\sim$0.17 (Hamilton et al. 2005). However, the effect was not completely uniform from cycle to cycle. The color changes were
initially attributed to either star B or the presence of small grains that would undergo wavelength dependent scattering, but the bluing was later considered to be an effect of forward scattering (Silvia & Agol 2008).

By 2010, the sharp-edged screen was covering the entire binary orbit and the system’s brightness was attributed solely to scattered light at all phases. The variations in flux during minimum light were revisited by examining photometry collected between 2005-2010. The fluctuations were attributed to either spots on the surface of star A and/or variations in the location of the disk edge between cycles. It was also noted that the location of the slope change at ingress was dependent on phase rather than magnitude of the system. The slope change was identified as the point in the light curve when star A was completely hidden by the ring material, so this implied that star A was disappearing from view at increasingly brighter magnitudes over time (Herbst et al. 2010).

Chiang & Murray-Clay (2004) predicted that the system would eventually rebrighten, but observational constraints prevented them from determining an exact timescale of light curve evolution (Winn et al. 2004, 2006; Chiang & Murray-Clay 2004). When the magnitude of the system at apastron began to get brighter in 2012, it was inferred that the trailing edge of the opaque screen was now beginning to uncover a portion of the orbit of star B (Capelo et al. 2012). This was confirmed by the optical color of the system, which had changed from the value of $V - I = 1.56$ obtained in 2008 (characteristic of a K6/K7 star) to $V - I = 1.04$. Near-infrared spectra of KH 15D spanning the wavelength range 0.9-2.5 µm were also more consistent with a K1 giant than a cooler star. The reappearance of star B on such a short timescale confirmed the general picture that was modeled by Winn et al. (2004) and Chiang & Murray-Clay (2004). The short duration of the complete occultation phase was also more consistent with the predictions of the
1. Introduction


1.4 What We Still Want to Know

Although still not detected directly by its emission, the fortunate orientation of the circumbinary ring in KH 15D provides us with a unique opportunity to study the earliest stages of structure formation in a young disk. Measurements of sodium absorption, corrected for the contribution from the ISM, showed a gas column density of \( \log N_{\text{NaI}} \sim 12.3 \, \text{cm}^{-2} \) within the ring and no variation with orbital phase (Lawler et al. 2010). This implies that the dust in the ring has settled into a thin layer embedded in a thick region of gas. The remaining gas is still being accreted onto the magnetosphere of star A, as shown by emission features located within the Na I D absorptions at the expected radial velocity of star A. This phase in disk evolution is thought to be the precursor to gravitational instability and subsequent formation of planetesimals in some models (Safronov & Zvjagina 1969; Goldreich & Ward 1973). We may be able to get an idea about the detailed structure of clumps in the ring by studying the system during eclipse. The screen acts as a natural coronograph at these phases and blocks enough of the contribution from the stars to potentially study non-stellar components.

Optical and near-infrared photometry obtained with the SMARTS consortium 1.3 m telescope at CTIO between 2010-2013 showed that the peak magnitude of the system had brightened to \( I \sim 14.8 \, \text{mag} \) by April 2013. The trend of increasing brightness over time was expected to continue until the entire surface of star B became directly visible at apastron. Although this was evident from the yearly trends, cycle-to-cycle variations were still present in the light curve, indicating that the newly visible trailing edge of the screen was clumpier than the leading
edge. In addition, color excesses of $E(I - J) = 0.6$ mag and $E(I - H) = 0.7$ mag were consistent with the excess flux expected from a young 10 $M_J$ planet (Windemuth & Herbst 2014). Both discoveries increased the appeal of KH 15D as a target for studying the structure of a protoplanetary disk.

Near-infrared spectra of KH 15D taken with NIRSPEC/Keck II revealed double-peaked $H_2$ emission features, characteristic of a shocked outflow at $T \sim 2800 \pm 300$ K (Deming et al. 2004). A comparison of the 1-0 $S(1)$ lines in spectra taken both in and out of eclipse showed that the line intensity did not change between phases, although the contrast between the emission feature and the continuum decreased when the system was brighter. The lines consisted of two distinct components, one of which was consistent with the radial velocity expected for KH 15D. The bluer component was located at a much higher radial velocity of -63 km/s. A filament centered on KH 15D was observed by (Tokunaga et al. 2004), adding further evidence that the system is still actively accreting. It will be important to characterize the nature of the accreting region in order to understand the circumbinary environment.

We have obtained several sets of data that will be analyzed with the goal of answering some of the remaining questions about KH 15D. First, we will continue collecting high-cadence photometry from CTIO in order to monitor the expected rebrightening of the system as the screen uncovers more of the orbital path of star B. We expect the magnitude of star B to reach 14.01 $\pm$ 0.01 mag in the $I$ band but will investigate the possibility that its emergence will not be smooth. We will also study the properties of the light curve at longer wavelengths by extending the photometric observations to the 3.6 and 4.5 $\mu$m bands on the Spitzer Space Telescope. The screen is opaque across the $VRIJHK$ bands, and we want to see if the trend continues into the near-infrared. Finally, we will examine near-
infrared spectra taken with the GNIRS instrument at Gemini North Observatory in order to search for the putative giant planet. These spectra can also be used to take a closer look at the emission lines associated with the bipolar outflow and to search for evidence of mineral structure within the ring. We hope that this work will provide insight into the non-stellar components of the KH 15D system and confirm predictions of its behavior made by the most current models.
Chapter 2

Data & Methods

KH 15D is a binary system, so we can characterize its observable properties with respect to where the stars are located along their orbital paths. However, most of the orbit has been occulted since frequent observations of the system began in the late 1990s. The orbital phase is therefore not yet well constrained by radial velocity measurements. We can use the eclipse phase to compare data from different years, although the motion of the screen causes the light curve to evolve on timescales as short as the orbital period. Hamilton et al. (2005) chose to use the photometric phase and defined the starting phase at the peak of the central brightness reversal. This location was chosen because its position on the light curve showed negligible variation from cycle-to-cycle. We phase-folded the photometry using the ephemeris

\[
\text{phase} = \frac{(\text{JD} - 2455786.31) \mod p}{p} \quad (2.1)
\]

where \( p = 48.37 \) days (Hamilton et al. 2005). Phase 0.0 corresponds approximately to mid-eclipse, now that the central brightness reversals are no longer such distinct features in the light curve. Note that this phase does not necessarily coincide with periastron, although it is likely close to it.

We have continued to examine the behavior of KH 15D by analyzing three different data sets that span a wide range of phases. First, we will present a
continuation of the high-cadence optical/near-infrared photometric campaign that was last updated by Windemuth & Herbst (2014). Next, we will use images from the Spitzer Space Telescope to extend our analysis to longer wavelengths than previously studied. Finally, we will look at near-infrared Gemini spectra that were collected at four different orbital phases. Each of these data sets and their reduction procedures will be described in detail in the following sections.

2.1 ANDICAM Photometry

We have continued to obtain ground-based optical and near-infrared photometry over the last two years using A Novel Dual Imaging CAMera (ANDICAM) on the 1.3 m telescope at Cerro-Tololo Inter-American Observatory (CTIO). The instrument is operated by the SMARTS consortium. Data were collected almost nightly from October 2013 through April 2014. Observations were resumed in September 2014 and continued until April 2015. Each night, four 150 s exposures are obtained in each of the three optical bands ($VRI$) along with 10-15 dithered exposures (30 s each) in the near-infrared bands ($JHK$). All images have a 10.2′ x 10.2′ field of view (see Windemuth & Herbst (2014) for a complete description of the data acquisition and reduction processes).

The magnitude of KH 15D in the ANDICAM images was determined using differential photometry. The optical images contain a subset of three of the seven optical reference stars listed by Hamilton et al. (2005) as calibrators. However, Windemuth & Herbst (2014) narrowed the list of reference stars down to two after detecting variability in the brightness of star D. The near-infrared photometry was calibrated using a set of five reference stars, although two of the five (stars 1 and 7) were faint compared to the background in the $K$ band and therefore were not
used to determine those magnitudes (Windemuth & Herbst 2014). The calibrated magnitudes of the optical and near-IR reference stars are given in Table 2.1 and Table 2.2, respectively.

To make sure the selected reference stars were stable throughout the most recent observing seasons, we calculated the difference in magnitude between two stars in a given band for each night of observations. This difference was simply [F]-[C] for the optical reference stars, where the brackets denote the measured magnitude of the star on a given night. For the near-infrared reference stars, differences were calculated with respect to star 4 (e.g. [1]-[4]). We then calculated the standard deviation, σ, of the data to quantify the night-to-night fluctuations in the magnitudes of the comparison stars. The resulting values are listed in Table 2.3 and Table 2.4. We found that the standard deviations were much less than 0.1 mag for most of the reference stars stars, making the differential photometry done with these calibrators a reliable way to determine the magnitude of KH 15D. However, star 2 showed more scatter than the others over both observing seasons. While the deviations weren’t large enough for us to discard star 2 as a calibrator, its stability should be checked in future observing seasons.

Table 2.1: VRI Reference Star Magnitudes from Hamilton et al. (2005), Windemuth & Herbst (2014)

<table>
<thead>
<tr>
<th>Designation</th>
<th>V</th>
<th>R</th>
<th>I</th>
</tr>
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<tbody>
<tr>
<td>C</td>
<td>12.969 ± 0.020</td>
<td>12.617 ± 0.020</td>
<td>12.240 ± 0.021</td>
</tr>
<tr>
<td>F</td>
<td>13.869 ± 0.020</td>
<td>13.375 ± 0.021</td>
<td>12.902 ± 0.021</td>
</tr>
</tbody>
</table>

The standard deviations of the reference stars presented in Table 2.3 and Table 2.4 are good indicators of the magnitude error in KH 15D during the bright phase. However, the flux measurements are much more uncertain when the system becomes fainter. Error bars for each data point were determined based on the
Table 2.2: JHK Reference Star Magnitudes from Skrutskie et al. (2006)

<table>
<thead>
<tr>
<th>Designation</th>
<th>SIMBAD ID</th>
<th>J</th>
<th>H</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cl* NGC 2264 FMS 2-1314</td>
<td>15.304 ± 0.048</td>
<td>14.564 ± 0.045</td>
<td>14.285 ± 0.073</td>
</tr>
<tr>
<td>2</td>
<td>V* OS Mon</td>
<td>13.422 ± 0.030</td>
<td>12.725 ± 0.023</td>
<td>12.549 ± 0.026</td>
</tr>
<tr>
<td>3</td>
<td>V* V427 Mon</td>
<td>12.205 ± 0.024</td>
<td>11.541 ± 0.024</td>
<td>11.356 ± 0.023</td>
</tr>
<tr>
<td>4</td>
<td>V* V816 Mon</td>
<td>13.110 ± 0.023</td>
<td>12.336 ± 0.023</td>
<td>12.181 ± 0.024</td>
</tr>
<tr>
<td>7</td>
<td>Cl* NGC 2264 FMS 2-1347</td>
<td>14.877 ± 0.060</td>
<td>14.254 ± 0.042</td>
<td>13.839 ± 0.100</td>
</tr>
</tbody>
</table>

Table 2.3: VRI Standard Deviation in Reference Star Mag Difference ([F]-[C])

<table>
<thead>
<tr>
<th>Year</th>
<th>V</th>
<th>R</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013/14</td>
<td>0.018</td>
<td>0.024</td>
<td>0.017</td>
</tr>
<tr>
<td>2014/15</td>
<td>0.020</td>
<td>0.015</td>
<td>0.025</td>
</tr>
</tbody>
</table>

nightly photometric error in the magnitudes of KH 15D and each of the reference stars. First, we calculated the error associated with the nightly deviations of the reference stars from their known magnitudes via the relation

\[
\sigma_c = \sqrt{\frac{\sum_{n=1}^{\text{# of stars}} \left( \sigma_{n,s}^2 + \sigma_{n,i}^2 \right)^{1/2}}{\text{# of stars}}} \tag{2.2}
\]

where \(\sigma_{n,s}\) is the error in the standard magnitude of the star and \(\sigma_{n,i}\) is the nightly uncertainty. This was combined with the nightly uncertainty in the magnitude of KH 15D (\(\sigma_{K,i}\)) to get

\[
\sigma_{K,f} = \sqrt{\sigma_{K,i}^2 + \sigma_c^2} \tag{2.3}
\]

The resulting magnitudes of the system and their associated errors will be presented in Chapter 3.
Table 2.4: JHK Standard Deviation in Reference Star Mag Difference ([x]-[4])

<table>
<thead>
<tr>
<th>Band</th>
<th>Year</th>
<th>1 - 4</th>
<th>2 - 4</th>
<th>3-4</th>
<th>7 - 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>2013/14</td>
<td>0.036</td>
<td>0.080</td>
<td>0.025</td>
<td>0.028</td>
</tr>
<tr>
<td>H</td>
<td>2013/14</td>
<td>0.047</td>
<td>0.083</td>
<td>0.025</td>
<td>0.035</td>
</tr>
<tr>
<td>K</td>
<td>2013/14</td>
<td>-</td>
<td>0.089</td>
<td>0.028</td>
<td>-</td>
</tr>
<tr>
<td>J</td>
<td>2014/15</td>
<td>0.030</td>
<td>0.086</td>
<td>0.021</td>
<td>0.025</td>
</tr>
<tr>
<td>H</td>
<td>2014/15</td>
<td>0.043</td>
<td>0.088</td>
<td>0.019</td>
<td>0.031</td>
</tr>
<tr>
<td>K</td>
<td>2014/15</td>
<td>-</td>
<td>0.087</td>
<td>0.029</td>
<td>-</td>
</tr>
</tbody>
</table>

2.2 Spitzer Photometry

2.2.1 Observations

Data on KH 15D were collected with the InfraRed Array Camera (IRAC) on the Spitzer Space Telescope during six separate observational runs spanning three distinct epochs. Four of the six sets of data (UT Oct. 2004, Oct. 2005, March 2006) were obtained when the orbital path of star B was still completely occulted at all phases. Although star A was directly visible at apastron, its orbit was becoming increasingly obscured by the advancing edge of the screen at this time. These observations were conducted during the so-called “cryogenic” period, when IRAC could be sufficiently cooled to return images from all four of its detectors (3.6, 4.5, 5.8, and 8 µm). The data were obtained by four different PIs (see Table 2.5) and are currently available in the Spitzer archive. Although each of these data sets was reduced at the time it was first obtained, the photometry was difficult to interpret since the background flux was comparable to the signal from KH 15D.

