NEAR-INFRARED VARIABILITY AMONG YOUNG STELLAR OBJECTS IN THE STAR FORMATION REGION CYGNUS OB7

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Received 2013 March 28; accepted 2013 June 8; published 2013 August 5

ABSTRACT

We present an analysis of near-infrared time-series photometry in J, H, and K bands for about 100 epochs of a 1° × 1° region of the Lynds 1003/1004 dark cloud in the Cygnus OB7 region. Augmented by data from the Wide-field Infrared Survey Explorer, we identify 96 candidate disk bearing young stellar objects (YSOs) in the region. Of these, 30 are clearly Class I or earlier. Using the Wide-Field Imaging Camera on the United Kingdom Infrared Telescope, we were able to obtain photometry over three observing seasons, with photometric uncertainty better than 0.05 mag down to J ∼ 17. We study detailed light curves and color trajectories of ∼50 of the YSOs in the monitored field. We investigate the variability and periodicity of the YSOs and find the data are consistent with all YSOs being variable in these wavelengths on timescales of a few years. We divide the variability into four observational classes: (1) stars with periodic variability stable over long timescales, (2) variables which exhibit short-lived cyclic behavior, (3) long-duration variables, and (4) stochastic variables. Some YSO variability defies simple classification. We can explain much of the observed variability as being due to dynamic and rotational changes in the disk, including an asymmetric or changing blocking fraction, changes to the inner disk hole size, as well as changes to the accretion rate. Overall, we find that the Class I:Class II ratio of the cluster is consistent with an age of < 1 Myr, with at least one individual, wildly varying source ∼100,000 yr old. We have also discovered a Class II eclipsing binary system with a period of 17.87 days.

Key words: accretion, accretion disks – infrared: stars – stars: formation – stars: pre-main sequence – stars: variables: general

Online-only material: color figures

1. INTRODUCTION

Young stellar objects (YSOs) were first highlighted because they are irregular optical variables (Joy 1942, 1945). As our understanding of these objects has grown we now consider them as composite systems. In addition to a star, there may be an accretion layer, a disk, and an outer envelope. Strong magnetic fields in the star can induce cool starspots, while the accretion can create hot spots in the photosphere. These individual components are dynamic, rotate, and experience various wave phenomena. Changes in any component may induce changes in luminosity. From optical studies, Herbst et al. (1994) identified three types of variability specifically associated with the most well known YSO class—T Tauri stars. One type of variability (called by Herbst et al. 1994 “Type I”) is characterized by a low-level periodic modulation of the stellar flux (a few 0.1 mag) and results from the rotation of a cool spotted photosphere. A second type of variability is associated with short-lived accretion-related hot spots at the stellar surface of TTs; this “Type II” variability has larger photometric amplitudes (up to 2 or 3 mag in extreme cases) and is most often irregular. They also noted some stars with month-long dips, presumed to be due to disk eclipses, which they labeled “Type III.”

Most variability studies have used optical monitoring. Type I variability allows direct measurement of the rotation period of YSOs by optical monitoring of the stellar flux. It has been in use regularly for this purpose over the last two decades (e.g., Attridge & Herbst 1992; Rebull 2001; Cohen et al. 2004; Parihar et al. 2009). However, the nature of YSOs favors near and mid-IR wavelengths. Near-infrared (NIR) studies of young stars allow for the direct detection of optically thick protoplanetary disks around these stars via excess K-band flux (Lada & Adams 1992). The study of near-infrared variability in young stars allows us to study changes in those disk structures. Studies of the Orion A molecular cloud and the Chameleon I molecular cloud established that NIR variability is present in YSOs (Carpenter et al. 2001, 2002). In Orion, as many as 93% of the variable stars were identified to be young stars, and a strong connection was established between variability and near-infrared excess. Studies of individual YSOs such as AA Tau and its analogs reveal insights into magnetospheric accretion processes linked to inner-disk dynamics (Bouvier et al. 2003, 2007; Donati et al. 2010). Other types of stars such as EX Lup (Aspin et al. 2010) and V1118 Ori (Audard et al. 2010) that exhibit large, eruptive mass accretion, due to infall events of M ∼ 0.1 M⊕, are easily studied in the near-infrared. During outburst, their near-infrared emission is dominated by hot spot radiation, emission reprocessed in the disk. Further, the inner disk edge appears to move inward and brightens in the near-infrared.

Recent mid-IR variability surveys with Spitzer provide insights into physical processes of young stars over short (~40 day) timescales. These surveys find 60%–70% of YSOs with infrared excess are variable (Morales-Calderón et al. 2009, 2011; Flaherty et al. 2013; Parks et al. 2013). Importantly, Morales-Calderón et al. (2011) also find a number of dust-eclipse events suggestive of AA Tau, giving insight into the structure and behavior of protoplanetary disks around stars of this age, as well as the importance of magnetically driven accretion onto young stars. Scholz (2012) studied the NIR variability of several young clusters including the ONC, NGC 1333, IC 348, and σ Orionis. He finds variability amplitudes are largest...
in NGC 1333, presumably because it has the youngest sample of YSOs. The frequency of highly variable objects also increases with the time window of the observations.

We have carried out a near-IR JHK survey of the photometric variability of objects in the Lyps 1003/1004 dark cloud within Cygnus OB7 (Cyg OB7) which we monitored for nearly two years. Cyg OB7, at a distance of around 800 pc (distance modulus $\mu = 9.5$; Aspin et al. 2009), is the nearest of nine OB associations identified in Cygnus. Cyg OB7 contains the dark clouds Lyps 1003 and Lyps 1004; previous studies of the cluster in this dark cloud have confirmed it as a region of active star formation. Thirteen T Tauri stars have been identified via near-infrared spectra (Aspin et al. 2009), two outbursting FUor objects (Reipurth & Aspin 1997; Movsessian et al. 2006; Greene et al. 2008), protostellar millimeter-emitting cores (Aspin et al. 2011), as well as Herbig–Haro outflows (Movsessian et al. 2003; Magakian et al. 2010) are also present.

In a recent paper, Rice et al. (2012; RWA; hereafter Paper I) presented first results of this multi-epoch monitoring campaign of the Cyg OB7 region. We examined photometry of 9200 stars, across 120 nights with precision better than 4%, identifying a sample of 30 YSOs, including 6 from Aspin et al. (2009). We found 93% of the YSOs varied significantly. The variability observed included color changes which caused sources to transit the disk/photosphere demarcation in the IR color–color diagram. While some of the changes may be rotationally modulated surface spots (hot or cold), other color changes were identified with changes in the disk structure, others required the inclusion of additional reddening as well, and still others appeared still more complicated.

In a companion paper, Wolk et al. (2013; hereafter Paper II) analyzed the subset of variable stars in this field that lack evidence of disks. Using the long-baseline, moderate-cadence time-series photometry, we identify periodic and stochastic variability in about 150 field stars. We conclude the rate of field star variability in the near infrared is about 1.6% in this field. Periodic variability is seen in about one-third to one-half of the variable field stars and is dominated by evolved eclipsing binary systems.

In this paper, we present a follow-up to the analyses presented in Papers I and II. We expand the J, H, and K variability study toward Cyg OB7 to include the examination of all disk bearing sources. We have also used period analysis on the YSOs. With long-baseline, moderate-cadence time-series photometry, we identify young stars with periodic, quasi-periodic and stochastic variability. We use empirical evidence to suggest that these are caused by rotational, dynamic, and eruptive events. In Section 2, we briefly restate the photometric reliability of the Wide-Field imaging CAMera (WFCAM) data. We also bring newly released Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) data to bear in identifying additional YSOs in the field. We then move on to discuss variability among the YSOs. Repeating the techniques used in Papers I and II, we find that the NIR variability among YSOs can be described by a limited number of families. These families include periodic, quasi-periodic, long-duration, and stochastic variables. Finally, in Section 4 we discuss the different phenomena and comment on possible physical mechanisms.

