NEAR-INFRARED PHOTOMETRIC MONITORING OF THE PRE–MAIN-SEQUENCE OBJECT KH 15D

NOBUHIKO KUSAKABE,1 MOTOHIDE TAMURA,1,2 YASUSHI NAKAJIMA,2 RYO KANDORI,2 AKIKA ISHIHARA,2 TETSUYA NAGATA,3 TAKAHIRO NAGAYAMA,3 SHOGO NISHIYAMA,4 DAISUKE BABA,4 SHUJI SATO,4 KOJI SUGITANI,5 EDWIN L. TURNER,6 LYU ABE,2 HIROSHI KIMURA,7 AND TETSUO YAMAMOTO7

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ABSTRACT

Extensive photometric monitoring of KH 15D, an enigmatic variable in the young star cluster NGC 2264, has been conducted. Simultaneous and accurate near-infrared photometry (JHK, bands) between 2003 December and 2005 March is presented, covering most of the variable phase. The infrared variability is characterized by a large-amplitude and long-lasting eclipse, as observed in the optical. The period of variability is 48.3 ± 0.2 days, the maximum photometric amplitude of variability is ∼4.2 mag, and the eclipse duration is ∼0.5 in phase units. These are consistent with the recent period, amplitude, and duration in the optical. The blueing of the J−H color (∼0.16 mag) during eclipse, which has been suggested before, is unambiguously confirmed; a similar blueing at H−K is less clear but is probably present at a similar level. The overall shape of the JHK light curves is very similar to the optical one, including a fair time symmetry and less stable flux during eclipse, with a slight hump near zero phase. Most of these variability features of KH 15D observed at near-infrared wavelengths can be explained with the recent model that employs an eclipse by an inclined, precessing disk and an outer scattering region around a pre–main-sequence binary.

Subject headings: circumstellar matter — planetary systems: protoplanetary disks — stars: individual (KH 15D) — stars: pre–main-sequence

1. INTRODUCTION

KH 15D (=V582 Mon; 6h41m10s.18, 9°28′35″5′′ (J2000)) is a K6–K7 pre–main-sequence star (Agol et al. 2004; Hamilton et al. 2001) in NGC 2264 (d = 760 pc) that shows unique variability. This is star No. 15 in field D of Kearns & Herbst (1998; see Moffei et al. 2005 for other identifications of this object). The optical variability is characterized by a large eclipse amplitude (maximum ∼4.0 mag in I band between 1999 and 2004; Barsunova et al. 2005; Johnson et al. 2005; Hamilton et al. 2005) and a long eclipse duration, about half its period (currently ∼24 out of ∼48 days; Winn et al. 2004; Johnson et al. 2005). The eclipse duration has been increasing with time, by 1–2 days per year. A great deal of information about this system has been obtained from archival studies (Winn et al. 2003; Johnson & Winn 2004; Johnson et al. 2005). The eclipses were formerly much shallower, and the system was brighter overall. During eclipse, a slight blueing of the star’s color indexes (Herbst et al. 2002; Hamilton et al. 2005), little or no change in spectral type (Hamilton et al. 2001), relatively large flux fluctuations (Herbst et al. 2002; Barsunova et al. 2005), and a dramatic increase in linear optical polarization (Agol et al. 2004) are observed. The latter measurements suggest that a substantial fraction or all of the light in eclipse is scattered light.

At near-infrared wavelengths, no color change or marginal blueing during eclipse is reported (Knacke et al. 2004). Molecular hydrogen emission at 2.12 μm, presumably associated with the mass outflow from this source, has been detected (Deming et al. 2004; Tokunaga et al. 2004), which may be circumstantial evidence for a disk around the central star (or stars). Recent spectroscopic monitoring has revealed that the system is in fact a single-lined spectroscopic binary with the same period as the eclipse (Johnson et al. 2004). These remarkable properties are now explained by the theory that a binary star is being gradually occulted by an inclined and precessing circumbinary disk (Winn et al. 2004) or narrow ring (Chiang & Murray-Clay 2004).

Despite the recent intense interest in this unusual object, a very limited amount of infrared monitoring has been reported, which is indispensable to understanding the occulting material, the dust extinction properties, and the contribution of thermal dust emission, if any. In order to better understand the enigmatic variability of this source, in 2003 December we started long-term monitoring of KH 15D at JHK, simultaneously. In this Letter, we present the magnitudes and colors for the first 16 months (54 independent data points), which covers most of its variable phase (δφ) and serves as the most extensive near-infrared monitoring data on KH 15D to date, and interpret the data based on the disk eclipse model for this system.