IRAC had exhausted its supply of liquid helium coolant by the time the last two sets of Spitzer images were collected. These data only cover 3.6 and 4.5 µm, since the shorter wavelength detectors don’t require operating temperatures to be
as low as their longer wavelength counterparts (Fazio et al. 2004). The fifth set of observations was obtained by the YSOVAR2 team as part of a larger campaign to monitor young variable objects in NGC 2264. These data were obtained in December 2011, when star A was completely hidden from view at all phases. The trailing edge of the screen had become the occulting edge and crossed just enough of the orbital path of star B for it to become partly visible at each apastron. In the high cadence YSOVAR2 monitoring program, sequential images were separated by less than 0.1 JD on average in both bands, although a few points were collected after ~1 JD had elapsed. The data span phases ~0.3-0.9, a range which includes peak brightness and ingress but does not include central eclipse.

A final set of observations was proposed to fill in the gaps in phase space in the 2011 photometry, although the new data would be collected at a lower cadence. Images were obtained on eight nights between December 2013 and January 2014. A larger fraction of star B was directly visible at apastron by then, although its surface was still partially occulted.

<table>
<thead>
<tr>
<th>UT Date</th>
<th>Wavelengths (µm)</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 Oct 5-12</td>
<td>4.5, 5.8, 8.0</td>
<td>Massimo Marengo</td>
</tr>
<tr>
<td>2004 Oct 08</td>
<td>3.6</td>
<td>Giovanni Fazio</td>
</tr>
<tr>
<td>2005 Oct 21-29</td>
<td>4.5, 5.8, 8.0</td>
<td>Massimo Marengo</td>
</tr>
<tr>
<td>2006 Mar 23-27</td>
<td>3.6, 4.5, 5.8, 8.0</td>
<td>Eric Agol</td>
</tr>
<tr>
<td>2011 Dec 3-2012 Jan 1</td>
<td>3.6, 4.5</td>
<td>John Stauffer (YSOVAR2)</td>
</tr>
<tr>
<td>2013 Dec 22-2014 Jan 20</td>
<td>3.6, 4.5</td>
<td>William Herbst</td>
</tr>
</tbody>
</table>

2.2.2 Data Reduction

IRAC has a 5.2’ x 5.2’ (256 x 256 pixel) field of view, so our images of KH 15D include HD 47887 and a portion of the Cone Nebula. The data from all
six sets of observations were passed through the Spitzer pipeline and combined into mosaics that are currently available through the archive. The final image products have a resolution of 0.6'' x 0.6'' per pixel. Photometry on the data from 2004-2006 was originally done by Scott Allen, a visiting REU student from Vassar College, who found that the background near KH 15D showed too much variation to obtain reliable aperture photometry. Instead of calculating an average background value, he fit a polynomial to the background to determine how it varied as a function of pixel. The resulting magnitudes showed infrared excess during the faint phase, when both stars were fully occulted. However, the data were too sparse to conclusively confirm this.

The high-cadence data from the 2011 observational run were processed by Rob Gutermuth of the YSOVAR2 team. Gutermuth used his own method to create mosaics from the original images, instead of using those produced by the Spitzer pipeline (Gutermuth et al. 2009). The program PhotVis was used to determine the magnitude of KH 15D through aperture photometry. An aperture radius of 2 pixels was chosen, with a sky annulus extending from the edge of the aperture to 6 pixels from its center (Gutermuth et al. 2008). Lists of 3.6 and 4.5 \( \mu \text{m} \) photometry were then sent to us for analysis.

Photometry for the 2013/14 data was done directly on the mosaics from the Spitzer pipeline, initially using the IRAF phot command. We chose an aperture radius of 10 pixels and a sky annulus that extended a distance of 12-20 pixels from KH 15D, as suggested in the IRAC Instrument Handbook. The results we obtained for the 2013/14 images were similar to what was reported by Gutermuth from the 2011 observations. The resulting light curve had an eclipse depth of \( \sim 2.5 \) mag.

The photometry showed a shallower eclipse depth than had been observed at
shorter wavelengths, but the images themselves indicated a change in flux between the bright and faint phases that was more consistent with prior observations. Furthermore, all images from the 2013/14 observations showed that the background was much brighter on the northern side of the image than on the southern side at both 3.6 and 4.5 $\mu$m. Some of the confusion comes from HD 47887, which is located slightly north of KH 15D. Closer inspection of the images taken during the faint phase showed that the filament identified by Tokunaga et al. (2004) in narrowband $K$ images is also bright in the Spitzer bands and contributes significantly to the flux on the north side of the system. The innermost part of the jet associated with this filament is contained in this region as well.

These bright background sources were only present on one side of the sky annulus we selected in IRAF, and some of their light spilled over into part of the KH 15D aperture as well. The `phot` command removes the background from the source aperture by subtracting the median value of counts per pixel within the sky annulus, which in this case led to an underestimate of the background at the northern edge of the aperture. `Phot` rejects outliers when calculating the median sky brightness and is typically very reliable. However, the contamination was so severe in this case that a better method of sky subtraction was required to obtain more accurate photometry.

Instead of calculating a median value of the background within some annulus and subtracting the same level of noise from every pixel, we used an approach similar to Allen’s method and determined how the sky brightness varied across the aperture. For each mosaic, we first extracted two copies of a 40 x 40 pixel box with KH 15D at its center. A 10 x 10 pixel square, including the star itself, was removed entirely from the center of the second box. We performed a linear interpolation across each row of the “empty” square to estimate the amount of
2. Data & Methods

background flux as a function of x pixel location. The interpolation was done in the north-south direction to match the orientation of the contaminating features in the images. The center of the image was filled in based on the background values determined by the interpolation. The entire 40 x 40 pixel box was subtracted from the first copy, which still contained KH 15D at its center. The system’s total flux was calculated by summing over all pixels within a 6 x 6 pixel aperture centered on the source in the background-subtracted image.

We tested the background interpolation for several different dimensions of the “empty” box and found that the resulting photometry was dependent on the parameters we selected for its size. The strength of the contaminating filament increased the further north we looked from KH 15D, so a box larger than 10 x 10 pixels would have more flux at its edge than would be encompassed in the final aperture. This would result in an overestimate of the background in the central pixel once the box was filled in with the interpolated sky brightness. The lower limit on the size of the box was set by the FWHM of KH 15D. A smaller box would allow pixels containing starlight to be included in the interpolation, again resulting in excess sky subtraction.

Figure 2.1 compares our method of sky subtraction to the phot method for one of the images that was taken during the faint phase, when the contrast between KH 15D and the background was lowest. We can see that a significant amount of flux is leftover on the north side of the aperture after subtracting a median background value from each pixel. The residual sky contribution was removed when we applied the interpolation method instead. We are therefore confident that our sky subtraction method sets a more accurate level for the background contamination in each image than the IRAF aperture photometry.

We can see from Figure 2.2 that the new photometry agrees with the IRAF
Figure 2.1: The IRAF *phot* command subtracts a median background value from each pixel within a specified annulus (top). However, KH 15D’s jet adds a significant amount of excess flux to the north side of the image. A different method of sky subtraction was required to remove its contribution. We found that the excess flux could be removed by fitting the background with an interpolating function (bottom).
magnitudes when the system is in its bright phase and increasingly deviates as KH 15D becomes faint. The constant contribution from background sources led to a perceived shallower eclipse depth in the light curve, but the effect disappeared after the contaminating features were removed. The resulting eclipse depth of \( \sim 4 \) mag was consistent with prior observations at shorter wavelengths. We applied our method to all of the images obtained from 2013/14. Although Allen utilized a similar procedure for his photometry on the 2004-2006 images, he used different parameters for the size of the original box as well as the central “empty” square. We ran each of these images through the new pipeline as well to ensure that our data reduction methods were consistent between all observations.

The 2011 images from the YSOVAR2 team were also re-examined once we realized how much of a discrepancy there was between the two methods of photometry during the faint phase. The mosaicking procedure adopted by Gutermuth produced images with slightly lower angular resolution per pixel than those compiled by the Spitzer pipeline. Although this didn’t have a noticeable effect during the bright phase, the raw data was not aligned accurately enough to apply our sky subtraction method to the resulting images during the faint phase. We acquired the original Spitzer mosaics and obtained photometry from those instead. Figure 2.3 shows that the resulting eclipse depth in the 2011 light curve was also greater than originally shown by the IRAF photometry, although the substantial amount of scatter at mid-eclipse makes it difficult to compare to shorter wavelength photometry.
Figure 2.2: The 2013/14 light curve produced from the photometry obtained with the IRAF phot command (black points) showed a much shallower eclipse depth at 3.6 and 4.5 μm than had been seen at shorter wavelengths. Our method of sky subtraction (red points) showed that the true eclipse depth was greater and more consistent with the change in brightness seen in the Spitzer images.
Figure 2.3: After seeing how much the light curve varied when the two different methods of sky subtraction were applied to the 2013/14 data, we re-examined the 2011 photometry that was originally done by the YSOVAR2 team (black points). Again, we found that the eclipses were much deeper when we used our background subtraction method (red points).
2.3 GNIRS Spectra

2.3.1 Observations & Preliminary Reductions

Near-infrared spectra of KH 15D, spanning the wavelength range 0.8-2.5 µm, were collected at four different orbital phases with the Gemini Near-Infrared Spectrograph (GNIRS) at Gemini-North Observatory (see Table 2.6). One spectrum was collected during a “bright phase” (UT Apr. 3, 2013), when star B was close to apastron although still partially obscured. A second spectrum was acquired when star B was fully occulted but close to the edge of the screen; this will be referred to as the “intermediate phase” (UT Feb. 6, 2013). The last two spectra were taken during the “faint phase” (UT Nov. 7, 2013; UT Dec. 25, 2013), when both stars were completely hidden and close to periastron. Starlight is maximally attenuated during the faint phase because of the high opacity of the ring material at these wavelengths, and scattered light is minimized because both stars are well below the edges of the occulting disk.

The spectra were reduced by Sandy Leggett, Head of Science Operations at Gemini North, using the standard procedure for GNIRS cross-dispersed data. The XD_G0526 filter was used for all four observations along with the short blue camera and 32 lines/mm grating. A slit width of 0.30″ was used for the bright and intermediate phase observations, corresponding to a resolving power of $R \sim 1800$. However, the slit width had to be increased to 0.45″ for the faint phase observations, resulting in lower resolution for those two spectra ($R \leq 1800$).

An argon arc lamp was used to calibrate the wavelength scale for all four spectra. Telluric atmosphere removal and flux calibration were done using reference stars that were observed at the same time the spectra were collected (see Table
Three of the five observed standards were A stars, which are typically chosen for near-infrared calibration because of the low number of significant absorption lines they exhibit at these wavelengths. The most prominent features in the spectra of A stars are hydrogen lines, which are much easier to identify and remove than the molecular lines that are abundant in cooler stars. The remaining two reference stars were F stars, which, although not as featureless as the A stars, have weaker hydrogen lines and are still too hot for molecular lines to form.

Observing conditions were partly cloudy on the night that the November faint phase spectrum was obtained. To compensate, KH 15D was observed for 1.8 hours during this observing run (compared to 0.8 hours on source when the December spectrum was obtained), resulting in similar S/N between the two spectra. However, variable seeing on the November night could have impacted observations of the standard stars. The resulting flux calibration is somewhat more uncertain than the flux calibration for the December spectrum, although both are accurate to $\sim 20\%$. The ANDICAM $JHK$ photometry that was obtained at the same time as the spectra could be used as an alternative to the flux standards, but the photometric uncertainty was once again higher for the November data than the December magnitudes. The uncertainty in the flux calibration is not high enough to discard the data, but the December spectrum will typically be considered more reliable in the following analysis.