2. OBSERVATION AND DATA REDUCTION

The data set in use here was fully described in Paper I. In brief, J, H, and K observations of the Cygnus OB7 region were obtained using the Wide Field Camera (WFCAM) instrument on the United Kingdom InfraRed Telescope (UKIRT), an infrared-optimized 3.8 m telescope atop Mauna Kea, Hawaii, at 4200 m elevation. The field of view of the study is about a 1 deg square centered on $21^\text{h}00^\text{m} +52^\circ30^\prime$ (J2000) near the “Braid Nebula star.” Our data consist of WFCAM observations taken from 2008 May to 2009 October in three observing seasons as part of a special observation program. Data were taken on 124 nights; of these, 100 were deemed to be of high quality in that they were internally consistent in color and magnitude to within 1% against night-to-night variations. Using the three seasons of UKIRT observations we obtained high-quality photometry—defined as having errors less than 5% at $J \sim 17$, $H \sim 17$, and $K \sim 16.5$ and no error flags—on 9200 stars. In Paper I, we did not include stars fainter than $J = 17$ nor brighter than $J = 11$ as bright stars would saturate in many epochs if the conditions were especially good seeing or if the star brightened.

In Paper I, YSOs were identified using the classical $J - H$, $H - K$ color–magnitude diagram (Lada & Adams 1992) which identifies stars with optically thick disks at K band. A total of 30 YSOs were identified in this way including seven which transited the photosphere/disk boundary as a result of observed variability (Rice et al. 2012). Variability was quantified for all sources in the field using the Stetson index (Stetson 1996). This is a method for quantifying correlated variability within samples which includes multiple colors each with different error characteristics. The resultant value is zero for a constant source and exceeds 1 for a source with strong, correlated variability. In Paper I, we indicated about 160 variable stars including 28 of the YSOs.

As described in Paper II we search for periodicity among all variable sources using two techniques: the Lomb-normalized periodogram (LNP; e.g., Press & Rybicki 1989) and the Fast $\chi^2$ algorithm (F$\chi^2$; Palmer 2009). Both are suited to period analysis on unevenly sampled data such as ours. The LNP method is a useful and popular way to analyze periodicity with an easily interpreted periodogram, which identifies multiple candidate periods and their relative probability. This tended to be more reliable on longer period data (period >1 day). The F$\chi^2$ method was empirically more reliable for complex variables such pulsating stars and for short-period (<1 day), highly stable, non-sinusoidal variables, such as eclipsing binaries.

2.1. WISE Data

Our goals for this paper include verification of the Class II nature of the sources detected in Paper I and investigation of variability among other disked stars in the field. Paper I was limited to YSOs in the fairly limited magnitude range discussed in the previous subsection, and with high-quality data in all three NIR bands. Recently the WISE point-source catalog became available (Cutri et al. 2012). WISE conducted a survey of the entire sky from 2010 January 7 to August 6 in the 3.4, 4.6, 12, and 22 $\mu$m bandpasses (hereafter W1, W2, W3, and W4). WISE achieved 5$\sigma$ point-source sensitivities better than 16.6, 15.6, 11.3, and 8.0 (W1–W4, respectively; Vega mag) in unconfused

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5 We label this index as $S$. Stetson originally used $J$, but this can be confused with the photometric filter (e.g., Carpenter et al. 2001).

4 Carpenter et al. (2001) compared the Stetson index to $\chi^2$ fits and concluded that $S > 0.55$ was sufficient to confirm variability. In Paper I, we concluded that $S > 1.0$ was preferable because the more conservative value prevented false detections in large samples. In the present paper, we identify three objects with $0.55 < S < 1.0$.  

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Table 1

| RWA Number | Photometry | WISE Colors | Other | Class |
|------------|------------|-------------|-------|-------|
|            | W1         | W2          | W3    | W4    | W1 – W2 | W2 – W3 | W3 – W4 | Name       |       |
| 1          | 9.83       | 9.22        | 7.10  | 4.48  | 0.61    | 2.12    | 4.74    | CN 2       | Class IIR |
| 2          | 9.19       | 7.23        | 3.65  | 1.06  | 1.96    | 3.58    | 6.16    | 21005+5217b | Class I  |
| 3          | 11.76      | 11.16       | 8.86* | 5.56  | 0.61    | 2.30    | 5.59    | Class IIR  |
| 4          | 10.26      | 9.67        | 7.24  | 4.59  | 0.59    | 2.43    | 5.08    | Class IIR  |
| 5          | 9.92       | 9.21        | 7.06  | 4.32  | 0.71    | 2.14    | 4.88    | Class IIR  |
| 6          | 12.03      | 11.55       | 9.70* | 7.65* | 0.48    | 1.85    | 3.91    | Class II   |
| 7          | 11.17      | 10.03       | 7.06  | 3.91  | 1.13    | 2.98    | 6.12    | 2100019+523515c | Class I  |
| 8          | 13.48      | 12.97*      | 10.59*| 7.85* | 0.51    | 2.38    | 5.12    | Class IIR  |

Notes.

* Photometric errors are larger than the typical photometric errors of <3% for W1 and W2 or <20% for W3 and W4.

a From Aspin et al. (2009).

AKARI ID.

b IRAS ID.

c WFCAM median colors are used for J, H, and K. WISE colors are presumed dominated by the brighter source IRAS 15N.

d With an angular resolution of 6.1', 6.4', 6.5', and 12.0' in the four bands. The WISE Source Catalog (WSC) contains the attributes for over 5 × 10^8 point-like and resolved objects. Catalog sources are required to have a measured S/N > 5 in at least one band, and to meet other criteria to assure a high degree of reliability (Cutri et al. 2012).

We extracted about 35,400 sources from the WSC in a 1.42 deg diameter centered at R.A. 315.1, decl. 52.5 which includes the entire square degree survey area and 0.62 deg^2 outside the RWA survey area. Table 1 provides the mid-IR colors of the YSOs identified in Paper I (“RWA 1–30”), while Table 2 lists near- and mid-IR colors for nine other previously known regions with an angular resolution of 6.1', 6.4', 6.5', and 12.0' in the four bands. The WISE Source Catalog (WSC) contains the attributes for over 5 × 10^8 point-like and resolved objects. Catalog sources are required to have a measured S/N > 5 in at least one band, and to meet other criteria to assure a high degree of reliability (Cutri et al. 2012).

Table 2

| Object ID | J (mag) | H (mag) | K (mag) | W1 (mag) | W2 (mag) | W3 (mag) | W4 (mag) | Other Name | Class |
|-----------|--------|--------|--------|----------|----------|----------|----------|------------|-------|
| 2MASS (J2000) |        |        |        |          |          |          |          |            |       |
| 205821.09+522927.7 | 11.54  | 9.81  | 8.31  | 5.46    | 3.38    | 0.57    | −1.50   | HH381 IRSa | Class I  |
| 210011.59+521817.3 | 11.38  | 10.48 | 10.02 | 9.27    | 8.79    | 7.31    | 6.04    | Cyg 19a   | Class II |
| 210003.76+523429.0 | 13.32  | 11.28 | 9.99  | 8.36    | 7.52    | 5.31    | 3.17    | CN3Naa    | Class I  |
| 210021.13+522705.2 | 12.43  | 12.04 | 11.96 | …       | …       | …       | …       | IRAS 15Nac | Class I  |
| 210021.40+522709.4 | 11.43  | 10.50 | 9.72  | 7.89    | 5.75    | 3.01    | 3.01    | IRAS 15Nac | Class I  |
| 210021.42+522257.1 | 17.36  | 16.69 | 14.05 | 11.27   | 8.70    | 5.30    | 3.20    | I20588+5221b | Class I |
| 210025.25+523017.0 | …      | …     | …     | 9.55    | 7.26    | 4.12    | 1.14    | Braid starab | Class I |
| 210038.77+522757.5 | …      | …     | …     | 11.89   | 8.89    | 6.58    | 3.52    | core#333Hb | Class I  |
| 210042.38+522600.8 | 18.26  | 15.51 | 14.06 | 11.82   | 9.63    | 7.24    | 3.94    | IRAS 14a   | Class I  |

Notes.