2. OBSERVATIONS

We carried out simultaneous imaging observations of a field centered around KH 15D in the near-infrared bands J (λ = 1.25 μm), H (1.63 μm), and Ks (2.14 μm). The observations were made during 2003 December and 2005 March with the near-infrared camera SIRIUS on the 1.4 m Infrared Survey Facility (IRSF) telescope at Sutherland, South Africa. The camera is equipped with three 1024 × 1024 pixel HgCdTe (HAWAII) arrays. Two dichroic mirrors enable simultaneous observations in the three bands. Details of the camera are

1 Department of Astronomical Science, Graduate University for Advanced Studies (Sokendai), Osawa, Mitaka, Tokyo 181-8588, Japan; kusakabe@optik.mtk.nao.ac.jp.
2 National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan; hide@subaru.nao.org.
3 Department of Astronomy, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan.
4 Department of Astrophysics, Faculty of Sciences, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan.
5 Graduate School of Natural Sciences, Nagoya City University, Mizuho, Nagoya 467-8501, Japan.
6 Princeton University Observatory, Peyton Hall, Princeton, NJ 08544.
7 Institute of Low Temperature Science, Hokkaido University, Sapporo 060-0819, Japan.
provided in Nagashima et al. (1999) and Nagayama et al. (2003). The image scale of the array is 0.45 pixel\(^{-1}\), giving a field of view of 7.7 \(\times\) 7.7.

We measured 54 independent data points during this period. We obtained 90 dithered frames with typical exposure times of 10 s, resulting in a total integration time of 900 s for each data point. Typical seeing was 1.4 (FWHM), ranging from 1\(^{\prime}\) to 2\(^{\prime}\), in the K band. The standard star No. 9116 in the faint infrared standard star catalog of Persson et al. (1998) was observed for photometric calibration.

We used the NOAO IRAF software package to reduce the data. We applied the standard procedures for near-infrared array image reduction, including dark current subtraction, sky subtraction, and flat-fielding (see Nakajima et al. 2005 for details of the SIRIUS image reductions). Identification and photometry of point sources were performed by using the DAOFIND and PHOT tasks in IRAF, respectively. The aperture radius for the photometry was 3 pixels (1.35).

### 3. Results

Figure 1 shows a JHK, composite color image of the observed region including KH 15D. The field also includes the famous infrared young stellar object NGC 2264 IRS 1 (Allen 1972) and the top of the Cone Nebula. Note that KH 15D, situated \(\sim 50^\circ\) to the south of IRS 1, is also somewhat affected by the nebula associated with IRS 1. In order to accurately measure the photometric variability of KH 15D, we employed relative photometry within the field. First we checked the variability of each source in the field compared with the median of all the sources among various nights. Then only the sources whose rms magnitude errors are less than 3 \(\sigma\) are selected. This process was repeated three times. Finally, six sources in the field whose nonvariability were confirmed with the above processes were selected.

Figure 2 shows the JHK light curves of KH 15D after calibrating with the photometric standard star (data in Table 1). The periodicity seen at optical wavelengths is clear even in this figure. We determined the periods of the J, H, and K\(_s\) light curves to be the same, 48.3 ± 0.2 days. This is also identical to the most recent optical period.

Phased light curves using the optical period of 48.36 days (Herbst et al. 2002) are shown in Figure 3. The overall shape of each light curve is very similar to the optical one:

1. The light curves at JHK, show fairly good symmetry with time, though the detailed shapes have some asymmetry. For example, the slopes of the first decrease or increase (\(\phi = -0.25\) to \(-0.15\) and \(\phi = 0.15\) to 0.25) are slightly different from each other. Similar changes in slope are observed in the optical (Herbst et al. 2002; Barsunova et al. 2004). Note that the beginning and ending of the eclipse is not as abrupt as seen in the 2001–2002 optical data (Herbst et al. 2002).

2. The maximum photometric variability amplitudes are nearly identical at J, H, and K\(_s\), \(\sim 4.2\) mag. These values are consistent with the optical amplitude of \(\sim 4.0\) mag (in I band between 1999 and 2004, after correcting for the monotonic flux-decrease trend; Barsunova et al. 2005; Johnson et al. 2005). The average amplitudes at JHK\(_s\) are \(\sim 3.6\) mag. Note that the large fluctuations during the eclipse make an accurate comparison of the values between infrared and optical difficult.