**Table 2.6: Properties of Gemini Spectra**

<table>
<thead>
<tr>
<th>UT Date</th>
<th>UT Start Time (hh:mm:ss)</th>
<th>Exposure Time (s)</th>
<th>Slit Width (arcsec)</th>
<th>Position Angle (deg)</th>
<th>Resolution ($\Delta\lambda/\lambda$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb. 6, 2013</td>
<td>06:31:38.3</td>
<td>300</td>
<td>0.30</td>
<td>90.0</td>
<td>1800</td>
</tr>
<tr>
<td>Apr. 3, 2013</td>
<td>06:15:52.4</td>
<td>90</td>
<td>0.30</td>
<td>90.0</td>
<td>1800</td>
</tr>
<tr>
<td>Nov. 7, 2013</td>
<td>12:56:43.6</td>
<td>300</td>
<td>0.45</td>
<td>90.0</td>
<td>$\leq 1800$</td>
</tr>
<tr>
<td>Dec. 25, 2013</td>
<td>12:21:56.9</td>
<td>300</td>
<td>0.45</td>
<td>90.0</td>
<td>$\leq 1800$</td>
</tr>
</tbody>
</table>
2. Data & Methods

Table 2.7: Telluric Standards from Skrutskie et al. (2006)

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Date Observed</th>
<th>Spectral Type</th>
<th>J</th>
<th>H</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(dd/mm/yy)</td>
<td></td>
<td>(mag)</td>
<td>(mag)</td>
<td>(mag)</td>
</tr>
<tr>
<td>HD 37650</td>
<td>Feb. 6, 2013</td>
<td>A</td>
<td>8.601 ± 0.027</td>
<td>8.579 ± 0.018</td>
<td>8.561 ± 0.018</td>
</tr>
<tr>
<td>HD 60778</td>
<td>Feb. 6, 2013</td>
<td>A1V</td>
<td>8.746 ± 0.019</td>
<td>8.662 ± 0.031</td>
<td>8.666 ± 0.023</td>
</tr>
<tr>
<td>HD 52431</td>
<td>Apr. 3, 2013</td>
<td>F5V</td>
<td>6.722 ± 0.021</td>
<td>6.548 ± 0.047</td>
<td>6.496 ± 0.018</td>
</tr>
<tr>
<td>HD 65158</td>
<td>Nov. 7, 2013</td>
<td>A0V</td>
<td>7.093 ± 0.023</td>
<td>7.134 ± 0.049</td>
<td>7.105 ± 0.017</td>
</tr>
<tr>
<td>HD 33140</td>
<td>Nov. 7, 2013; Dec. 25, 2013</td>
<td>F2V</td>
<td>8.435 ± 0.026</td>
<td>8.269 ± 0.036</td>
<td>8.207 ± 0.023</td>
</tr>
</tbody>
</table>

Nightly ANDICAM optical and near-infrared observations of KH 15D were also in progress at the time the GNIRS spectra were acquired. Table 2.8 lists the $VRIJK$ magnitudes of the system on the nights that the spectra were obtained. Note that the uncertainty in the $K$ band magnitude from the December night is likely much higher than 0.1 mag due to confusion in the image. The system was observed with ANDICAM within 1 JD of the April 3rd, November 7th, and December 25th, 2013 Gemini observing runs. However, the closest data points to the intermediate phase observation on February 6th were obtained almost 2 days after the spectrum. In order to consider the spectrum in the context of the system’s photometric behavior at that time, we needed to use the light curves to estimate the magnitudes of KH 15D on that date. The cycle-to-cycle variations in the shape of the light curve were small at this time, so data from the two preceding cycles as well as the two following cycles were phase-folded to fill in gaps in the light curve. The data was then fit with a univariate spline interpolation over a range of ±0.10 in phase, and errors were estimated from the goodness of fit. The resulting magnitudes are denoted by asterisks in Table 2.8.

Table 2.8: Brightness of KH 15D at time of GNIRS Observations

<table>
<thead>
<tr>
<th>UT Date</th>
<th>Julian Date (2456000.0)</th>
<th>Phase</th>
<th>V</th>
<th>R</th>
<th>I</th>
<th>J</th>
<th>H</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb. 6, 2013</td>
<td>329.78</td>
<td>0.24</td>
<td>18.84 ± 0.1 1</td>
<td>17.93 ± 0.1 1</td>
<td>17.58 ± 0.1 1</td>
<td>16.64 ± 0.1 1</td>
<td>15.94 ± 0.1 1</td>
<td>16.39 ± 0.1 1</td>
</tr>
<tr>
<td>Apr. 3, 2013</td>
<td>385.77</td>
<td>0.39</td>
<td>16.40 ± 0.02</td>
<td>15.66 ± 0.02</td>
<td>15.25 ± 0.02</td>
<td>14.14 ± 0.02</td>
<td>13.43 ± 0.02</td>
<td>13.29 ± 0.02</td>
</tr>
<tr>
<td>Nov. 7, 2013</td>
<td>603.61</td>
<td>0.90</td>
<td>19.51 ± 0.1</td>
<td>18.76 ± 0.1</td>
<td>18.03 ± 0.07</td>
<td>17.22 ± 0.08</td>
<td>16.75 ± 0.1</td>
<td>17.49 ± 0.7</td>
</tr>
<tr>
<td>Dec. 25, 2013</td>
<td>651.55</td>
<td>0.89</td>
<td>19.49 ± 0.2</td>
<td>18.32 ± 0.08</td>
<td>17.96 ± 0.06</td>
<td>17.59 ± 0.1</td>
<td>16.76 ± 0.08</td>
<td>15.18 ± 0.1</td>
</tr>
</tbody>
</table>
Chapter 3

Results

The three sets of data discussed in Chapter 2 each illuminate different aspects of the near-infrared behavior of KH 15D. We compare the new ANDICAM photometry to results from past observing campaigns to see whether it agrees with the long-term behavior predicted by models. The Spitzer photometry allows us to investigate whether the high opacity of the screen continues at longer wavelengths. The GNIRS spectra were obtained to search for evidence of a putative giant planet that could be truncating the outer edge of the circumbinary ring. They are also useful for studying molecular hydrogen and He I emission lines and for assessing whether there is a mineral signature in the reflectance spectrum. Results from all three sets of observations are presented in this chapter.

3.1 ANDICAM Photometry

3.1.1 Long-Term $I$ Band Evolution: Star B Emerges

The light curve of KH 15D consists of high cadence photometry collected at various observatories in the $I$ band extending as far back as 1995. This allows us to consider the current $I$ band behavior of the system in the context of its long-term evolution. Windemuth & Herbst (2014) predicted that KH 15D would brighten over time as the trailing edge of the occulting screen uncovered the orbital path
3. Results

of star B. Figure 3.1 shows that the peak magnitude of the system has, in fact, brightened during each of the last two observing seasons, which confirms that an increasingly large fraction of the surface of star B is becoming visible at apastron.

The magnitude of KH 15D at maximum brightness was $I = 14.45 \pm 0.02$ during the 2013-14 observing season. This brightened to $I = 14.14 \pm 0.02$ in 2014-15, which is slightly brighter, but within the errors, of its expected peak brightness of $I = 14.19 \pm 0.06$ (Windemuth & Herbst 2014). The value for the system’s expected magnitude was estimated from the magnitude determined from archival plates when both stars were directly visible ($I = 13.57 \pm 0.06$ mag; Winn et al. (2006)) and CCD measurements obtained when star A alone was unocculted ($I = 14.47 \pm 0.04$ mag). An additional constraint on the unocculted brightness of star B is the photometry obtained at VVO in 1996, when star B was emerging from behind the leading edge of the screen at periastron. The magnitude of the system was measured at $I = 14.01 \pm 0.01$ at this time, which is somewhat brighter than the expected value from Windemuth & Herbst (2014). The two $I$ band magnitude limits indicate that we are now seeing most, if not all, of the surface of star B at apastron.

If all of star B is now directly visible, it has taken $\sim 4$ years to emerge. It took about the same amount of time for star A to disappear, which is consistent with the two stars having similar radii. The symmetry of the long-term light curve shows that the rate at which the screen is migrating across the orbital path is the same at both the leading and trailing edges, therefore supporting the model of a rigidly precessing circumbinary ring.

The phase-folded $I$ band light curve shows that the duration of the eclipses has decreased slightly since star B began to emerge in late 2011 (see Figure 3.2). The system becomes fully occulted around $I \sim 17$ mag, where there is an inflection
Figure 3.1: The long-term $I$ band photometry of KH 15D shows how the magnitudes of minimum and maximum brightness have evolved over time. The system has become brighter during each of the last two observing seasons, which is consistent with the model of an opaque screen slowly uncovering the orbital path.
point in the light curve at both ingress and egress. KH 15D was fainter than this for 31 days per cycle in 2011-2013, 27 days per cycle from 2013-2014, and 23 days per cycle in 2014-2015. The eclipse duration is therefore decreasing at a rate of roughly 2 days yr$^{-1}$. This is consistent with the rate that Hamilton et al. (2005) noted for the lengthening of the eclipse duration between 2001 and 2005. The eclipse depth remains $\sim$4 mag across the $VRIJH$ bands, as expected for ring material that is completely opaque at these wavelengths (see Figure 3.3). However, the amount of scatter at mid-eclipse is much greater in the $K$ band photometry than in the other five bands. In previous years, this was attributed to increased confusion in the images and a detection limit of $K \sim 16$ (Windemuth & Herbst 2014). While these factors could still be important in the most recent photometry, it is possible that we are also seeing an increase in transparency at 2.2 $\mu$m. The implications of this will be addressed in a later section.

3.1.2 Cycle-to-Cycle Variations

Although Figure 3.1 shows that KH 15D has steadily been getting brighter each year, the behavior of the light curve is not perfectly uniform between individual cycles. The effect is most noticeable when the photometry is plotted as a function of Julian Date instead of phase (see Figure 3.4). The increase in brightness does not appear to progress at the same rate from cycle-to-cycle. During the 2013-14 observing season, the system got brighter during each of the first three cycles but dimmed by 0.04 mag during the last cycle (see Table 3.1). The peak magnitude was fainter still for the first two cycles of the 2014-15 season before brightening again by 0.05 mag during each of the last two cycles.

The non-uniformity of the cycle-to-cycle light curves could be explained by the
Figure 3.2: The phase-folded $I$ band photometry of KH 15D shows how the shape of the light curve has evolved over long timescales. The duration of the eclipses has decreased since star B re-emerged, as shown by photometry from 2011-2013 (purple), 2013-2014 (pink), and 2014-2015 (black). However, the eclipse depth has not changed significantly.
3. Results

Figure 3.3: The eclipse depth remained at $\sim 4$ mag across bands $V$, $R$, $J$, and $H$ while star B emerged, as seen in photometry from 2011-2013 (purple), 2013-2014 (pink), and 2014-2015 (black). The uniformity of the eclipse depth across these five bands verifies that the trailing edge of the screen is completely opaque between 500 nm and 1.75 $\mu$m. However, the amount of scatter at mid-eclipse in the $K$ band implies that the ring material becomes slightly more transparent at 2.2 $\mu$m.
presence of hills and valleys located within the occulting edge of the circumbinary ring. Alternatively, spots on the surface of star B could sometimes result in less observed flux than expected at peak brightness. If spots are the reason for the deviations, we can expect to see redder colors during the cycles when the system became dimmer. Clumps within the ring, however, might not cause color changes during maximum light, unless they were less opaque at the ANDICAM wavelengths than the bulk of the ring material. The amount of reddening at maximum light would therefore make it possible to distinguish between spots and clumps as the source of the variations.

Herbst et al. (1994) found that changes in $V$ and $I$ magnitudes caused by cool spots on T Tauri stars followed the relation $dV/dI = 0.7$. For a $V$ band variation of 0.03 mag, we can expect a 0.02 mag change in $I$ and a color change of $V - I = +0.01$. Between the third and fourth cycles of the 2013-2014 observing season, when the system became 0.03 mag fainter in $V$ at maximum light, the $V-I$ color at peak brightness reddened by 0.03 mag (see Table 3.1). The difference in color between the first two cycles in 2014-2015 was $\Delta (V - I) = 0.01$ mag when the peak $V$ mag again became 0.03 mag fainter. Although our observations are consistent with what we would expect for a spotted stellar surface, the $V$ band fluctuations aren’t large enough to result in significant color changes. The color changes are around the same magnitude as the photometric errors in the data, making it difficult to confirm that the reddening is real. The reddening of the $V-I$ and $R-I$ colors between the 2013-2014 and 2014-2015 data can be attributed to the continued rise of star B. As more of its surface is revealed during the bright phase, more of its light is directly visible and dominates the contribution from the bluer, forward scattered light.