Typical photometric errors are <2% for W1 and W2 and <20% for W3 and W4.

a Aspin et al. (2009).

b Khanzadyan et al. (2012).

c Sources are not resolved in WSC or 2MASS. WFCAM median colors are used for J, H, and K. WISE colors are presumed dominated by the brighter source IRAS 15N.

We extracted about 35,400 sources from the WSC in a 1.42 deg diameter centered at R.A. 315.1, decl. 52.5 which includes the entire square degree survey area and 0.62 deg^2 outside the RWA survey area. Table 1 provides the mid-IR colors of the YSOs identified in Paper I (“RWA 1–30”), while Table 2 lists near- and mid-IR colors for nine other previously known regions with an angular resolution of 6.1', 6.4', 6.5', and 12.0' in the four bands. The WISE Source Catalog (WSC) contains the attributes for over 5 × 10^8 point-like and resolved objects. Catalog sources are required to have a measured S/N > 5 in at least one band, and to meet other criteria to assure a high degree of reliability (Cutri et al. 2012).
YSOs in the field. Errors are generally quite small, exceeding 3% in W1 and W2 only for RWA 8, 14, and 28 with a largest error of 14%. Errors in the redder channels are generally <5% and only exceed 20% for RWA 8, 10, 14, 21, 23, and 33. By far the two largest errors occur on RWA 10 and RWA 14 which have errors of about 50% in W3 and W4, respectively. RWA 9 is surprisingly excluded from the WISE PSC although the source is present in WISE atlas images.

Previously, with both near and mid-IR surveys, color–color and color–magnitude diagrams have proven to be powerful tools in identifying Class I and Class II objects (Lada & Adams 1992; Allen et al. 2004; Megeath et al. 2004; Gutermuth et al. 2009). This is because stars without disks have spectral energy distributions (SEDs) that decrease with decreasing energy. Stars with modest disks (i.e., Class II objects) have SEDs which fall less slowly. As the classes work back toward Class 0 the SEDs flatten out and can even rise, indicating the most energy is radiated at the longest wavelengths (Robitaille et al. 2006).

Recently, Koenig et al. (2012) used multi-color filtering akin to that used for IRAC and MIPS (Gutermuth et al. 2009) to identify pre-main-sequence (PMS) stars in the WISE fields. To locate YSO candidates in Cyg OB7, we followed an approach similar to Koenig et al. (2012) but with some modifications based on the field.

To summarize, after excluding faint sources to remove background galaxies, resolved polycyclic aromatic hydrocarbon regions, and shocks, Koenig et al. (2012) used a color cut of $W1 - W2 > 0.25$ and $W2 - W3 > 1.0$ to identify YSOs. The 29 WISE-detected RWA sources all fit within these parameters. We also filtered out all stars brighter than $W1 = 8.5$ which tend to have very red colors indicative of a saturation issue. The known disked objects have $W2 - W3 > 1.3$ and we use this as the second requirement on YSOs in the region (Figures 1 and 2). Further, we also require the errors to be low, <0.04 in W1 and <0.2 in W3.

In total there are 66 strong YSO candidates in the 1 deg$^2$ field. Of these, 39 have been previously identified (Aspin et al. 2009; Rice et al. 2012; Khanzadyan et al. 2012). These are included in Tables 1 and 2. The 27 new YSO candidates in the field studied in Papers I and II are listed in Table 3.

To check the validity of the color cuts, we examined additional WISE colors. We found that all of our YSO candidates have $W2 - W4 > 2.5$ and all but one have $W2 - W4 > 3.2$ (Figure 3). Likewise 8 of the 13 confirmed PMS stars from Aspin et al. (2009), including the Braid Nebula star (V2495 Cyg), were recovered. On the other hand, three PMS candidates studied and rejected by Aspin et al. (2009), CN1S, CN6N, and HH627 star, were not identified as PMS candidates by the WISE color method. Examination of the surface distribution of the new YSO candidates shows that all the new YSO candidates lie near the Lynds 1003/1004 dark cloud. All are within the borders of the known YSOs, except for a few, just to the east of RWA 2, which are very close to the middle of the L1004 dark cloud (Figure 4).

Since the only criteria used in the selection of these stars were based on the WISE point-source catalog, we were able to expand the study region to include all stars in the 1.4 deg diameter circle containing all of the Lynds 1003/1004 dark clouds. We identified 31 additional YSO candidates with $W1 - W2 > 0.25$ and $W2 - W3 > 1.3$; these are listed in Table 4. While these sources cannot be investigated further with regard to their variability properties, they provide additional insight into the structure of the cluster as a whole (Section 4.4).

Koenig et al. (2012) used data from Rebull et al. (2010) as a template and found that the reddest parts of the WISE color–color diagrams correspond to protostars (this is also found in, e.g., Gutermuth et al. 2009; Robitaille et al. 2006).
Table 3
2MASS and WISE Colors of New YSO Candidates in the Monitored Field

| Object ID  | J (mag) | H (mag) | K (mag) | W1 (mag) | W2 (mag) | W3 (mag) | W4 (mag) | Class   |
|-----------|--------|--------|--------|---------|---------|---------|---------|--------|
| 205736.61+522117.0 | 12.45  | 11.44  | 10.76  | 9.36    | 9.01    | 7.18    | 5.14    | Class II |
| 205745.36+521331.4 | 13.19  | 12.58  | 12.30  | 11.73   | 11.47   | 9.58    | 7.20    | Class II |
| 205811.89+522923.3 | 14.76  | 12.88  | 11.99  | 11.58   | 11.19   | 8.75    | 4.88    | Class IIR|
| 205816.27+522832.8 | 14.90  | 12.77  | 11.82  | 11.25   | 10.77   | 8.35    | 4.26    | Class IIR|
| 205837.72+521845.1 | 15.48  | 14.28  | 13.84  | 12.42   | 12.13   | 10.54   | 8.33    | Class II |
| 205842.10+522545.7 | 17.41  | 15.89  | 14.18  | 11.60   | 9.90    | 7.48    | 4.73    | Class I  |
| 205854.11+525255.3 | 15.44  | 14.00  | 13.31  | 12.80   | 12.55   | 10.28   | 7.08    | Class IIR|
| 205904.15+523007.8 | 16.48  | 15.48  | 13.85  | 12.75   | 11.31   | 8.64    | 4.06    | Class I  |
| 205904.29+523302.6 | 16.36  | 14.15  | 12.82  | 12.30   | 11.88   | 9.57    | 7.25    | Class IIR|
| 205926.05+522607.6 | 15.22  | 13.80  | 13.21  | 12.55   | 12.27   | 9.59    | 5.89    | Class IIR|
| 205939.84+520039.6 | 17.41  | 15.89  | 14.18  | 11.60   | 9.90    | 7.48    | 4.73    | Class I  |
| 205954.11+522553.3 | 15.44  | 14.00  | 13.31  | 12.80   | 12.55   | 10.28   | 7.08    | Class IIR|
| 205955.04+523039.6 | 15.44  | 14.00  | 13.31  | 12.80   | 12.55   | 10.28   | 7.08    | Class IIR|
| 205904.15+523007.8 | 16.48  | 15.48  | 13.85  | 12.75   | 11.31   | 8.64    | 4.06    | Class I  |
| 205904.29+523302.6 | 16.36  | 14.15  | 12.82  | 12.30   | 11.88   | 9.57    | 7.25    | Class IIR|
| 205926.05+522607.6 | 15.22  | 13.80  | 13.21  | 12.55   | 12.27   | 9.59    | 5.89    | Class IIR|
| 205939.84+520039.6 | 17.41  | 15.89  | 14.18  | 11.60   | 9.90    | 7.48    | 4.73    | Class I  |
| 205954.11+522553.3 | 15.44  | 14.00  | 13.31  | 12.80   | 12.55   | 10.28   | 7.08    | Class IIR|
| 205955.04+523039.6 | 15.44  | 14.00  | 13.31  | 12.80   | 12.55   | 10.28   | 7.08    | Class IIR|

Note. Typical photometric errors are <2% for W1 and W2 and <20% for W3 and W4.