3. The flux during the eclipse is less stable, and there is a clear flux hump near \(\phi = 0\). The hump at JHK\(_s\) is at a level of 0.5 mag and continues for about \(\sim 4\) days. This hump is also included in the optical (Herbst et al. 2002; Barsunova et al. 2005). Two minima occur, at \(\phi \sim 0.1\); the minimum at \(\phi = 0.1\) appears deepest.

4. The duration of the eclipse in 2003–2005 (0.52 in phase units at FWHM) is longer by 30% than the optical duration in 2001–2002 (0.4; Herbst et al. 2002) and is rather consistent with the most recent (2003–2004) optical data (0.5; Hamilton et al. 2005). There is no difference of the duration phase among J, H, and K\(_s\).

Figure 4 shows the phased color curves of KH 15D (\(J-H\), \(H-K\)). Outside of eclipse, the \(J-H\) and \(H-K\) colors of KH...
15D are constant, 0.68 ± 0.01 and 0.28 ± 0.02 mag, respectively, which match those of K7-type T Tauri stars (e.g., V410 Tau) with slight reddening (AV ~ 1 mag). Knacke et al. (2004) derived the same spectral type from the average noneclipse colors of J − H = 0.67 and H − K = 0.18. Note that the IRSF-SIRIUS color system is almost identical to the MKO system. The derived spectral type is consistent with the optical one (Hamilton et al. 2001; Agol et al. 2004).

Most striking is the clear change of infrared colors during the eclipse. As seen in Figure 4, the blueing of J − H color (Δm = 0.16 mag) during the transit is unambiguously confirmed by our observations. Such blueing was first reported in the optical (Herbst et al. 2002; see Hamilton et al. 2005 for the most recent optical data) but only marginally suggested in the near-infrared by Knacke et al. (2004). The blueing of the H − K color is less clear but seems to be at a similar level (Δm ~ 0.1 mag). The average J − H and H − K colors during eclipse are 0.52 ± 0.05 and 0.18 ± 0.12 mag, respectively.

No positional shift of KH 15D is observed between the on- and off-eclipse periods, which suggests that contamination by an interferer is unlikely to be the cause of the blueing. In order to cross-check this, we considered possible blue sources. Such a source would have to have a color of J − H < 0.52 (= 0.68 − 0.16) mag to explain the observed blueing. Since the visual extinction at the location of KH 15D is larger than AV = 10 mag, or J − H = 1.1 (Simon & Dahm 2005), the intrinsic color must be J − H < 0.58. No foreground or background star or background galaxy with such a blue intrinsic color is expected to interlope in our 1.35 aperture radius.

### 4. Discussion

The most plausible model of these enigmatic variable features of KH 15D is that a binary star in a mutual orbit with high eccentricity is being gradually occulted by an inclined and precessing circumbinary disk (Winn et al. 2004) or narrow ring (Chiang & Murray-Clay 2004). The existence of such a companion has recently been confirmed by radial velocity measurements (Johnson et al. 2004); the orbital parameters agree well with the prediction by Winn et al. (2004). The long-term change of the variability characteristics revealed by archival studies (Winn et al. 2003; Johnson & Winn 2004; Johnson et al. 2005) can also be explained with the same idea. Today, only one component of the binary is visible (we refer to this