In addition to the cycle-to-cycle variations in the system’s brightness at max-
3. Results

Minimum light, the shape of the light curve at mid-eclipse also varies between cycles (see Figure 3.4). A few show a bump in the light curve at mid-eclipse, but the shape of the bump is not consistent with the mid-eclipse re-brightenings observed when star A was directly visible at apastron and star B approached the leading edge of the screen at periastron. The slight increases in brightness are not significant when compared to the amount of scatter present in the photometry at minimum light, indicating that scattered light from star A as it approaches the trailing edge of the screen near periastron is not yet contributing significantly to the system’s brightness.

| Table 3.1: V Band Cycle-to-Cycle Peak Magnitudes and Average Colors |
|-------------------|---|---|---|---|
| Year               | Cycle | V    | V-R  | V-I  | R-I  |
| 2013-2014          | 1    | 16.08 ± 0.02 | 0.47 | 1.22 | 0.52 |
|                    | 2    | 15.94 ± 0.04 | 0.52 | 1.25 | 0.53 |
|                    | 3    | 15.72 ± 0.02 | 0.53 | 1.22 | 0.54 |
|                    | 4    | 15.75 ± 0.02 | 0.50 | 1.26 | 0.54 |
| 2014-2015          | 1    | 15.79 ± 0.02 | 0.52 | 1.31 | 0.58 |
|                    | 2    | 15.82 ± 0.02 | 0.50 | 1.32 | 0.58 |
|                    | 3    | 15.62 ± 0.02 | 0.51 | 1.29 | 0.56 |
|                    | 4    | 15.53 ± 0.02 | 0.42 | 1.30 | 0.55 |

3.1.3 Color Evolution

The system’s colors continue to remain fairly constant as its brightness begins to decrease (see Figure 3.5), again confirming that the trailing edge of the screen is completely opaque across the VRJHK bands. The diamonds in Figure 3.5 represent photometry from 2013-2014, while the x’s denote data collected between 2014 and 2015. Both data sets show a slight bluing effect at ingress, which has been attributed to forward scattering when star B is first completely occulted by
Figure 3.4: The light curves show that the eclipses do not have the same shape from cycle to cycle, nor do they reach precisely the same brightness. This could be caused by irregularities in the circumbinary ring, which would soften the sharpness of the edge of the screen. Spots on the surface of the star could also be responsible, but the deviations in brightness are not large enough to confirm this.
the screen. Figure 3.6 shows that the bluing is more prominent in $V-J$ and $V-H$ than in $V-R$ and $V-I$. In the 2014-2015 data (x’s), for example, the $V-J$ and $V-H$ colors became $\sim 0.10$ mag bluer between phases 0.70 and 0.75. The $V-R$ and $V-I$ colors became just $\sim 0.05$ mag bluer over the same phase interval.

All four colors shown in Figure 3.5 become much redder at magnitudes fainter than $V \sim 18.5$, which correspond to mid-eclipse. A possible source of the reddening was described by Windemuth & Herbst (2014), who detected color excesses of $E(I-J) = +0.6$ and $E(I-H) = +0.7$ at minimum light. The additional flux is consistent with the expected contribution from a 1 Myr giant planet of $\sim 10 M_J$.

Figure 3.7 compares the 2011-2013 (pink) $I-J$ and $I-H$ colors from Windemuth & Herbst (2014) to the 2013-2014 (blue) and 2014-2015 (cyan) data. Although the system no longer becomes as faint at mid-eclipse as it did between 2011 and 2013, both colors still show significant reddening at these phases. Additional signatures of a putative planet were searched for in the GNIRS spectra and will be discussed in later sections.

3.1.4 $K$ Band Photometry and Color Evolution

Figures 3.2 and 3.3 show that there is significantly more scatter in the $K$ band photometry at minimum light than in the other five ANDICAM bands. Windemuth & Herbst (2014) identified a detection limit of $K \sim 16$ mag due to residual flat-fielding errors and used a smaller aperture for the $K$ band photometry than for the $J$ and $H$ data in order to correct for the lower S/N. Bands $V$ through $H$ show that KH 15D has now become slightly brighter at all phases since the 2010-2013 photometry was collected, making it brighter than $K \sim 16$ mag during minimum light in the more recent data. If the amount of scatter is a true feature
Figure 3.5: The 2013-2014 data are represented by circles and the 2014-2015 photometry by x’s. The system’s colors remain fairly constant in $V-R$ and $V-I$ and redden dramatically at magnitudes fainter than $V \sim 18$. The transition corresponds to star B’s disappearance behind the screen. However, the $V-J$ and $V-H$ colors become slightly bluer as the system gets fainter. The bluing has been attributed to forward scattering effects at the edge of the ring (Silvia & Agol 2008).
Figure 3.6: The system’s colors plotted against the phase at which they were obtained show noticeable differences between the 2013-2014 (circles) and 2014-2015 (x’s) photometry. The 2014-2015 colors remain fairly constant for a longer fraction of the orbital phase than the 2013-2014 data, indicating that KH 15D is now spending less time in a fully occulted state. We also see a bluing effect at ingress that is stronger in $V-J$ and $V-H$ than in $V-R$ and $V-I$. 
Figure 3.7: Windemuth & Herbst (2014) noted color excesses of $E(I-J) = +0.6$ and $E(I-H) = +0.7$ at minimum light in the 2011-2013 photometry (pink) and attributed the reddening to a 1 Myr, 10 $M_J$ giant planet. The system does not become as faint in the 2013-2014 (blue) and 2014-2015 (cyan) data, but it still undergoes significant reddening at faint phases.
of the $K$ band light curve, the ring material could be somewhat more transparent here than at shorter wavelengths.

Figure 3.8 shows that the 2014-2015 $V-K$ color becomes slightly redder as the system gets fainter. The trend reverses around $V \sim 16$, as the system returns to the bluer color it showed at peak brightness. This is in contrast to the $V-J$ and $V-H$ colors, which steadily become bluer as star B sets behind the screen and only redden at minimum light. The reddening in the $K$ band implies that the opacity of the ring material is lower at $\lambda \sim 2.2 \mu m$ than at shorter wavelengths. However, this is the first observing season since $K$ band observations of KH 15D began in 2011 that such reddening has been detected. We do not have sufficient data to compare the current $V-K$ color to the color of the system when star A was the directly visible component and reached a similar peak brightness, but the reddening should be monitored in future observing seasons as the geometry of the system continues to evolve with respect to our line of sight.

### 3.2 Spitzer Photometry

#### 3.2.1 Light Curves

The Spitzer photometry was obtained at three distinct epochs, which is evident from the shapes of the 3.6 and 4.5 $\mu m$ light curves (see Figure 3.9). Star A was the only stellar component that was directly visible at the time the 2004-2006 observations were done, and its entire surface was unocculted at maximum brightness near apastron. The resulting light curves indicate a shorter eclipse duration and a sharper egress than the other two data sets. The system also rose to a flat maximum, corresponding to those phases when star A was fully visible. Star B began to emerge by 2011, when the system was observed by the YSOVAR2 team,
Figure 3.8: Although the $V-K$ colors followed the same trend as the shorter wavelengths and stayed constant as the system became fainter in the 2013-2014 data (top), they showed a slight reddening in the 2014-2015 photometry (bottom). The reddening implies that the material currently occulting star B is slightly more transparent than the material that was obscuring it just a year ago.
although only a small portion of the star was directly visible. The eclipse duration was longer than it was between 2004 and 2006, and the magnitude at maximum brightness was fainter. The fraction of star B that was un eclipsed had increased substantially by the time the 2013-2014 data were collected, corresponding to an increase in peak brightness. Egress was noticeably sharper in the 2011 data but not as abrupt as it was in the 2004-2006 photometry. It was also evident that the full eclipse duration had shortened, although it was still longer than it had been from 2004-2006.

The eclipse depth is more difficult to determine at 3.6 and 4.5 \( \mu m \) than at shorter wavelengths because of the large amount of scatter in the photometry obtained at minimum light. However, the system had an approximately 3.5 mag decline in brightness over the orbital period during 2011 and 2013-2014. This is consistent with the eclipse depth observed in the \( VRIJHK \) bands. The eclipse depth may have been deeper at 3.6 \( \mu m \) between 2004 and 2006, although this is only based on two data points with high uncertainties.

### 3.2.2 Color Evolution

High cadence \( I \) band photometry was obtained within 0.5 JD of many of the dates on which Spitzer data were collected, making it the best band to compare to the Spitzer magnitudes over the full orbital phase. Figure 3.10 shows how the \( I-[3.6] \) and \( I-[4.5] \) colors behave as KH 15D becomes fainter. In the 2011 and 2013-2014 data, the system becomes somewhat redder between peak brightness and \( I \sim 16 \) mag, when star B is fully occulted, before returning to a bluer color. This is much different from the \( VRIHJK \) colors, which remain fairly constant until the phase when star B disappears.
Figure 3.9: The shapes of the phase-folded light curves show that the Spitzer observations were carried out during three distinct epochs. Star A was the only directly visible component when the 2004-2006 data was obtained (purple). A small fraction of star B was directly visible at apastron during the 2011 observations (black), and more of its surface had emerged by 2013-2014 (pink).
The reddening may imply that some 3.6 and 4.5 \( \mu \text{m} \) starlight is able to get through the edge of the ring material before the screen becomes fully opaque at some height below the edge of the ring. The bluing occurs when the star crosses the boundary between the optically thin and optically thick regions, possibly because forward scattering begins to dominate the observed brightness. A similar trend is suggested by the data from 2004-2006, but the sparser sampling of the light curve makes it difficult to analyze. The color behavior of the system during the 2011 observing run, from which we have very high cadence data, will be discussed in detail in Chapter 4.

3.3 GNIRS Spectra

In 2013, four near-infrared spectra were obtained with GNIRS at Gemini-North Observatory in order to search for evidence of a hot, young giant planet (see Figure 3.11). One spectrum was collected when star B was directly visible (bright phase), although it had not completely emerged from behind the screen at the time. The second spectrum was acquired when star B was just about to emerge from behind the occulting screen and was very close to its edge (intermediate phase). The final two spectra were obtained at mid-eclipse (faint phase), when the starlight was reduced as much as possible and signatures of a putative planet would be easiest to detect. The most notable features in the spectra are presented below.

3.3.1 Faint Phase Emission Lines

Some of the most prominent features in the GNIRS spectra are the strong emission lines visible during the intermediate and faint phases. These include the He I feature at 1.083 \( \mu \text{m} \) and \( \text{H}_2 \) lines beyond 2 \( \mu \text{m} \). The \( \text{H}_2 \) emission features have
Figure 3.10: The 2011 and 2013-14 Spitzer colors redden as the system’s brightness starts to decline. The colors become much bluer at the inflection point where star B is first completely occulted and redden again at minimum brightness. This implies that 3.6 and 4.5 μm starlight is able to travel through the edge of the ring material.
Figure 3.11: Near-infrared spectra of KH 15D were obtained at four different orbital phases using GNIRS at Gemini-North Observatory with the intent to search for a putative giant planet. Atmospheric features near 1.4 and 1.9 $\mu$m have been removed for clarity, and all four spectra are plotted in flux units of $W \text{ m}^{-2} \mu\text{m}^{-1}$. The November faint phase spectrum has been shifted to a higher flux for ease of comparison with the December faint phase spectrum.
previously been attributed to the bipolar outflow associated with the system’s jet (Tokunaga et al. 2004; Deming et al. 2004). Table 3.2 lists the 10 H₂ lines we have identified in the three spectra, along with the statistical weight \((g_j)\) and Einstein coefficient \((A_{ij})\) for each transition. The five features that were measured by Deming et al. (2004) are denoted by asterisks. Equivalent widths were measured for all 10 lines, although values for several lines that were noisy in the intermediate and December faint phase spectra have been omitted. The continuum emission, \(F_c\), was assumed to be flat in the immediate vicinity of each line and was estimated by fitting a constant to the region. The equivalent width of the line was then determined as \(\sum_{\lambda_0-0.005}^{\lambda_0+0.005} \left(1 - \frac{F_\lambda}{F_c}\right) \Delta \lambda \mu \text{m}\), where \(\Delta \lambda\) is the average wavelength separation between adjacent data points. The uncertainty in \(F_c\), which is the dominant source of error in these measurements, was estimated by repeating the continuum fit at various randomly selected endpoints within a fixed wavelength range.