Figure 3. Mid-IR two-color diagram for WISE sources with good photometry at W3 and within 5.0 deg of the Braid Nebula star. Symbols are as in Figure 1. The lower dashed lines to the left indicate the Class II region, and the upper dashed lines indicate the Class I/0 region.

Koenig et al. (2012) used color cutoffs of 2.0 and 4.0 in W2 − W3 and W2 − W4, respectively, to distinguish Class I and Class II sources. All three must agree to identify the object as Class I; if only the redder two colors indicate Class I then the object is noted as Class IIIR. Using these color cuts for 96 YSOs in the WISE field, we find 32 clear Class II sources and 30 clear Class I sources; most of the remainder show ambiguous colors we identify as Class IIIR in Tables 1–3. Restricting ourselves to the 66 YSOs in the UKIRT monitored field, we find 22 clear Class II sources and 20 clear Class I sources. The results are consistent and imply the region is quite young—with nearly equal numbers of stars by Class.

3. RESULTS

In this section, we take a detailed look at the JHK variability of the disked stars in the field with sufficient data quality. This includes the 30 sources from Paper I, and CN 3N, Cyg 19, HH381 IRS, IRAS 14, IRAS 15N, and IRAS 15S (Aspin et al. 2009). To this we add 13 of the YSOs revealed by analysis of the WISE data (see Section 2.1) which also have good UKIRT monitoring data. Our input catalog is 49 stars; Table 5 summarizes much of the analysis. Columns 2–4 give the full range of variability observed in the J, H, and K bands and the colors. Column 5 is the full range of the color change seen in J − H. Columns 6–11 list the slope and errors of linear fits to the data in the color–color and color–magnitude plots. The slopes are fitted using a Deming regression, which is a special case of a total least squares fit that accounts for the errors on both axis (Deming 1943). There are some cases in which the data distribution is not sufficiently linear to give a meaningful fit. In those cases, there is no entry. Column 12 lists the Stetson index. Column 13 lists the period in days or indicates the nature of the variability. Nine of thirteen WISE sources and four of six Aspin et al. (2009) sources are found to have a Stetson index >1. Combined with the results of Paper I, the over-
3.1. Types of Variability

We divide the light curves by taxonomy as a way to gain insight into the physical causes of the changes. There are three traits which we focus on: periodicity, changes in color–color space, and changes in color–magnitude space. Some sources were strongly periodic. Others seemed cyclic, in the sense that their signals when up and down somewhat regularly, but the actual frequency and amplitude did not appear stable. We identified this group as quasi-periodic (“QP” in Table 5). Still other sources experienced monotonic changes in one direction for weeks or months, sometimes reversing. We identified these as long duration (“LD” in Table 5). The remainder are considered stochastic.

In Paper I, we found some sources appeared to follow the CTTS locus in color–color space (Meyer et al. 1997), while others followed the reddening vectors, still others followed a hybrid track between the two; finally, a few sources moved very little or even had a negative slope. In the color–magnitude diagrams, most sources moved to the red as sources became fainter, but some moved markedly in the opposite direction (e.g., RWA 9 and RWA 19; see also Figures 5 and 6). Notably, several sources showed both behaviors. We indicate sources that became bluer as they became dimmer with a negative sign on the slopes given in Table 5. Below we comment on some of the correlations in these trends.

About one-quarter of the stars are seen to vary with cycles of 2.5 to 10 days (Figure 7). The periodic signal was not as strong as for the eclipsing binaries in the field noted in Paper II. Typical K-band flux changes for these stars were between 0.25 and 1.0 mag, with an rms deviation off of this signal of 10%–50%. These stars became redder as they became fainter. Often the color changes tracked the reddening vector, but for several stars, the color change tracked the CTTS locus (Meyer et al. 1997). RWA 1 is the prototype for this class (Figure 8). It has a fairly stable 9.1 day period with a K-band peak to trough amplitude of about 0.8 mag. However, this can change by 0.2 mag cycle to cycle. The scatter about the nominal trajectory is about 10 times the observational error. The observed change in the color–magnitude diagram is nearly linear: for 1 mag total observed change in K, the change in H − K was about 0.5. The JHK color–color change is highly phase dependent, with faint phases nearly being consistent with a normal photosphere and bright phases reaching the edges of the CTTS locus.

About one-fifth of the stars appear to be quasi-periodic, meaning they show successive rises and falls in flux that do not occur with a stable frequency or amplitude. We identify these as “QP” in Table 5. Some examples of these are shown in Figure 9. RWA 8 shows a “U”-shaped decline and rise of 0.3 K mag in season 2. In season 3, the same star shows a periodicity which ranges from about 4 days to about 10 days and modulates with an amplitude which varies from 0.1 to 0.2 mag. RWA 15 shows a 19.34 day period, but only in season 2. 2MASS 210058.34+522856.1 and 2MASS
210024.05+521451.0 (Figure 9) show similar behavior with periods of 4.8 and 23.6 days, respectively, in season 2 and different periods in evidence in season 3. 2MASS 205855.04+523039.6 shows a 20.05 day period in season 3 and a 47.29 day period in season 2—both with similar periodogram peak power \( \sim 12 \). Interestingly, most of these stars show relatively small changes in their position in the color–color diagram, most of these stars show a tendency to become redder (in \( K - H \)) as the star becomes brighter in the \( KHK \) color–magnitude diagram. We will discuss this further in Section 3.2.

Another group of stars were long duration—possibly irregular variables, identified as “LD” in Table 5 (see Figure 10). These stars could show large changes in \( K \) magnitude. RWA 2 showed an amplitude change of 2 \( K \) mag and RWA 7 had a change of 1 \( K \) mag. It is not clear that these objects truly form a common group since they showed a wide variety of trajectories in color space. After RWA 2 and RWA 7, other stars with long-duration, slow changes tended to have smaller changes, but several still showed at least half a magnitude change at \( K \) including RWA 9, RWA 12, RWA 17, and RWA 19. Four of the newly identified \( WISE \) candidates also show long-duration high-amplitude changes. Among these, 2MASS 210058.34+522856.1 shows a long-term trend of \( \Delta K > 0.6 \) in addition to its short-term rises and falls on timescales which vary from 5 to 15 days.

Some stars had strong variability, but no dominant period. For example, RWA 6 was not seen to vary in any one season. However, it brightened by about 0.1 \( K \) mag between seasons 1 and 2. The net effect was significant correlated variability. IRAS 15N showed a similar one-time shift. It became fainter by 0.1 mag in season 3. The amplitude of the changes in RWA 10 and RWA 11 were only about 0.1 mag RWA 20 and RWA 25 changed by up to 0.4 mag, but these changes were essentially colorless. 2MASS 205745.36+521331.4 showed a 0.04 mag decline in brightness in season 3, and was about 0.16 mag brighter at \( J \) than during the Two Micron All Sky Survey (2MASS).