### Table 1

| JD | J   | J − H | J − K | H − K |
|----|-----|------|------|------|
| 2,453,028.42 | 18.68 ± 0.03 | 0.51 ± 0.04 | 0.25 ± 0.02 | 2,453,318.60 |
| 2,453,028.38 | 13.42 ± 0.02 | 0.65 ± 0.03 | 0.27 ± 0.01 | 2,453,318.51 |
| 2,453,066.41 | 16.51 ± 0.03 | 0.54 ± 0.04 | 0.16 ± 0.04 | 2,453,322.54 |
| 2,453,075.28 | 17.16 ± 0.02 | 0.47 ± 0.03 | 0.13 ± 0.02 | 2,453,384.42 |
| 2,453,078.30 | 17.07 ± 0.02 | 0.52 ± 0.03 | 0.13 ± 0.03 | 2,453,386.36 |
| 2,453,291.99 | 13.42 ± 0.02 | 0.68 ± 0.02 | 0.27 ± 0.02 | 2,453,388.41 |
| 2,453,292.59 | 13.41 ± 0.01 | 0.67 ± 0.01 | 0.30 ± 0.01 | 2,453,398.21 |
| 2,453,293.59 | 13.41 ± 0.01 | 0.67 ± 0.01 | 0.30 ± 0.01 | 2,453,400.22 |
| 2,453,302.61 | 13.45 ± 0.00 | 0.69 ± 0.01 | 0.28 ± 0.02 | 2,453,407.22 |
| 2,453,366.61 | 14.53 ± 0.00 | 0.67 ± 0.01 | 0.34 ± 0.02 | 2,453,405.25 |
| 2,453,307.67 | 16.31 ± 0.02 | 0.56 ± 0.03 | 0.26 ± 0.04 | 2,453,409.28 |
| 2,453,309.55 | 16.73 ± 0.01 | 0.65 ± 0.02 | 0.28 ± 0.03 | 2,453,405.35 |
| 2,453,312.55 | 17.19 ± 0.01 | 0.54 ± 0.01 | 0.04 ± 0.03 | 2,453,406.28 |
| 2,453,313.59 | 17.35 ± 0.01 | 0.58 ± 0.02 | 0.16 ± 0.04 | 2,453,406.36 |
| 2,453,315.57 | 17.34 ± 0.01 | 0.49 ± 0.02 | 0.13 ± 0.03 | 2,453,407.21 |
| 2,453,317.60 | 17.29 ± 0.01 | 0.54 ± 0.02 | 0.29 ± 0.02 | 2,453,409.37 |
| 2,453,318.46 | 17.16 ± 0.01 | 0.53 ± 0.02 | 0.17 ± 0.03 | 2,453,411.22 |
| 2,453,318.53 | 17.20 ± 0.01 | 0.61 ± 0.02 | 0.25 ± 0.02 | 2,453,415.26 |

### Figure 3

Phased light curves of KH 15D (JHKs) from 2003 December to 2005 March. A period of 48.36 days was used for phasing.

### Figure 4

Phased color curves of KH 15D (J − H, H − Ks) from 2003 December to 2005 March. A period of 48.36 days was used for phasing. The horizontal lines show the average colors outside of eclipse.
component as star A), with the other component (star B) being entirely hidden behind the disk. By employing this theory, we consider the near-infrared and optical features to be explainable as follows:

a) Both the large variability amplitude and the long-lasting periodic eclipses that are almost independent of the observed wavelengths (VRIJHK) are well explained with a gradual occultation by a knife-edge screen. In this case, the screen is either a circumbinary disk or ring, and the disk dust size responsible for the screening must be much larger than the observed wavelengths (>2 μm). The rough time symmetry of the light curve is also explained by this theory. The detailed asymmetric features during the eclipse are probably due to the fine structure and kinematics of the disk or ring, which need future detailed modeling.

b) The blueing of near-infrared color, as well as that in the optical, indicates that the eclipse is not due to the disk dust absorption, which causes “reddening.” As described below, the blueing can also be explained by the eclipsing-disk model, with an outer scattering region. This is consistent with the increase of optical polarization during eclipse, which suggests that a large fraction of the light in eclipse is scattered (Agol et al. 2004).

The polarization data suggest that the scattering region is not completely obscured by the occulting material. The dust in this scattering region, which is distinct from the screening dust mentioned above, must be responsible for both the color blueing and the polarization. In order to explain these, we have calculated light scattering by dust grains in the nonocculted, scattering region. We have assumed the scattering region to be a hemisphere over the eclipsing disk, the dust spatial distribution to follow \( n(a) \propto a^{−15} \) (corresponding to free-falling dust), the dust material to be silicate (Laor & Draine 1993), and the dust size distribution to follow \( a^{−5} \) with \( a_{\text{min}} = 0.5 \) nm and \( a_{\text{max}} = 5 \) μm. The radius of the hemisphere is 2.6 AU, with its equatorial plane inclined by 20° to the line of sight (Winn et al. 2004). The result of color changes and optical polarization of the integrated scattered light are \( \Delta m = 0.16 \) mag for \( J−H \), 0.18 mag for \( H−K_s \), and \( p_{\text{optical}} = 2\% \), respectively. Although detailed modeling of the geometry and dust grains is beyond the scope of this Letter, this simple model quantitatively well reproduces both our observed color changes and the polarizations by Agol et al. (2004).