**Table 3.2: Near-Infrared H₂ Transitions (Turner et al. 1977; Dabrowski 1984)**

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Central Wavelength (µm)</th>
<th>Transition</th>
<th>Energy (K)</th>
<th>(g_j)</th>
<th>(A_{ij}) ((10^{-7} \text{ s}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.0338</td>
<td>S2 (1-0)</td>
<td>7584</td>
<td>9</td>
<td>3.98</td>
</tr>
<tr>
<td>2*</td>
<td>2.1218</td>
<td>S1 (1-0)</td>
<td>6956</td>
<td>21</td>
<td>3.47</td>
</tr>
<tr>
<td>3*</td>
<td>2.2235</td>
<td>S0 (1-0)</td>
<td>6471</td>
<td>5</td>
<td>2.53</td>
</tr>
<tr>
<td>4*</td>
<td>2.2477</td>
<td>S1 (2-1)</td>
<td>12550</td>
<td>21</td>
<td>4.98</td>
</tr>
<tr>
<td>5*</td>
<td>2.4066</td>
<td>Q1 (1-0)</td>
<td>6149</td>
<td>9</td>
<td>4.29</td>
</tr>
<tr>
<td>6</td>
<td>2.4134</td>
<td>Q2 (1-0)</td>
<td>6471</td>
<td>5</td>
<td>3.03</td>
</tr>
<tr>
<td>7*</td>
<td>2.4237</td>
<td>Q3 (1-0)</td>
<td>6956</td>
<td>21</td>
<td>2.78</td>
</tr>
<tr>
<td>8</td>
<td>2.4375</td>
<td>Q4 (1-0)</td>
<td>7586</td>
<td>9</td>
<td>2.65</td>
</tr>
<tr>
<td>9</td>
<td>2.4548</td>
<td>Q5 (1-0)</td>
<td>8365</td>
<td>33</td>
<td>2.55</td>
</tr>
<tr>
<td>10</td>
<td>2.4756</td>
<td>Q6 (1-0)</td>
<td>9286</td>
<td>13</td>
<td>2.45</td>
</tr>
</tbody>
</table>

Figure 3.12 shows that the contrast between the H₂ lines and the continuum appears to increase as KH 15D becomes fainter, in accordance with expectation if the emission lines are arising from a source well away from the star itself. Although the November and December faint spectra were obtained at similar phases, the
3. Results

Figure 3.12: The equivalent widths of the H$_2$ lines appear to increase from the intermediate phase (black) to the faint phase (November in blue, December in red) spectra. Cloudy weather on the night of the November observing run resulted in a less accurate flux calibration for that spectrum than the others, but the absolute line fluxes are about the same in the intermediate and December faint phase spectra (see Table 3.4). This is what we would expect for lines that originate in a region far from the star.
December lines consistently have smaller equivalent widths (see Table 3.3). The wavelengths of the \text{H}_2 emission features are contained within the $K$ band, so broadband photometry from the two nights that the spectra were collected could help to account for the deviation in line strengths between cycles. The system had a magnitude of $K = 17.4 \pm 0.7$ mag on Nov. 7, 2013 and $K = 15.2 \pm 0.1$ mag on Dec. 25, 2013. However, the system was not significantly brighter in the $VRIJH$ bands during the December observations. If KH 15D was truly brighter at this phase in December than it was in November, the \text{H}_2 equivalent widths from both spectra are consistent with the trend of increasing line strength with decreasing system brightness.

Although the photometric error is lower for the December $K$ band magnitude, the value itself is brighter than the magnitude of the system during the intermediate phase. The peak brightness of the system at maximum light did increase between the times that the December and intermediate spectra were collected, but not so much as to explain the jump in faint phase magnitude. Furthermore, the system was still fainter in $VRIJH$ on the December night than it was when the intermediate phase observations were conducted. Since the December magnitude was obtained near mid-eclipse, it should be interpreted carefully; the $K \sim 16$ detection limit described by Windemuth & Herbst (2014) often has a significant impact on the faint phase photometry. The ANDICAM data alone aren’t enough to explain the differences in line strengths between the November and December spectra.

The absolute fluxes for each \text{H}_2 line in the three spectra are presented in Table 3.4 and show that, on average, the line fluxes are more consistent between the intermediate and December spectra than between the November and December spectra. As discussed in Chapter 2, cloudy weather during the November ob-
3. Results

serving run resulted in a poor flux calibration for that spectrum. However, the uncertainty introduced by the flux calibration will be reduced when the line flux ratios of the H$_2$ features are analyzed in Chapter 4.

Table 3.3: Near-Infrared H$_2$ Equivalent Widths (Å)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0338</td>
<td>-3.64 ± 0.01</td>
<td>-14.49 ± 0.2</td>
<td>-7.66 ± 0.1</td>
</tr>
<tr>
<td>2.1218</td>
<td>-9.14 ± 0.04</td>
<td>-48.10 ± 0.4</td>
<td>-</td>
</tr>
<tr>
<td>2.2235</td>
<td>-3.80 ± 0.02</td>
<td>-12.33 ± 0.1</td>
<td>-7.92 ± 0.03</td>
</tr>
<tr>
<td>2.2477</td>
<td>-</td>
<td>-6.67 ± 0.05</td>
<td>-</td>
</tr>
<tr>
<td>2.4066</td>
<td>-10.76 ± 0.1</td>
<td>-45.09 ± 3</td>
<td>-27.06 ± 1</td>
</tr>
<tr>
<td>2.4134</td>
<td>-5.37 ± 0.3</td>
<td>-24.24 ± 5</td>
<td>-12.44 ± 2</td>
</tr>
<tr>
<td>2.4237</td>
<td>-16.06 ± 0.1</td>
<td>-64.49 ± 0.6</td>
<td>-51.41 ± 2</td>
</tr>
<tr>
<td>2.4375</td>
<td>-</td>
<td>-26.40 ± 0.4</td>
<td>-16.56 ± 0.4</td>
</tr>
<tr>
<td>2.4548</td>
<td>-9.67 ± 0.1</td>
<td>-45.92 ± 1</td>
<td>-31.16 ± 0.6</td>
</tr>
<tr>
<td>2.4756</td>
<td>-</td>
<td>-32.07 ± 0.9</td>
<td>-21.84 ± 1</td>
</tr>
</tbody>
</table>

Table 3.4: Near-Infrared H$_2$ Absolute Fluxes (10$^{-19}$ W m$^{-2}$)

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0338</td>
<td>0.924 ± 0.1</td>
<td>2.01 ± 0.2</td>
<td>0.952 ± 0.2</td>
</tr>
<tr>
<td>2.1218</td>
<td>2.00 ± 0.1</td>
<td>5.87 ± 0.1</td>
<td>-</td>
</tr>
<tr>
<td>2.2235</td>
<td>0.714 ± 0.08</td>
<td>1.19 ± 0.1</td>
<td>0.719 ± 0.03</td>
</tr>
<tr>
<td>2.2477</td>
<td>-</td>
<td>0.609 ± 0.07</td>
<td>-</td>
</tr>
<tr>
<td>2.4066</td>
<td>1.56 ± 0.2</td>
<td>4.62 ± 0.6</td>
<td>2.31 ± 0.5</td>
</tr>
<tr>
<td>2.4134</td>
<td>0.728 ± 0.7</td>
<td>2.08 ± 2</td>
<td>1.00 ± 1</td>
</tr>
<tr>
<td>2.4237</td>
<td>2.16 ± 0.1</td>
<td>5.35 ± 0.07</td>
<td>3.97 ± 0.2</td>
</tr>
<tr>
<td>2.4375</td>
<td>-</td>
<td>2.18 ± 0.1</td>
<td>1.25 ± 0.2</td>
</tr>
<tr>
<td>2.4548</td>
<td>1.33 ± 0.2</td>
<td>3.52 ± 0.2</td>
<td>2.39 ± 0.1</td>
</tr>
<tr>
<td>2.4756</td>
<td>-</td>
<td>2.14 ± 0.2</td>
<td>1.36 ± 0.4</td>
</tr>
</tbody>
</table>

The strength of the He I line was measured using the same procedure that was applied to the H$_2$ lines. Figure 3.13 shows that the helium feature is much weaker in the spectrum from the intermediate phase than in the faint phase spectra, although it appears that a point is missing near the central wavelength. It would be difficult to distinguish blue or redshifted absorption components in these low resolution spectra ($R \leq 1800$), but the line appears to be pure emission at all
three orbital phases. The equivalent widths of the line were $-43.5 \pm 0.4$ Å in the November spectrum and $-26.3 \pm 0.1$ Å in the December spectrum, corresponding to absolute fluxes of $(24.0 \pm 0.5) \times 10^{-19}$ W m$^{-2}$ and $(13.7 \pm 0.3) \times 10^{-19}$ W m$^{-2}$, respectively. The S/N for the feature in the intermediate spectrum was too low to obtain accurate measurements, but we measured lower limits of $EW = -1.00 \pm 0.003$ Å and $F = (1.1 \pm 0.3) \times 10^{-19}$ W m$^{-2}$. The contrast between the strength of the He I line in spectra obtained at different phases is much greater than the differences between H$_2$ lines, which were prominent (although weaker) in the intermediate phase spectrum. Possible explanations will be discussed in Chapter 4, although further analysis requires follow-up observations to re-examine the He I line during an intermediate phase.

### 3.3.2 Reflectance Spectra from Forward Scattered Light

We obtained reflectance spectra from the GNIRS data based on the procedure of Vilas et al. (1984), who removed the solar contribution from spectra of the surface of Mercury by dividing out a standard spectrum of the Sun. The spectral features of star B are diminished in the faint phase spectra, but we divided both by the spectrum acquired during the bright phase to further reduce its contribution. The resulting reflectance spectra still contained strong narrowband features, such as the He I and H$_2$ lines described previously. These features were removed entirely, and the weaker emission lines were smoothed out by applying a 50 point moving average to the data. The spectra were then normalized using the continuum fitting function in ENVI, which is an IDL based software package designed for use with remote sensing data. The slopes of the spectra decrease towards longer wavelengths, showing that there is more flux at shorter wavelengths (see
Figure 3.13: The spectrum taken during the intermediate phase (black) does not show significant He I emission, but the lines are quite strong in each of the faint phase spectra. The feature’s equivalent width was greater in November (blue) than December (red), but the absolute flux of the line was similar in both spectra.
Figure 3.14). This is consistent with forward scattering, which is more likely to scatter blue light than red light into our line of sight.

The reflectance spectra show broad continuum absorption features around 1 and 2 \( \mu \text{m} \), which is where characteristic absorptions in the reflectance spectra of olivine and pyroxene minerals are expected to appear. These minerals comprise \( \sim 2/3 \) of the material in the ordinary chondritic meteorites in the solar system (McSween et al. 1991), so it is likely that they are highly abundant in other circumstellar disks as well. The most distinguishable features in the reflectance spectra have been identified in Figure 3.14 and will be compared to reference spectra of common pyroxene minerals in Chapter 4.

### 3.3.3 Potential to Detect Giant Planet Signatures

Chiang & Murray-Clay (2004) noted that the inner and outer edges of the circumbinary ring must be confined in order for rigid precession to occur. The sharpness of the inner edge has been attributed to tidal forces, which truncate the ring at a distance of \( \sim 1 \) AU from the central binary. Meanwhile, spreading at the outer boundary could be prevented by a young giant planet shepherding the ring. Although a third body has not yet been detected through radial velocity measurements, Windemuth & Herbst (2014) measured color excesses in \( I-J \) and \( I-H \) near minimum light that are consistent with the additional flux expected for a 1 Myr, 10 \( M_J \) planet.

The GNIRS data were obtained at various orbital phases with the goal of isolating spectral signatures of the putative planet from features of the stars. This could be accomplished during the faint phase, when most starlight between 0.8 and 2.5 \( \mu \text{m} \) is attenuated by the optically thick ring material. First, however, the
Figure 3.14: The boundaries of the prominent broad absorption features in the faint phase KH 15D reflectance spectra are denoted by arrows. Each of these features will be compared to reference spectra of various minerals in Chapter 4.
residual stellar contribution needed to be removed from the faint phase spectra. The bright spectrum and both faint spectra were split into eight regions, and the continuum was fit as a constant in each region. Scale factors were then determined by dividing the faint phase continuum fits by the values obtained for the bright phase. The bright phase spectrum was then multiplied by the appropriate scale factors and subtracted from each of the two faint phase spectra (see Figure 3.15). A 50 point moving average (similar to what was used for the reflectance spectra) was applied to smooth out the narrow features and noise. The results are plotted in Figure 3.16.

Spiegel & Burrows (2012) developed model spectra of young giant planets to compare the effects of different formation mechanisms on the subsequent evolution of a planet, assuming four different types of atmospheres. We have compared their model spectra for a 1 Myr, 10 $M_J$ planet to the KH 15D data in Figure 3.17. We can see that the December spectrum in particular has significant peaks in emission near the location of each peak in the model spectra. However, further work will need to be done to disentangle signatures of a putative planet from those of minerals within the circumbinary ring.
Figure 3.15: The top panel shows the original bright phase spectrum, with CO absorption lines between 2.3 and 2.35 µm. The bright spectrum was scaled down to the flux level of the faint spectrum; both are shown in the middle panel. The scaled bright spectrum was then subtracted from the faint spectrum (bottom panel) to remove the spectral signatures of star B.
Figure 3.16: Residual stellar features have been removed from the faint phase spectra by scaling the bright spectrum down and subtracting it from each. A 50 point moving average was then applied to smooth out the remaining narrow features. The bottom panel in each column shows the resulting star subtracted spectrum that may contain signatures of a putative giant planet.
Figure 3.17: We have compared the KH 15D spectra (solid, black) to model spectra of a 1 Myr, 10 $M_J$ planet from Spiegel & Burrows (2012) (dashed, colored). Each model spectrum assumes a different type of planetary atmosphere. Although we see significant emission peaks in the KH 15D data near the location of features in the model spectra, we will need to determine which are signatures of a planet and which can be attributed to grains within the ring.
Chapter 4
Analysis

The ANDICAM photometry described in Chapter 3 is consistent with models of KH 15D as a binary system with components of similar radii surrounded by a circumbinary ring. The ring must be rigidly precessing at an inclination to the binary orbital plane in order to produce the decline and eventual rebrightening seen in the long-term $I$ band light curve. High cadence observations at optical and near-infrared wavelengths have been in progress since 1996, so the data collected since then provide a framework for analyzing the Spitzer photometry and GNIRS spectra.