A periodogram of RWA 28 shows significant power in \( K \) band at a period near 4.8 days. Indeed the data folded on this period show a signal of about 0.05 \( K \) mag which is similar to the errors (Figure 11). Similar signals are not seen in the other bands—however, these have more noise than the \( K \) band. Three of the \( WISE \) sources were also found to have \( S < 0.55 \): 2MASS 210246.43+523114.0, 2MASS 210311.54+523124.3, and 2MASS 210110.57+521512.9. The first two of these sources are very faint at \( J \) (~19.7 and 18.2, respectively) which works against the identification of weak variability. The last source varies by less 0.05 mag in any channel.

### 3.2. Observed Color Changes

Strong secular color changes are seen among the YSOs. This is in stark contrast to stars studied in Paper II, wherein the minimal color changes were consistent with the eclipse model in which the net effect of the eclipse was to fractionally
reduce the contribution from the Wien tail of one of the two stars, or in the case of a pulsation, change the temperature by a few percent. Neither effect changes the near-IR color significantly. The slopes in Table 5 can be compared to expected values for common cases. For example, significant NIR color changes would be expected if, for example, the flux change were induced by a portion of the disk blocking the star as in Aspin Stars.

### Table 5

| ID       | Median $K$ | $\Delta J$ | $\Delta H$ | $\Delta K$ | $(J - H)$ | $(J - H)/(H - K)$ | $S$ | Period (days/oth.) |
|----------|------------|-------------|-------------|------------|------------|------------------|-----|-------------------|
| RWA 1    | 10.98      | 1.85        | 1.46        | 1.13       | 0.45       | 4.97             | 0.13 | 42.96             | 9.11 |
| RWA 2    | 11.85      | 2.74        | 2.67        | 1.77       | 0.75       | ...              | ...  | 61.95             | LD   |
| RWA 3    | 12.21      | 0.11        | 0.14        | 0.09       | 0.12       | 9.62             | 3.14 | 17.87             | 6.35 |
| RWA 4    | 10.82      | 0.34        | 0.34        | 0.12       | 13.08      | 5.54             | ...  | 8.59              | 0.09 |
| RWA 5    | 10.78      | 0.34        | 0.34        | 0.12       | 3.84       | 0.23             | 2.84 | 7.72              |     |
| RWA 7    | 12.74      | 0.09        | 0.09        | 0.11       | 0.07       | ...              | ...  | 0.91              |     |
| RWA 8    | 12.65      | 0.81        | 0.89        | 0.93       | 0.20       | ...              | ...  | 2.03              |     |
| RWA 9    | 14.40      | 0.43        | 0.30        | 0.32       | 0.34       | 1.81             | 0.14 | 2.77              |     |
| RWA 10   | 12.87      | 0.26        | 0.30        | 0.36       | 0.08       | ...              | ...  | 8.61              | LD   |
| RWA 11   | 13.19      | 0.13        | 0.15        | 0.20       | 0.07       | ...              | ...  | 3.33              |     |
| RWA 12   | 10.96      | 0.10        | 0.09        | 0.17       | 0.05       | 4.64             | 1.81 | 3.40              |     |
| RWA 13   | 10.74      | 0.73        | 0.61        | 0.57       | 0.15       | 6.08             | 0.82 | 14.45             | LD/QP|
| RWA 14   | 10.63      | 0.46        | 0.45        | 0.43       | 0.16       | 3.98             | 0.50 | 7.95              | 9.37 |
| RWA 15   | 14.09      | 1.26        | 1.01        | 0.72       | 0.26       | 4.91             | 0.19 | 25.05             |     |
| RWA 16   | 12.43      | 1.27        | 0.96        | 0.89       | 0.47       | 3.66             | 0.43 | 16.58             |     |
| RWA 17   | 11.25      | 0.53        | 0.52        | 0.41       | 0.12       | 5.76             | 0.58 | 11.50             | 4.84 |
| RWA 18   | 10.38      | 0.94        | 0.65        | 0.51       | 0.34       | 3.02             | 0.08 | 24.21             |     |
| RWA 19   | 11.12      | 0.66        | 0.57        | 0.61       | 0.18       | 6.81             | 1.08 | 11.53             |     |
| RWA 20   | 10.66      | 0.61        | 0.75        | 0.58       | 0.25       | -3.23            | 0.65 | 16.15             |     |
| RWA 21   | 9.79       | 0.61        | 0.58        | 0.61       | 0.13       | 14.05            | 5.79 | 14.92             |     |
| RWA 22   | 11.16      | 1.20        | 0.95        | 0.67       | 0.28       | 4.33             | 0.19 | 19.91             | 3.72 |
| RWA 23   | 11.24      | 0.33        | 0.35        | 0.45       | 0.08       | ...              | ...  | 7.59              |     |
| RWA 24   | 13.48      | 0.33        | 0.31        | 0.35       | 0.10       | 6.91             | 1.00 | 6.74              | 2.81 |
| RWA 25   | 11.01      | 0.28        | 0.24        | 0.29       | 0.07       | 8.82             | 1.92 | 12.02             |     |
| RWA 26   | 10.61      | 0.36        | 0.30        | 0.32       | 0.19       | 3.41             | 0.38 | 6.50              |     |
| RWA 27   | 13.71      | 1.33        | 1.22        | 1.05       | 0.49       | 6.69             | 1.51 | 5.8               |     |
| RWA 28   | 12.83      | 1.60        | 1.26        | 0.79       | 0.33       | 7.23             | 0.35 | 6.58              |     |
| RWA 29   | 15.08      | 0.17        | 0.09        | 0.08       | 0.17       | 0.96             | 0.06 | 4.8               |     |
| RWA 30   | 14.26      | 0.16        | 0.20        | 0.23       | 0.10       | ...              | ...  | 3.61              | LD   |
| Aspin Stars | 10.98      | 0.60        | 0.63        | 0.78       | 0.16       | 37.64            | 29.74 | 15.64             | 22/QP|
| CN 3N    | 9.68       | 1.14        | 0.72        | 0.56       | 0.43       | 2.62             | 0.06 | 0.88              | 17.11|
| Cyg 19   | 9.90       | 0.42        | 0.38        | 0.35       | 0.16       | 3.85             | 0.96 | 9.79              | 9.5  |
| HH381 IRS| 9.72       | 0.15        | ...         | ...        | ...        | ...              | ...  | 13.75             | 32   |
| IRAS 14  | 14.23      | 0.64        | 0.34        | ...        | ...        | -2.49            | 0.96 | 1.80              |     |
| IRAS 15N | 9.70       | 0.18        | 0.23        | 0.24       | 0.16       | ...              | ...  | 6.79              |     |
| IRAS 15S | 11.95      | 0.07        | 0.08        | 0.04       | 0.06       | 2.01             | 0.34 | 0.67              |     |

**Notes.**

* Period of eclipse.

* Dominated by measurement errors.
Indeed, in the $J, J-H$ color–magnitude diagram most stars get redder as they get fainter, although the slopes are often somewhat steeper than prescribed by the ISM reddening law (Figure 5). This implies less differential reddening or $R > 3.1$ ($R \sim 3.1$ typical of the ISM; Rieke & Lebofsky 1985). This result is consistent with studies of massive star-forming regions such as η Carinae which find $R \sim 4$ presumably due to grain growth (Povich et al. 2011). On the other hand, all show scatter along the extinction track in excess of that expected based on the data quality, and, more importantly, many stars show the opposite trend in the $K, H-K$ color–magnitude diagram.