Since there is no sign of \( H−K_s \) color excess, the possible thermal emission from the disk suggested from the model or the \( H_2 \) outflows appear insignificant in the near-infrared.

c) The hump near \( \phi = 0 \) is probably due to some flux contribution from the unseen star (star B) of the binary in Winn’s model, because star B is nearest to the occulting edge at the middle of the eclipse. The amplitude is \( \sim 0.5 \) mag at \( JHK_s \), almost identical to the amplitude at \( I \) (in 2002–2003, Johnson et al. 2005). The optical color tends to be slightly bluer near this hump compared with other colors during eclipse (Hamilton et al. 2005), which may support the interpretation that some additional light (from star B) increases at this time. Since such a change in our near-infrared colors near this hump is not conclusive, more accurate and intensive monitoring during this phase is necessary.

5. CONCLUSIONS

We have conducted \( JHK_s \) monitoring of KH 15D, in NGC 2264, between 2003 December and 2005 March. The main conclusions of this Letter are as follows:

1. The \( JHK_s \), light curves are very similar to the optical light curve, showing fairly good time symmetry and a slight flux hump near zero phase.
2. The \( JHK_s \) period is the same as that in the the optical, 48.3 days.
3. The maximum \( JHK_s \), variability amplitude is \( \sim 4.2 \) mag.
4. The eclipse durations are identical among \( J, H, \) and \( K_s \) (0.52 in phase units from 2003 to 2005).
5. The blueing of \( J−H \) color (\( \Delta m = 0.16 \) mag) during transit is unambiguously confirmed, while the blueing of \( H−K_s \) appears at a similar level.

These near-infrared variability features can be explained with the model employing an eclipse by an inclined and precessing disk or ring around a pre–main-sequence binary. The dust in the disk causing the eclipse is very large (\( a > 2 \) μm), and therefore the eclipse is independent of wavelength, while the dust responsible for the scattered flux during eclipse is outside of the disk and smaller (\( a_{\text{max}} \sim 5 \) μm), causing the color blueing and polarization only during this phase.

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REFERENCES

Agol, E., Barth, A. J., Wolf, S., & Charbonneau, D. 2004, ApJ, 600, 781
Allen, D. 1972, ApJ, 172, L55
Barsunova, O. Yu., Grinin, V. P., & Sergeev, S. G. 2005, Astrofizika, 48, 1
Chiang, E. I., & Murray-Clay, R. A. 2004, ApJ, 607, 913
Deming, D., Charbonneau, D., & Harrington, J. 2004, ApJ, 601, L87
Hamilton, C. M., Herbst, W., Shiht, C., & Ferro, A. J. 2001, ApJ, 554, L201
Hamilton, C. M., et al. 2005, AJ, 130, 1896
Herbst, W., et al. 2002, PASP, 114, 1167
Johnson, J. A., Marcy, G. W., Hamilton, C. M., Herbst, W., & Johns-Krull, C. M. 2004, AJ, 128, 1265
Johnson, J. A., & Winn, J. N. 2004, AJ, 127, 2344
Johnson, J. A., et al. 2005, AJ, 129, 1978
Kearns, K. E., & Herbst, W. 1998, AJ, 116, 261
Knacke, R., Fajardo-Acosta, S., & Tokunaga, A. T. 2004, AJ, 128, 2977
Laor, A., & Draine, B. T. 1993, ApJ, 402, 441
Maffeï, P., Ciprini, S., & Tosti, G. 2005, MNRAS, 357, 1059
Nagashima, C., et al. 1999, in Star Formation 1999, ed. T. Nakamoto (Nobeyama: Nobeyama Radio Obs.), 397
Nagayama, T., et al. 2003, Proc. SPIE, 4841, 459
Nakajima, Y., et al. 2005, AJ, 129, 776
Persson, S. E., Murphy, D. C., Krzesinski, W., Roth, M., & Rieke, M. J. 1998, AJ, 116, 2475
Simon, T., & Dahm, S. E. 2005, ApJ, 618, 795
Tokunaga, A. T., et al. 2004, ApJ, 601, L91
Winn, J. N., Garnavich, P. M., Stanek, K. Z., & Sasselov, D. D. 2003, ApJ, 593, L121
Winn, J. N., Holman, M. J., Johnson, J. A., Stanek, K. Z., & Garnavich, P. M. 2004, ApJ, 603, L45