4.1 Preparing CMDs at Spitzer Wavelengths

Figure 3.10 shows that the $I$-[3.6] and $I$-[4.5] colors become redder as the system gets fainter. The reddening is present from maximum brightness until $I \sim 15.5$ and appears to follow a roughly linear trend. In addition, closer inspection of the Spitzer colors reveals that they behave differently at ingress and egress. This is easiest to see in the data from 2011, which were collected at a higher cadence than the 2004-2006 and 2013-2014 photometry. The following analysis will focus on that set of observations.

Although Spitzer photometry was obtained every $\sim 0.1$ JD during the 2011 observing run, the $I$ band observations were conducted less frequently. The color-
magnitude diagrams do not contain as many points as the Spitzer light curves, making it difficult to model any trends. The following section describes the methods used to fill in the CMDs and get a more detailed picture of the system’s infrared color evolution.

4.1.1 Interpolation of Phase-Folded $I$ Band Photometry

Since $I$ band photometry was collected regularly from fall 2011 through spring 2012, colors could be calculated using $I$ band data obtained at the same phases as the Spitzer photometry but during different cycles. At this time, the occulting screen had begun to uncover a fraction of star B at apastron, resulting in slight cycle-to-cycle variations in the shape of the light curve. To minimize the uncertainty associated with including photometry from different cycles, only data from two cycles before and two cycles after the simultaneous observations were added to the CMDs.

Although the inclusion of $I$ band photometry from additional cycles increased the number of phases for which $I-[3.6]$ and $I-[4.5]$ colors could be measured, there were still many Spitzer data points without corresponding $I$ magnitudes. However, there was now enough photometry to determine how the magnitude of the system varied with phase. The data were split into two sections (bright and faint), and a univariate spline interpolation was applied to each (see Figure 4.1). The resulting functions were used to estimate an $I$ magnitude for each phase with Spitzer photometry. The shape of the light curve at $I > 17$ in the second cycle after the Spitzer data were collected was quite different from previous observations. These points were omitted from the interpolation. The estimated magnitudes for phases between $\sim 0.35$ and 0.38 are brighter than the measured magnitudes, so
Figure 4.1: A univariate spline interpolation was applied to five cycles of $I$ band data to generate a relationship between magnitude and phase (black curves). The red diamonds represent photometry from the cycle when Spitzer data were also collected, while the black circles are points from adjacent cycles. The black x’s are data that were obtained two cycles after the Spitzer photometry; these were omitted from the interpolation because of faint phase deviations between the shape of the light curve during this cycle and the cycles preceding it.

The corresponding colors will have a higher uncertainty than those calculated at other phases.

Figure 4.2 compares the measured $I$-[3.6] and $I$-[4.5] colors to those calculated using interpolated $I$ band magnitudes. The estimated colors agree with the observed values, except during egress when the interpolation is more uncertain. Both the photometry and the estimated colors show that the shapes of the CMDs are much different at ingress than they are at egress. As the system becomes fainter
at ingress, its colors become redder until \( I \sim 17 \), which corresponds to the phase when star B completely disappears behind the screen. The system then becomes bluer until \( I \sim 17.5 \). At egress, however, the colors only become slightly bluer as the system becomes brighter, and only slight reddening is seen. This implies that the occulting material is somewhat more optically thick at egress than at ingress, which can be explained by the nearly edge-on orientation of the orbital path of the stars. Star B is further away from us at egress, so starlight must travel through more dust to reach us at this phase.

### 4.2 Modeling Reddening at Spitzer Wavelengths

Figure 3.5 shows that KH 15D maintains fairly constant \( V-R \) and \( V-I \) colors before becoming slightly bluer at the phases when star B first disappears behind the edge of the screen. The slope of the bluing increases for \( V-J \) and \( V-H \), but no reddening is observed until minimum light in any of the four colors. This implies that starlight is not able to pass through the ring material, which is completely opaque at these wavelengths. Forward scattered light, which causes the bluing, is the only contribution to the system’s brightness when the stars are not directly visible. However, the system behaves differently in \( V-K \) and at the slightly longer Spitzer wavelengths (3.6 and 4.5 \( \mu m \)), becoming redder as it becomes fainter instead of remaining at its original color (see Figure 3.8, Figure 3.10).

The reddening in the \( I \) vs. \( I-[3.6] \) and \( I \) vs. \( I-[4.5] \) CMDs is consistent with the behavior expected for extinction by grains with sizes on the order of the wavelength of the observed light. This would place an observational constraint of \( \sim 5 \, \mu m \) on the size of the smallest particles that make up the occulting material, which agrees with the grain sizes determined from models of the system (Chiang & Murray-
4. Analysis

Figure 4.2: The $I$-[3.6] and $I$-[4.5] CMDs have different shapes at ingress and egress. The colors become distinctly redder as the system gets fainter at ingress, but the trend is not as pronounced at egress. Model colors determined from the interpolation of $I$ band photometry (red dashes) are somewhat bluer than the measured colors (black circles) at ingress between $I \sim 16 - 16.5$ mag. This is due to the uncertainty in the $I$ band light curve interpolation at these phases.
Clay 2004; Agol et al. 2004). To confirm the source of the reddening, we compared the data to a simple model. For extinction by dust grains, we expect that the flux reaching us through the ring material will follow the relation $F_\lambda = F_{\lambda,0} \exp^{-\tau_\lambda}$, where $F_{\lambda,0}$ is the original flux from the star and $\tau_\lambda$ is the wavelength-dependent optical depth. It can be assumed that $\tau_\lambda \sim \infty$ across the VRIJH bands, as expected for completely opaque occulting material.

However, not all of the light from star B is covered by the ring material at all phases. When star B is at least partially unocculted, the flux we detect has a component that is directly visible in addition to the reddened component. There is also some amount of forward scattered light present in the system at all phases, which will be set constant as a first approach. The flux observed on a given night, $F_t$, is therefore the sum of the scattered ($F_s$) and non-scattered ($F_*$) components. If we assume $f_d$ is the fraction of the stellar surface that is directly visible at a given phase, $F_t$ becomes

$$F_t = F_s + f_d F_* + (1 - f_d) F_* e^{-\tau_\lambda} \quad (4.1)$$

The $I$ magnitudes may be used to estimate $f_d = \frac{F_i - F_*}{F_*}$, since starlight in this band apparently does not penetrate the optically thick ring material. For this calculation, we need to know how bright the system would be if the entire surface of star B were directly visible. For the $I$ band, we used the value $I_* = 14.14 \pm 0.02$ that was measured during the 2014-2015 observing season. The $[3.6]_*$ and $[4.5]_*$ magnitudes were estimated from the bluest colors in the CMDs, under the assumption that direct light from star B dominates the contribution from reddened light until a substantial fraction of its surface is occulted by the ring material. During egress, the reddening is reduced and the system reaches bluest
colors of $I - [3.6] \sim 1.8$ and $I - [4.5] \sim 1.6$ as it becomes brighter (see Figure 4.2). We expect this trend to hold until star B has emerged completely, implying Spitzer magnitudes of $[3.6]_s \sim 12.34$ and $[4.5]_s \sim 12.54$ for the fully visible star.

Values for $m_s$ were obtained by the same method used to extract $m^*$ from the CMDs. We can estimate $I_s - [3.6]_s \sim 1.9$ and $I_s - [4.5]_s \sim 1.6$, assuming $I_s \sim 17.0$ when the entire surface of star B becomes fully occulted. The flux from scattered light in the two Spitzer bands can then be estimated from $[3.6]_s \sim 15.1$ and $[4.5]_s \sim 15.4$.

The fraction of the stellar surface that is directly visible is not necessarily equivalent to the fraction of the total flux received. Limb darkening effects can result in less direct light reaching us when a fraction of the limb is revealed than when the same fraction emerges from a location close to the center. Assuming the surface of the star is circular, we can obtain the limb-darkened flux ratio as

$$f_{ld} = \begin{cases} 
C \times \left[ 2 \int_0^{y_{max}} \int_0^{\sqrt{1-y^2}} 1 - u \left( 1 - \frac{x}{\sqrt{x^2 + y^2}} \right) dxdy + \int_0^{y_{max}} \int_0^{\sqrt{1-y^2}} 1 - u \left( 1 - \frac{x}{\sqrt{x^2 + y^2}} \right) dxdy \right] & : f_d > 0.5 \\
C \times \left[ 2 \int_{y_{min}}^{1} \int_0^{\sqrt{1-y^2}} 1 - u \left( 1 - \frac{x}{\sqrt{x^2 + y^2}} \right) dxdy \right] & : f_d < 0.5
\end{cases}$$

where $-1 \leq x, y \leq +1$ and $u$ is the wavelength-dependent limb-darkening coefficient. The values $u_{[3.6]} = 0.2069$ and $u_{[4.5]}$ were adopted from Claret et al. (2013).

In this coordinate system, we have defined $(x, y) = (0, 0)$. If $f_d$ is greater than 0.5, the entire top half of the stellar surface is directly visible. The limits of integration are then $y_{max} = 1$ and $y_{min} = -2 \times (f_d - 0.5)$. If $f_d$ is less than 0.5, $y_{max} = 1$ and $y_{min} = 1 - (2 \times f_d)$. The constant $C$ is a normalization factor and can be calculated as

$$\frac{1}{C} = 4 \int_0^1 \int_0^1 1 - u \left( 1 - \frac{x}{\sqrt{x^2 + y^2}} \right) dxdy$$  \tag{4.2}
If the optical depth of the ring material were constant over the range of a stellar diameter, we would expect to see linear reddening with decreasing $I$ mag until the entire surface of star B becomes occulted by the ring at $I \sim 17$. The curves shown in Figure 4.2 indicate that the optical depth actually varies over shorter distance scales. We can extract a function for the optical depth as a function of star B’s position with respect to the edge of the ring material by using the interpolated/measured $I$ and Spitzer magnitudes to estimate the flux coming from the system in the form of Equation 4.1. We can then use the measured $[3.6]$ and $[4.5]$ magnitudes to solve for the optical depth, $\tau$, as a function of the visible fraction, $f$, of star B.

Figure 4.3 shows that the optical depth decreases until $1 - f \sim 0.80$ before increasing again until star B is fully occulted at $1 - f = 1$. However, the initial increase in transparency is not consistent with Figure 4.2. The slope of the reddening curve increases as the system becomes fainter, implying that the average optical depth also increases as the star sets further below the edge of the ring. The increase in optical depth can likely be attributed to the values we selected for $F_*$. Our estimates for the magnitudes of the system at 3.6 and 4.5 $\mu$m when the entire surface of star B is directly visible are uncertain and could be having a significant impact on the values of $\tau_\lambda$ we have derived. The estimated values of $F_*$ are much more reliable, so our extinction model still provides a good estimate of optical depth for $1 - f \geq 0.80$.

For extinction by a population of $\sim 5 \mu$m grains, the optical depth should be proportional to the wavelength of light. The ratio of optical depths at 3.6 and 4.5 $\mu$m should then be roughly $\tau_{[3.6]}/\tau_{[4.5]} = 4.5 \mu$m/$3.6 \mu$m = 1.25. The median value from the bottom panel of Figure 4.3 is $\tau_{[3.6]}/\tau_{[4.5]} = 1.04$, implying that $\tau_{[3.6]}$ is slightly lower or $\tau_{[4.5]}$ slightly higher than expected. However, the ratio
Figure 4.3: Equation 4.1 can be used along with the magnitude equation to calculate the optical depth of the system at 3.6 and 4.5 μm as a function of the directly visible fraction, \( f \), of the surface of star B. The red, dashed lines indicate where star B is fully occulted around \( I \sim 17 \) mag. Figure 4.2 implies that \( \tau_{[3.6]} \) and \( \tau_{[4.5]} \) should increase as the star sets behind the ring material. Our estimates for \( F_* \) are more uncertain than for \( F_s \), so the figure is most reliable for \( 1 - f \geq 0.80 \) (green, dashed lines), when \( \sim 80\% \) of the stellar surface has disappeared behind the ring.
increases as star B disappears behind the ring and approaches the expected value as star B disappears behind the ring. In addition to confirming that we are seeing extinction of starlight by dust grains in the circumbinary ring at 3.6 and 4.5 μm, this model allows us to map out the optical depth of the ring over much smaller distance scales than are typically possible.

### 4.2.1 Application of Spitzer Extinction Model to I-K Colors

Figure 3.8 shows that the $V-K$ color also becomes redder as the system becomes fainter. This trend has not previously been detected at 2.2 μm, suggesting that we are looking along a different line of sight to the circumbinary ring than in previous epochs. We can study the $K$ band reddening by applying the toy model developed for the Spitzer photometry to the ANDICAM data. For consistency between the three bands, we will look at the $I-K$ color instead of $V-K$ (see Figure 4.4).