Many stars in the quasi-periodic group grew redder as they grew brighter (as seen in the color–magnitude diagram). 2MASS 205736.61+522117.0 follows a regular pattern that becomes about 0.8 brighter at $K$ and 0.15 mag redder in $H-K$. In the color–color diagram the path of the star follows a path between the CTTS locus ($(J-H)/(H-K) \sim 0.55$; Meyer et al. 1997), and the direction of the K-M main sequence ($(J-H)/(H-K) \sim -1.0$). The trajectories of several of the stars in the quasi-periodic group parallel the CTTS locus.

Stars in the long-duration group showed variations of 0.5 and 1.5 at $K$. The observed color changes were between $-0.1$–1.5 in $H-K$. Stars were seen to get both brighter and fainter as they became redder. RWA 7 (Figures 5 and 16) is a source which shows both behaviors. Some of these stars follow the CTTS locus in the color–color diagram, while other more closely parallel the reddening vector or even the K/M branch of the main sequence.

From an observational perspective, the light curves of YSOs are both complex and ordered. Some are very periodic, but even these have unaccounted noise on top of the periodic pattern. Others seem periodic briefly, but appear to have other overriding affects. All the light curves have individual characteristics—unlike eclipsing or pulsating variables, no two are alike. On the other hand, when color changes are included, patterns emerge. The periodic sources typically get redder as they get dimmer, while many of the quasi-periodic sources showed the opposite behavior. In the next section, we investigate possible physical basis for the behaviors.

4. DISCUSSION

4.1. Sources of Variability

There are many reasons why the luminosity of a YSO might change. Some mechanisms include extinction changes, cool spots, hot spots, changes in the accretion rate, changes in the inner disk radius, or perhaps even the inclination of the inner disk region. Herbst et al. (1994) noted that each of these effects would be characterized by different colors and timescales. Changes in the overall extinction may be the simplest to imagine. Perhaps induced by the disk, extinction can cause practically unlimited changes in the apparent flux of a star. However, such changes should move the star in the direction of the reddening vector. For ISM-like dust, an $A_V$ change of 5 mag corresponds to a calculated $\Delta J$ and $\Delta K$ of about 1.25 and 0.5, respectively, with a change of $\Delta(J-H)$ of $\sim -0.48$ and $\Delta(H-K)$ of about 0.27 (Rieke & Lebofsky 1985; Indebetouw et al. 2005). Motion in this direction clearly occurs in certain phases of the light curves shown in Figures 5, 8, 13, 15, and 16.
Cool spots, like those on the Sun, were first identified as a contributor to the variability of PMS stars in the 1980s (Vrba et al. 1985). They have been used since as a method of measuring stellar periods (e.g., Attridge & Herbst 1992). But there is a limit to the variability cool spots can induce, since the spot is typically only 1000–1500 K cooler than the nominal photosphere. Carpenter et al. (2001) examine modulation induced by cool starspots in the NIR. They used a fairly simple spot model which assumes a photospheric temperature of 4000 K, appropriate for a 1 Myr, $\sim 0.5 M_\odot$ star (D’Antona & Mazzitelli 1997). The change in luminosity at any given wavelength is given roughly as $\Delta m(\lambda) = -2.5 \log(1 - f B_\lambda(T_{\text{spot}})/B_\lambda(T_*))$ (where $B_\lambda(T)$ is the Planck function). Using a maximum spot coverage of 30% the maximum, the $\Delta J$ and $\Delta K$ calculated were about 0.35 to 0.30, respectively, with a color change $<0.05$. In the $I$ band, the observed luminosity change due to cool spots is typically $<15\%$ (Cohen et al. 2004). The implied color change due to a lower effective temperature is $<5\%$. Hence, in the $JHK$ color spaces, cool spots have almost no effect. This is consistent with what is seen in some of the least variable objects.

Hot spots, thought to arise from accretion, can cause a larger signal than cool spots since the temperature difference is typically larger (a factor of two or three hotter than the surrounding photosphere). For warm spots (8000 K) and a spot coverage of 30%, the maximum $\Delta J$ and $\Delta K$ are calculated to be about 1 and 0.6, respectively, with a change of $\Delta(J - H)$ of 0.2 and $\Delta(H - K)$ of about 0.15 (Carpenter et al. 2001). Truly hot spots ($>10,000$ K) on K and M stars can induce signals as high as 1 mag at $J$ and color changes of 40% in $J - K$, even with small filling factors (Scholz et al. 2009). In the $JHK$ color–color diagram, hot spots and extinction generally move objects in opposite directions, making them hard to disentangle.

In many cases, the relation of the disk to the accretion appears to be fundamentally important to the observed variability. Changes to a few key individual parameters can explain much of what is observed. Meyer et al. (1997) examined the positions of dereddened Class II objects located in Taurus in the $JHK$ color–color diagram. They noticed that the dereddened positions corresponded to a line in $JHK$ color–color space—the CTTS locus. Furthermore, they showed that the observed colors could be accounted for by a model which combined the stellar photosphere with a variable accretion rate, a variable location of the inner disk boundary, and variable disk inclination. This model is somewhat degenerate in that a single point in the color–color diagram can be achieved with several combinations of the three parameters. While more complex parameterizations of similar models now exist (e.g., Robitaille et al. 2006), these only add to the degeneracy. The degeneracy is broken somewhat by using additional color–space analyses. The $K, H - K$ and $J, J - H$ color–magnitude diagrams were shown to be useful (see Carpenter et al. 2001, especially Figure 25).
Figure 7. Sample of YSOs with stable periods of 3–40 days. For each star, the $K$-band light curve folded over the listed period. The stars are labeled in their individual windows. Data for all three seasons are used for all stars except RWA 4 and RWA 13 which showed the strongest periods in season 3.

(A color version of this figure is available in the online journal.)

Table 6

Expected Observed Properties of Different Physical Changes

| Type of variability          | $\Delta J$ | $\Delta K$ | Typical Period | $\Delta J$ | $\Delta K$ | $\Delta (J - H)$ | References |
|------------------------------|------------|------------|----------------|------------|------------|-----------------|------------|
| Extinction ($\Delta A_V = 5$) | 1.25       | 0.5        | Non-periodic$^a$ | 2.6       | 1.8        | 1.7             | 1          |
| Cold spots                   | 0.15       | 0.1        | 4–12 days      | ~5         | ~1.5       | ~1.5            | 2.3        |
| Hot spots                    | 1.5        | 0.6        | 4–12 days      | ~2         | ~5.7       | ~1.5            | 2.4        |
| Change in accretion rate$^b$ | log $-8.5 - \log -7 M_\odot$ yr$^{-1}$ | 0.6        | 0.75           | ?          | -4 : -5     | -2 : -5         | 0.4 : 0.6  |
| Change to inner disk$^b$     | edge radius 1–4 $R_*$ | 0.5        | 0.75           | ?          | -1.25 : -5  | -1.4 : -4       | ~0.35      |

Notes.

$^a$ Changes in extinction could be imagined both as long-term trends which would not be periodic, or as features in a disk which could be periodic or quasi-periodic.

$^b$ The resultant slope in color space due to changes of accretion rate depend on the inner hole size and the inclination of the inner disk. Likewise, the slope of a trajectory due to changes inner hole size depends on the accretion rate and the inclination of the inner disk.

References. (1) Rieke & Lebofsky 1985; (2) Carpenter et al. 2001; (3) Scholz et al. 2005; (4) Scholz et al. 2009; (5) Meyer et al. 1997.

Table 6 gives the typical observed behaviors expected for the physical phenomena discussed above. The values are meant to be representative. In the first row we indicate the change induced by an increase in extinction. While we give the values for $A_V = 5$, the full range is effectively limitless. One can envision dust as an acute phenomena wherein a large quantity of dust temporarily obscures the star. Extinction may also be periodic as in the AA Tau phenomena where in a warp in the disk is regularly or semi-regularly seen to obscure the central star (Bouvier et al. 2003, 2007). The color vectors, whether $\Delta K$/($\Delta (H - K)$, $\Delta J$/($\Delta (J - H)$ or $\Delta (J - H)$/($\Delta (H - K)$), are well known (Rieke & Lebofsky 1985; Lada & Adams 1992; Indebetouw et al. 2005) to within changes due to the particle size distribution in the dust (i.e., $R_f$).