Our measurements from the most recent observing season, which indicate that most of the surface of star B is now directly visible, suggest that the peak $K$ band magnitude of star B is $K = 12.4 \pm 0.1$. The average $I-K$ color of the system during the three brightest nights of this cycle was $\sim 1.7$. The inflection point in the light curve when star B disappears behind the ring appears to have shifted to a brighter magnitude of $I \sim 16.8$ since 2011, corresponding to $K = 16.8 - 1.7 = 15.1$.

We can compare the $I-K$ color we measured to the standard near-infrared colors of K stars determined by Bessell & Brett (1988). A star with a spectral type of K1 III (stellar classification by Capelo et al. (2012)), should have $V-I = 1.08$ and $V-K = 2.50$. The $I-K$ color should then be $\sim 1.42$, resulting in $K = \ldots$
Figure 4.4: The Spitzer extinction model was applied to the $I-K$ color, rather than $V-K$, to maintain a consistent approach for the three bands. The system becomes somewhat redder as it transitions from peak brightness to $I \sim 15$ mag and returns to a bluer color as star B continues to set behind the screen. The transition to optically thick ring material appears to occur closer to the edge of the occulting material at 2.2 $\mu$m than it does at 3.6 and 4.5 $\mu$m.
14.14−1.42 = 12.7 when all of star B is directly visible and $K = 16.8−1.42 = 15.4$ when the star is fully occulted. The expected color of star B is bluer than what we measured, which is not unexpected at 2.2 $\mu$m. If even a small fraction of the stellar surface is still occulted by the ring material near apastron, we would observe a redder color because of the increased transparency in the $K$ band. Furthermore, confusion from other bright sources in the field is also a factor at this wavelength. We have used the standard colors from Bessell & Brett (1988) in this model instead of our measured values since we are still unsure of the true peak brightness of the system when star B is entirely visible.

The fraction of star B that was directly visible at each phase was again obtained from the $I$ magnitudes, and the limb darkened flux ratios were calculated using a coefficient of $u = 0.3003$ (Claret et al. 2013). Figure 4.5 shows that Equation 4.3 returns negative values of $\tau$ for $1−f$ between 0 and 0.3. As with the Spitzer model, this can be attributed to the uncertainty in our estimate of the peak brightness of the system, which is based on the spectral classification of star B. Beyond $1−f \sim 0.3$, the optical depth increases as more of the star disappears, in agreement with Figure 4.4. The $K$ band photometry was not obtained with as high of a cadence as the 2011 Spitzer photometry, so it will be more difficult to derive a functional form for the optical depth from this data. However, the reddening at 2.2 $\mu$m can be studied further when ANDICAM observations resume in fall 2015.

### 4.3 $H_2$ and He I Emission as Outflow Signatures

#### 4.3.1 Deriving an Excitation Temperature for Shocked $H_2$

As described in Section 3.3.1, the molecular hydrogen emission features between $\sim 2$ and 2.5 $\mu$m seen in the faint and intermediate phase GNIRS spectra
4. Analysis

Figure 4.5: Optical depths calculated from Equation 4.3 for the $K$ band photometry are most reliable when more than $\sim 30\%$ (green, dashed line) of the light from star B is occulted by the ring material. Prior to this phase, the uncertainty in our estimate for the $K$ band magnitude when the entire surface of star B is directly visible causes the Spitzer extinction model to return negative values of $\tau$. 

![Optical Depth of Occulting Ring Edge](image)
have previously been associated with the system’s jet, which produces a thermally excited bipolar outflow (Tokunaga et al. 2004; Deming et al. 2004). The features were attributed to shock heating of ambient hydrogen based on the measured line intensity ratio $2-1 \ S(1)/1-0 \ S(1) = 0.24 \pm 0.05$, which is well below the value of $\sim 0.5$ expected for UV fluorescence. Deming et al. (2004) measured the intensity of five of the hydrogen lines in a spectrum acquired at phase $\sim 0.17$ (similar to our intermediate phase) and found a best-fit temperature of $T \sim 2800 \pm 300$ K for the emitting region. However, it was noted that the observed line strength ratios did not agree with the expected values for this temperature within the measured uncertainties. In the GNIRS spectra, we have identified five additional H$_2$ lines along with those measured by Deming et al. (2004) and will extract more detailed information about the emitting region.

Table 4.1 gives the line flux ratios of the H$_2$ features in the GNIRS spectra (calculated from the absolute line fluxes in Table 3.4). The intensity of the (1-0) Q1 line (\(\lambda = 2.4066 \, \mu m\)) was used as the normalizing flux instead of the (1-0) S1 line (\(\lambda = 2.1218 \, \mu m\)), which had a low S/N in the December spectrum. Although the equivalent width of the (1-0) Q3 line was greater than that of the 1-0 (Q1) line in all three spectra, the uncertainties were lower for 1-0 (Q1). The (2-1) S1 feature (\(\lambda = 2.477 \, \mu m\)) could only be measured for the November spectrum. We obtained a ratio of $2-1 \ S(1)/1-0 \ S(1) = 0.10 \pm 0.02$, which is much lower than the expected ratio of $\sim 0.5$ expected for UV fluorescent gas. This result confirms that the source of the emission is primarily shock excitation and not UV fluorescence.

A thermal excitation temperature ($T$) can be determined by assuming $\ln \left( \frac{F}{gA} \right) = -E/T$, where $F$ is the absolute flux of the line, $g$ and $E$ are the statistical weight and energy of the upper level, and $A$ is the Einstein coefficient for spontaneous
emission. The line flux ratios then obey the expression

\[
\ln \left( \frac{F_{\text{line}}}{F_{\text{ref}}} \right) = \frac{-1}{T} (E_{\text{line}} - E_{\text{ref}}) + \ln \left( \frac{g_{\text{line}}A_{\text{line}}}{g_{\text{ref}}A_{\text{ref}}} \right)
\]

(4.3)

The subscript \textit{ref} in Equation 4.3 refers to the properties of the (1-0) Q1 line. Table 3.2 lists the line parameters \( A, g, \) and \( E \) for each of the ten \( \text{H}_2 \) lines we observed.

**Table 4.1:** Near-Infrared \( \text{H}_2 \) Line Flux Ratios (x / (1-0) Q1)

<table>
<thead>
<tr>
<th>Central Wavelength (( \mu m ))</th>
<th>Transition</th>
<th>Intermediate</th>
<th>Faint (Nov. 2013)</th>
<th>Faint (Dec. 2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0338</td>
<td>1-0 (S2)</td>
<td>0.592 ± 0.09</td>
<td>0.434 ± 0.07</td>
<td>0.413 ± 0.1</td>
</tr>
<tr>
<td>2.1218</td>
<td>1-0 (S1)</td>
<td>1.28 ± 0.2</td>
<td>1.27 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>2.2235</td>
<td>1-0 (S0)</td>
<td>0.457 ± 0.07</td>
<td>0.257 ± 0.04</td>
<td>0.312 ± 0.06</td>
</tr>
<tr>
<td>2.2477</td>
<td>2-1 (S1)</td>
<td>-</td>
<td>0.132 ± 0.02</td>
<td>-</td>
</tr>
<tr>
<td>2.4066</td>
<td>1-0 (Q1)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2.4134</td>
<td>1-0 (Q2)</td>
<td>0.466 ± 0.5</td>
<td>0.450 ± 0.4</td>
<td>0.433 ± 0.4</td>
</tr>
<tr>
<td>2.4237</td>
<td>1-0 (Q3)</td>
<td>1.39 ± 0.2</td>
<td>1.16 ± 0.1</td>
<td>1.72 ± 0.4</td>
</tr>
<tr>
<td>2.4375</td>
<td>1-0 (Q4)</td>
<td>-</td>
<td>0.472 ± 0.06</td>
<td>0.543 ± 0.1</td>
</tr>
<tr>
<td>2.4548</td>
<td>1-0 (Q5)</td>
<td>0.852 ± 0.2</td>
<td>0.762 ± 0.1</td>
<td>1.04 ± 0.2</td>
</tr>
<tr>
<td>2.4756</td>
<td>1-0 (Q6)</td>
<td>-</td>
<td>0.462 ± 0.07</td>
<td>0.588 ± 0.2</td>
</tr>
</tbody>
</table>

Deming et al. (2004) compared the spectrum obtained at phase \( \sim 0.17 \) to a spectrum taken out of eclipse (similar to our bright phase) in which the 1-0 S(1) feature was resolved. The strength of the feature in the bright spectrum was much weaker than it was when the star was fainter, and the difference in strength was attributed to the increase in continuum flux when the stellar surface was revealed. If this were true in our spectra, we would expect the line flux ratios to remain roughly constant with orbital phase, despite the difference in absolute flux. The values in Table 4.1 for each line do not always agree within the measured uncertainties for all three spectra. However, we do not know the exact location of the emitting region detected in each of the three spectra and could simply be probing slightly different areas.
The most reliable flux ratios \( \left( \frac{\sigma_{F_{\text{line}}/F_{\text{ref}}}}{F_{\text{line}}/F_{\text{ref}}} \leq 0.20 \right) \) from Table 4.1 were used in a least-squares fit to equation 4.3. The resulting temperatures for the shock-excited H\(_2\) are 2400 ± 300 K (November), 3000 ± 200 K (December), and 2800 ± 500 K (intermediate). The value obtained from the December spectrum is likely more uncertain than ±200 K, given the low S/N of some of the features. The temperatures from the November and intermediate spectra are consistent with each other and the 2800 ± 300 K result given by Deming et al. (2004). At the time the Deming et al. (2004) observations were conducted, the entire surface of star A was directly visible near apastron, and star B was fully occulted at all phases. When our spectra were acquired in 2013, star A was fully occulted at all phases and only part of star B was directly visible near apastron. The geometry of the system was quite different when the two sets of spectra were obtained, so the consistency between temperatures measured during two different epochs further confirms that the emission comes from the base of the bipolar outflow.

Figure 4.6 compares the measured flux ratios to the expected values for H\(_2\) at the best-fit temperatures (calculated from Equation 4.3). Lines with \( \frac{\sigma_{F_{\text{line}}/F_{\text{ref}}}}{F_{\text{line}}/F_{\text{ref}}} \geq 0.20 \) have been omitted. The December spectrum only had two features that fell under this limit, again implying that the uncertainty in the temperature obtained from these data is actually greater than for the other two spectra. Although the measured flux ratios do not agree with the best-fit temperature for each individual feature, there is strong agreement between the values we have obtained from the spectra and what is expected for shock-excited H\(_2\) in a bipolar outflow.
Figure 4.6: A comparison of the measured flux ratios to those expected for shock-excited H$_2$ at the best-fit temperatures derived in this section shows that our measured values are consistent with each other and with the value of 2800 ± 300 K obtained by Deming et al. (2004). The agreement between our data and previous work done when star A was the only directly visible component further confirms that the features originate in the bipolar outflow detected by Tokunaga et al. (2004).
4.3.2 He I Chromospheric Emission

As shown in Figure 3.13, the He I feature at 1.083 $\mu$m does not have significant red or blue shifted absorption components that are typically associated with accreting T Tauri systems. The accretion rate is inversely related to age, so the amount of UV excess that can be attributed to accretion processes decreases with respect to the chromospheric UV emission as the star ages (Ingleby et al. 2011). When common accretion signatures at UV wavelengths are drowned out by chromospheric emission, the H$\alpha$ line can be used in conjunction with the He I line to identify weakly accreting systems.

High resolution ($R \sim 44,000$) optical spectra of KH 15D revealed a broad H$\alpha$ profile in addition to [O I] emission lines during eclipse, which were attributed to a bipolar jet (Mundt et al. 2010). The features confirmed that the system is still weakly accreting, so we would expect the He I line to show evidence of this during the faint phase as well. The faint phase spectra have low resolution ($R \leq 1800$), so it is possible that absorption is present but unresolved. However, the strength of the emission line in both the November and December faint phase spectra is unusual, along with its reduction in the intermediate phase spectrum. The changing line flux indicates that the amount of chromospheric emission is actually greater near periastron than when star B is close to the edge of the ring, although additional measurements at much higher spectral resolution are required to confirm this.
4.4 Evidence for Solar System Minerals in the Ring

The GNIRS reflectance spectra shown in Figure 3.14 have prominent absorptions near 1 and 2 μm, where some of the most common minerals in our solar system have characteristic features. A Python fitting function, modeled after the spectral feature fitting function in ENVI (Clark et al. 1990), was written to examine the agreement between the continuum removed KH 15D data ($O_c$) and reference spectra of olivine and pyroxene ($L_c$). A linear least-squares algorithm was applied to scale the reference spectrum of a given mineral and shift it upwards to match the KH 15D spectrum via the relationship

$$L_c' (\lambda) = a + bL_c (\lambda)$$  \hspace{1cm} (4.4)

where $a$ and $b$ are constants. The optimal values of $a$ and $b$ can be obtained from the equations

$$a = \frac{\Sigma O_c - b\Sigma L_c}{n}$$

$$b = \frac{\Sigma O_c L_c - \Sigma O_c \Sigma L_c / n}{\Sigma L_c^2 - (\Sigma L_c)^2 / n}$$  \hspace{1cm} (4.5)

where $n$ is the number of data points in the spectrum.