In the second row we itemized cold spots; these are well studied. Over a timespan of a few months, spots are expected to be periodic with the rotation period of the star, which for young stars is a few days (e.g., Attridge & Herbst 1992; Rebull
change in tandem with the hole becoming smaller as accretion rates increase.

We can interpret much of the observed variability in terms of these parameters—spots, extinction, and disk changes. The models are not optimal for detailed light-curve analysis, but they do provide anecdotal evidence of the kinds of behaviors responsible for the observed changes. In Figures 8 and 11–16, we have labeled the lower panels with vectors derived from Carpenter et al. (2001) and Meyer et al. (1997). RWA 26 (Figure 12) is perhaps the simplest of the group to understand. The 5.8 day period is very stable and the color shifts in the color–color diagram and the color–magnitude diagram are both dominated by extinction changes. The slopes in the color–magnitude diagrams are steeper than expected from ISM extinction and the scatter in this signal is still about 20%. The data shown in the lower-left panel of Figure 12 show that RWA 26 moves nearly along the reddening vector, while the lower-right panel of Figure 12 shows a similar effect—an increase in extinction by \( \sim 5.0 A_V \) at the intermediate phases compared to phases 0 and 1. There is considerable spread in the data by nearly 30% above what would be expected if extinction was the only source of the changes. This indicates other factors at work. We further notice that the overall data distribution moves up and to the left in time in both color–magnitude diagrams, slowly over the 550 days of observing (most clearly in the lower-left panel where color indicates time, not phase). This is indicative of a steady increase in the accretion rate by, perhaps, a factor of 30 (Carpenter et al. 2001).

The data shown in the lower-left panel of Figure 8 show that RWA 1 moves nearly along the CTTS locus. This is

\[ R_V = 3.1 \text{ and } A_K = A_V = 0.112. \]
Figure 9. Examples of stars with many up and down cycles but no fixed period. K-band data are shown. Season 2 light curves are shown except for RW A 8 and RW A 27 which have both seasons 2 and 3 shown.

(A color version of this figure is available in the online journal.)

different from RW A 26 and indicates that RW A 1 has a similar extinction change but less of a change in the disk and accretion characteristics. The lower-right panel of Figure 8 shows that phases 0.0–0.4 are consistent with a drop in extinction by $\sim 5 A_V$. This is followed by a pattern that is consistent with a periodic decrease in cool spots and an increase in hot spots. So, it appears that the extinction is changing in a way that is nearly canceled out by the change in accretion in a 9.11 day period. But this is not the only plausible explanation for the observed changes. Even with this additional interpretation, the noise on the signal is $\sim 20\%$ which is much higher than expected based on the observational statistics, and is indicative of additional factors at work.

The case of RW A 4 (Figure 13) also can explain some of the noise. The star is clearly periodic with a period of about 6.35 days. Extinction changes by 2.0 in $A_V$ as is shown in the color–color plot in the figure, but extinction appears independent of phase. On the other hand, the lower-right panel shows extinction change to be part of the periodic cycle. Higher extinction is seen between phase 0.1 and 0.4. The remainder of the data can be understood by asserting that the size of the hole in the inner disk changes by a factor of two—out of phase with the extinction. Such a hole would induce $\pm 10\%$ noise on the extinction based signal.

4.2. Objects with Similar Light Curves

With these physical concepts in mind we revisit the observational results from Section 3. We start with the strongly periodic stars similar to RW A 1 (Figure 8). In the color–magnitude diagrams, the color changes appear to be dominated by reddening with some evidence of both warm and cool spots. In the color–color diagram, the object moves parallel to the CTTS locus. Meyer et al. (1997) argue this is indicative of changes either to the accretion rate, hole size, or inclination. However, the result that $K$-band flux is at a minimum when the star is at
the extreme end of the CTTS implies a maximum disk cross-section between the star and the Earth when accretion is high. This is reminiscent of the AA Tau phenomenon in which the rotation of a circumstellar disk with a high-latitude "warp" can periodically obscure the star (Bertout 2000; Bouvier et al. 2003). Morales-Calderón et al. (2011) remind us that any process which creates overdense asymmetric regions in the inner disk could produce the flux dips. Stars can also be obscured by "clouds" of
relatively high opacity in the disk atmosphere or geometric warps in the inner disk.

We classify RW A 1 with other stars that show a dominant period and a trend toward reddening as the $K$-band flux drops. While there are at least seven other such sources, no two are alike in terms of period, amplitude, or color range. On the other hand, a couple are worth mentioning in particular. The $K$-band magnitude of RW A 4 dims by $\sim0.3$ mag over the 1.5 yr observations while $H$ dims by about 0.1 mag and $J$ does not noticeably change. At the same time, it has periodic variability.
of 0.2 mag in \( K \) (0.35 in \( J \)) with a period of about 6.34 days (Figure 13). The long-term and periodic components of this variability are orthogonal in color–magnitude space. The flux of the star shows a constant downward trend with a mean \( K \) of 10.75 in season 1 and 10.9 in season 3. While the approximately weekly color cycles indicate a change in extinction, the long-term trends indicate a drop in accretion.

Unlike the periodic sources, many of the quasi-periodic sources were noted to become redder as they become brighter in the \( K, H - K \) color–magnitude diagram. RWA 8 (Figures 5 and 14) is typical of this group. Rapid cyclic variations are seen, sometimes on timescales of a few days and sometimes on timescales of months. There is a general trend in the color data which shows the star moving along the CTTS locus and taking on the appearance of an increasingly active CTTS. The \( K, H - K \) color–magnitude diagram shows that the behavior is consistent with an increase in the accretion rate of a factor of about 30 with a concurrent increase in the extinction of 0.1–0.2 \( A_K \).

The data are consistent with accretion rate changes \( \sim 30 \times \) with extinction changes of a few of \( A_V \). Another star in this group is an eclipsing binary, RWA 3, which has a 17.87 day period. The 2% eclipsing system rate among the YSOs in the region is consistent with the \( \sim 1\% \) rate seen in the field. No disked source was found to have a period <2 days. The eclipsing binary nature of this star may make spectroscopic probes of this behavior possible.

Most of the observed signals are not periodic at all and need to be understood in terms of unique events or long-period trends. Among the most fascinating stars were two of the long-duration objects—RWA 2 and RWA 7 (Figures 15 and 16). RWA 2 exhibits changes of 3 mag at \( J \) and full period cycles on timescales of 2 months. The color data appear continuous between seasons 1 and 2, but follow a different track in season 3. One explanation of these data is a steady decrease in dust obscuration by about 1.0 \( K \) mag, followed by a sudden drop in the accretion rate and then a slow return to the original level of extinction. Incorporating 2MASS data, we find the total range in \( J \) is at least 4 mag. The \( J - K \) color varies from 2.9 (2MASS) to about 5 when the star is at its faintest. The trajectory of the star in \( JHK \) color–color and color–magnitude space is indicative of changes in both reddening (diagonal lines in the color–magnitude diagram) and accretion rate (the distance from the lower-left corner in the color–magnitude diagram or the distance from the reddening band in the color–color diagram). In \( J, J - H \) space the data from the first two seasons follow a steep negative slope (\( \sim -2 \)), data in the third season have a...
Av = 10
accretion drops by 30x
hole size doubles

Figure 15. Top: one and a half year’s worth of K-band data for RW A 2. Left: the J - H, H - K color–color diagram shows changes which neither follow the reddening vector nor the CTTS locus. Right: K, H - K color–magnitude diagram shows that the bulk of the change can be accounted for by asserting a decrease in the reddening by A_K = 1, followed by a dramatic change in the accretion and disk parameters between seasons 2 and 3, and then an increase in the reddening by A_K = 1. Time is indicated in the color version.