A variety of reference spectra from the JPL spectral library were used for the initial comparison between the mineral features and the broad absorptions in the KH 15D data. The ENVI version of the spectral feature fitting function uses a convolution to resample the data from the field and match its resolution to that of the reference spectrum. However, the GNIRS data have much higher resolution
than the reference spectra and were therefore degraded to match the resolution of the reference spectra.

### 4.4.1 Identification of Mineral Features

The locations of the most prominent absorptions in the GNIRS reflectance spectra were selected for comparison to the reference spectra (See Figure 3.14). The two reflectance spectra are not identical and appear to have slightly different distinguishing features. The differences can be attributed in part to forward scattered light reflecting off of slightly different regions in the ring at the times that the spectra were obtained.

The group of minerals that were compared to the data in our first approach are listed in Table 4.2 along with their chemical compositions. Augite, diopside, enstatite, and hypersthene (common pyroxenes) can each contain Fe$^{2+}$, Mg$^{2+}$, or Ca$^{2+}$ as a cation in the crystal structure. Interactions between the cation and adjacent anions cause the orbital energy levels of the electrons in the crystal to split, resulting in broad absorption features around 1 and 2 $\mu$m in their reflectance spectra (Gaffey 1976). The location and strength of the features is dependent on the type of cation, so it is important to look at a broad range of pyroxenes when trying to identify minerals within the circumbinary ring.

**Table 4.2: Candidate Minerals**

<table>
<thead>
<tr>
<th>Mineral Name</th>
<th>Composition</th>
<th>Color (in Figure 3.14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Augite</td>
<td>(Ca, Na)(Mg, Fe, Al, Ti)(Si, Al)$_2$O$_6$</td>
<td>Blue</td>
</tr>
<tr>
<td>Diopside</td>
<td>CaMgSi$_2$O$_6$</td>
<td>Green</td>
</tr>
<tr>
<td>Enstatite</td>
<td>Mg$_2$Si$_2$O$_6$</td>
<td>Red</td>
</tr>
<tr>
<td>Hypersthene</td>
<td>(Mg, Fe$^{2+}$)$_2$Si$_2$O$_6$</td>
<td>Gold</td>
</tr>
<tr>
<td>Olivine</td>
<td>(Fe, Mg)$_2$SiO$_4$</td>
<td>Magenta</td>
</tr>
</tbody>
</table>

Figure 4.7 shows that hypersthene and enstatite are the best matches to the
first 1 μm feature in the November spectrum, and the 2 μm feature in the augite and diopside reference spectra matches the broad absorptions at the same wavelength in both of the KH 15D spectra. However, none of the minerals in Table 4.2 have features at the location of the 1.1 μm absorption that is present in both spectra. The minerals that agree best with our data can be combined to see whether a mixture can reproduce all of the KH 15D absorptions. This requires estimates for the approximate abundance of each mineral.

The emission spectra of olivine and pyroxene have also been studied in detail in other systems, such as GQ Lup (McClure et al. 2012). Although GQ Lup is not a binary, it is around the same age as KH 15D (3 Myr) and provides a rough baseline for predicting the composition of the circumbinary ring in our system. The population of crystalline silicates in the inner disk of GQ Lup was modeled as half enstatite and half forsterite (the Mg endmember in olivine). Our enstatite and olivine reference spectra can be linearly combined to form a mixture with similar abundances simply by multiplying each spectrum by 0.5 and adding the two together. The result is shown in Figure 4.8.

Although GQ Lup has a significant abundance of crystalline forsterite, the features in the olivine reference spectrum do not quite match the KH 15D data. To obtain a more representative mixture, we removed the olivine and included augite and diopside. Hypersthene was left out, because it matched the same feature as enstatite. The enstatite was kept at an abundance of 50%, and the other two were set at 25% each. The second mixture provides a somewhat better fit to the 1 μm feature in both spectra, but it is clear that further analysis is required to constrain the abundances of these minerals in KH 15D.

The biggest factor affecting our comparison is the difference between the population of grains in KH 15D and the minerals that the reference spectra were
4. Analysis

**Figure 4.7:** Various reference spectra of olivine (pink) and pyroxenes were compared to the KH 15D data to see which had characteristic features closest to the prominent absorptions in the reflectance spectra. Augite (blue) and diopside (green) both have strong absorptions near the location of the $\sim 2 \mu m$ feature in the KH 15D data. The $1 \mu m$ features are more difficult to characterize, but hypersthene (cyan) and enstatite (red) appear to match the location of the first absorption in the November spectrum.
4. Analysis

Figure 4.8: Two linear combinations of minerals were created for comparison to the KH 15D data. The red, dashed line shows a mixture of 50% enstatite and 50% olivine. Abundances were chosen based on the composition of crystalline silicates in the inner disk of GQ Lup (McClure et al. 2012). The blue, dashed line shows a mixture that was created from the minerals that provided the best individual matches to the KH 15D spectra. The composition here is 50% enstatite, 25% diopside, and 25% augite.
collected from. While the crystalline form of these minerals has been detected in the inner and outer regions of the disk in GQ Lup, most of the dust population close to the star is in the form of amorphous silicate, similar to the grains found in the ISM (McClure et al. 2012). The JPL reference spectra were likely produced from larger, crystalline particles. Both the state of the grains and their sizes are known to impact the strength and shape of features in reflectance spectra and need to be considered carefully in future work.
Chapter 5
Summary & Conclusions

5.1 Summary

In this thesis, we have presented the results of three separate sets of optical and near-IR observations of the eclipsing T Tauri binary KH 15D. High cadence photometry was obtained with ANDICAM on the 1.3 m telescope at CTIO from October 2013-April 2014 and again from September 2014-April 2015. The system was also observed with the Spitzer Space Telescope in December 2011 as part of a campaign by the YSOVAR2 team. Follow-up observations at a lower cadence were conducted between December 2013 and January 2014 to obtain information at eclipse phases that were not observed during the 2011 run. Finally, we obtained four near-infrared spectra with GNIRS at Gemini-North Observatory during three different eclipse phases in 2013. The data have provided the following information about the behavior of KH 15D:

- The maximum brightness of the system has increased over the last two years, reaching a peak magnitude of $I = 14.14 \pm 0.02$. This is slightly brighter than the expected $I$ band magnitude for a K1 star (Windemuth & Herbst 2014), implying that star B is now fully emerged at apastron. Figure 3.1 shows that the leading edge of the occulting screen took $\sim 4$ years to cover the orbit of star A, while the trailing edge revealed the path of star B within the
same amount of time. This strongly supports models of a rigidly precessing circumbinary ring.

- We continue to see uniform eclipse depths across bands $VRIJH$, as expected if the occulting material is opaque at these wavelengths. Figure 3.3 shows that the eclipse depth has not changed significantly since the system began to brighten in 2011, but the eclipse duration is steadily decreasing as star B emerges.

- Increased scatter in the $K$ band photometry at minimum light shows that the ring has become slightly more transparent at $2.2 \mu m$. This is supported by the system’s $V-K$ colors between 2014 and 2015 (see Figure 3.8), which became redder as star B first began to move behind the screen before becoming bluer when most of its surface was covered by the ring material. The recent reddening implies that we are looking along a different line of sight to the circumbinary ring than in previous years.

- Extending our photometric analysis out to $3.6$ and $4.5 \mu m$ with the Spitzer data shows that the reddening observed in the $K$ band data this year was present at longer wavelengths as early as 2011 (see Figure 4.2). The reddening is consistent with extinction by dust grains with minimum sizes on the order of the wavelength of light. This result is the first direct detection of the occulting material and provides observational confirmation of the $\sim 5-10 \mu m$ grain size predicted by Chiang & Murray-Clay (2004) and Agol et al. (2004).

- $H_2$ emission features were detected in the GNIRS spectra during the intermediate and faint phases and have line flux ratios that are more consistent
with a shock-excited emitting region than UV fluorescence. The thermal excitation temperatures derived from the line flux ratios are consistent with the value obtained by Deming et al. (2004), confirming that the features originate in a bipolar outflow that is far enough from the stars to be unobscured during eclipse.

• The He I feature at 1.083 µm was also detected in the intermediate and faint phase GNIRS spectra. Although often used as a signpost for accretion, the lines do not show resolved blue or redshifted absorption components in any of the three spectra. The strengths of the feature measured in the faint phase spectra are unusual, but characterization requires higher resolution observations.

• Reflectance spectra of the system were obtained by dividing each of the faint phase GNIRS spectra by the bright phase spectrum. The spectra show prominent absorptions around 1 and 2 µm, which are consistent with characteristic features of olivine and pyroxene minerals.

• We have removed the stellar features from the faint phase spectra by subtracting the scaled bright spectrum from each. This could allow us to detect signatures of a putative giant planet, but further work is needed to identify which features can be attributed to the planet and which are associated with dust in the circumbinary ring.
5.2 Future Work

5.2.1 Why study a protoplanetary environment in the near-IR?

Observations of dust in protoplanetary disks are normally carried out at much longer wavelengths than 2.2, 3.6, and 4.5 \( \mu m \). The light from the host star in a typical system overwhelms the contribution from the disk, making it difficult to obtain detailed information about grains smaller than \( \sim 5 \mu m \). Furthermore, WTTS do not have significant excess emission at IR wavelengths compared to their younger CTTS counterparts, making it even more difficult to study the properties of circumstellar disks in this regime. The unique orientation of KH 15D provides an opportunity to study the near-infrared properties of a protoplanetary environment and perhaps piece together a more complete picture of the grain size distribution within an evolving disk.

Calvet et al. (2002) discovered an inner gap in the disk of the 10 Myr system TW Hya, which would be consistent with its lack of excess near-IR emission. However, the system also displays signatures of weak accretion, implying that there is still optically thin material in the disk at radii \( \leq 4 \text{ AU} \). Models of the opacity at near-infrared wavelengths along with the observed excess emission at longer wavelengths provided evidence for grain growth, in agreement with models of the solar nebula. Continued high-cadence observations of KH 15D in the near-infrared could allow us to find evidence of grain growth in an even younger system by providing a means to directly measure an opacity function for dust grains within the circumbinary ring. This in turn can provide more information about the grains producing the reflectance features we have detected in the GNIRS
spectra, allowing us to better constrain the abundances of solar system minerals in a young, protoplanetary environment.

5.2.2 Could there be stronger emission near periastron?

Our near-infrared spectra have shown that the excitation temperatures extracted from the line flux ratios are roughly consistent between the intermediate and faint phases. Furthermore, the temperatures agree with the value obtained by Deming et al. (2004) when star A was the directly visible component in the system. This confirms that the features originate in a shock-excited bipolar outflow that is uneclipsed when the stars move behind the ring. However, the He I line at 1.083 µm seems to display more flux during minimum light, when the stars are near periastron.

Previous work has cited tidal interactions between star A and star B as a potentially important factor during the faint phase. Herbst & Moran (2005) reported an x-ray flux for KH 15D during its bright phase that is an order of magnitude lower than the measured values for other K stars in NGC 2264. The low x-ray luminosity was attributed to an anomalously low rate of production at these wavelengths, rather than absorption of radiation along the line of sight. Although tidal interactions between the stellar magnetospheres near periastron were cited as a possible cause of the flux reduction, the effect hasn’t been studied closely at x-ray wavelengths in other PMS binaries.

Hamilton et al. (2012) discussed higher accretion rates near periastron as an explanation for the significant increase in H\alpha equivalent widths from ingress to egress. However, models of accretion in eccentric binaries indicate that the accretion rate should be highest just before periastron, corresponding to an expected
decrease in Hα EW during egress. Higher resolution observations of the He I feature at various orbital phases could lend further insight into the nature of accretion rates in tight binary systems and help resolve the discrepancy between observations of KH 15D and current models.

5.2.3 Can we identify signatures of a planet?

The model spectra from Spiegel & Burrows (2012) show distinct peaks around 1, 1.2, 1.6, and 2.1 µm. The KH 15D data, in particular from December, also show increased emission near these wavelengths, although the strength and shape of the features are not entirely consistent with the model spectra. Confirmation that we have truly detected signatures of a giant planet will require careful identification of as many stellar features as possible, since accurate removal of star B from the faint phase spectra is essential.

An additional complication is the similarity between features in the reflectance spectra (Figure 3.14) and the star-subtracted spectra (Figure 3.16, bottom panels). Before we can attribute features in the star-subtracted spectra to light from a giant planet, we must convince ourselves that we have detected peaks in emission rather than reflection. In addition to a fine-tuned star subtraction method, a more rigorous model of the minerals producing the reflectance spectra will be crucial to disentangling the signatures of the two components.

The geometry of KH 15D has allowed us to study detailed features of a protoplanetary environment at shorter wavelengths than are typically possible for systems with low accretion rates, providing insight into planet formation processes in a regime that is usually inaccessible. We expect that the occulting screen will gradually uncover more of the orbital path of star B in the next few years, mak-
ing the peak magnitude of the system brighter and the eclipse duration shorter. Although the new epoch will provide an opportunity to study other aspects of KH 15D, near-IR observations will be less useful for characterizing features of the circumbinary ring when star B is no longer eclipsed for a significant portion of the orbital period.
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