Av = 4
accretion drops by 30x
hole size doubles

Figure 16. Top: light curve showing one and a half year’s worth of K-band data for RW A 7. Bottom left: the J - H, H - K color–color diagram. Bottom right: K, H - K color–magnitude diagram shows that the change can be accounted for by asserting a decrease in the reddening by A_K = 0.4, followed by a dramatic change in the accretion and disk parameters. Time is indicated in the color version.

similar slope, displaced by about 1 J mag brighter, and start with a brief period which resembles decreasing extinction. L' imaging and K-band spectroscopy show RW A 2 has strong H2 and Brγ emission and is the member of a resolved binary (700 AU [0'9] separation) with a very red companion (C. A. Aspin, unpublished). The observed mid- and far-IR fluxes of RW A 2 are consistent at the 10%-20% level from the IRAS epoch until the current one. Thus, most of the flux variations are
confined to the near-IR. We fitted SED models to the median $JHK$ results in the near-IR as well as $Ak$, $IRAS$, and $Herschel$ data at 12, 18, 25, 60, 70, 90, 140, 160, 250, 350, and 500 $\mu$m. From the best-fitted model of the SED of RWA 2 using the models of Robitaille et al. (2006) we derive an age for the RWA 2 protostar of $<100,000$ yr, $AV \sim 15$, and an envelope mass of order a solar mass, which is similar to, or greater than, the mass of the central object.

RWA 7 is similar to RWA 2 in that the overall observed change was about 1 $K$ mag. Further, the observed light-curve changes did not appear monotonic. The data from seasons 1 and 2 show local maxima (Figure 16). The color–color diagram, on the other hand, indicates a steadier process—an apparent circulation. The color that starts near 1.1, 1.45 ($H-K$, $J-H$) moves fairly steadily toward 1.30, 1.55 down to 1.2, 1.45, arriving back near 1.1, 1.45. However, despite having the same colors at the end as the beginning the star is clearly not in the same state. The $K$, $H-K$ color–magnitude diagram gives the clearest insight. In this panel of Figure 16, we see that the trajectory of the star is dominated in the first season by a change in extinction of about $4AV$. This trend continues through about 2008 October 15 when the trajectory suddenly shifts—coincident with a small double peak in the light curve. After this time, and for at least the next year, the trajectory follows a very steady path which can be described as a decrease in the accretion rate by a factor of $\sim 30$ and a doubling of the size of the central hole. In $J$, $J-H$, the trajectory is similar, though not as sharp. The uninterrupted nature of the color–magnitude diagrams hints at a periodic phenomena in which we have missed a near integer number of half-cycles. For example, we may have missed a $\sim 100$ day minimum between seasons 1 and 2 and a full $\sim 200$ day period between seasons 2 and 3.

4.3. Unusual Objects

One of the difficulties in studying variability in the NIR is that the origin of variability can be very complex and the different effects can either amplify or dampen the combined impact on the resultant light curve depending on circumstances. As a result, there are many light curves which appear interesting but are not easily explained. Probably the most unusual was RWA 27 (Figure 9). The star was reasonably well behaved with a $K$ magnitude of about $12.9 \pm 0.3$ and $H-K = 0.65 \pm 0.1$ for all but about 50 days of the observed epochs. However, starting about 2008 October 15 the star suddenly showed overnight changes of up to 1 mag at $K$. Further, $\Delta(H-K) > 1.05$ during this period. The median $J$ mag, which was typically about $14.6 \pm 0.1$, fell to 16.4. Overall this is fairly consistent with a compact dust-like occulting object. This object would be optically thin, with a maximum extinction of about 1 $A_K$ that intersected our line of sight every few days, obscuring increasing fractions of the star and then passing out of our line of sight again. RWA 19 showed a similar, but less extreme behavior: it took 4 days to drop 0.3 $K$ magnitudes with $H-K$ color changes consistent with reddening, and then recovered just as quickly. In this case the $J$ color change was very similar to the $H$-band change and hence not consistent with ISM reddening.

4.4. The Scope of the Cluster

Of the 13 $WISE$ YSO candidates monitored, 9 ($69\% \pm 23\%$) were found to be variable in the near IR bands, via the $S$ index. This is approximately consistent with the rate of variability found in the Paper I and Aspin et al. (2009) samples. This gives us strong confidence in the $WISE$ selections outlined in Section 2.1, including candidates listed in Table 4 which are outside the monitored field. The sources outside the field are found equally to the west and east of the RWA field. In Table 4, we identify the groups of multiple YSOs within an arccminute of each other. The “Western group” is a clump of six candidates near 20:26:52, +52:20; three of these are identified as Class I sources. The “RWA 2 tip” is a clump of four candidates at the end of the same portion of Lynds 1004 which contains the remarkable object RWA 2. Three of these objects are identified as Class I. A final group “Southclump” is comprised of three stars within 10′ of 21:03:38+52:17:40 containing a Class I and two Class II stars. The compactness of this Southclump raises concerns about the independence of the photometry at the longer wavelengths.

Myers (2012) has recently produced a model of protostar mass and luminosity evolution in clusters which can be used to estimate cluster age. The model assumes a constant protostar birthrate and core-clump accretion. Model parameters reproduce the initial mass function and match the protostar luminosity distributions in nearby star-forming regions. Figure 9 in their paper presents a calibration of the model to measure cluster ages and from the observed numbers of protostars and Class II objects. In Cyg OB 7 we have found 32 clear Class II sources and 30 clear Class I sources with the remainder showing colors somewhat between the two. Using this model in an “intermediate case” and dividing the Class IIR sources evenly between protostars and Class II objects we obtain a cluster age of between 1.0 and 0.5 Myr for Cyg OB7.

5. CONCLUSIONS

In this paper, we have studied the NIR variability of young stars in the Cyg OB7 cluster based on $\sim 100$ nights of monitoring spaced over about 550 days. We started by enhancing our candidate list using the recently released $WISE$ point-source catalog as well as a previously published catalog from Aspin et al. (2009). In total, we identified 96 total YSO Candidates of which 66 were in the monitored field. The number of these objects which were of the appropriate brightness for monitoring was 49. Of the 49, 41 were found to have strongly correlated variability in the monitored bands via the Stetson index. There were three additional cases of marginally correlated variability. If we include the marginal cases, the result is consistent with entire YSO population being variable in the near-IR on timescales of $<10$ yr, usually on timescales of $<2$ yr. This compares to less than 2% of the field stars being variable over the $\sim 2$ yr epoch. We have discovered one eclipsing binary YSO in the field, RWA 3. It is a good candidate for follow-up spectroscopy to determine the mass and evolutionary state of the individual members.

We then studied the shape of the light curves and noticed some emergent patterns. First, a little over one-fourth of the sources appeared periodic with periods of a few days. In general, these periodic sources showed color trends consistent with reddening. The color changes tended to be a bit steep in the sense that there was more change in brightness for a given color change than expected for ISM reddening. This implies less differential reddening than seen in the ISM (i.e., $R \sim 3.1$). Another subset of sources identified as “quasi-periodic,” showed patterns of brightening and then becoming fainter with cycles of a few days, but the duration and amplitude of the brightening differed cycle to cycle. Several of these sources showed color changes in the color–magnitude diagram perpendicular to that expected.
by reddening. A third group of sources showed large changes of >0.5 K mag. These were generally smoothly varying with timescales over a month. A plurality of sources showed purely stochastic variations.

We argue that changes in a limited range of parameters—disk obscuration, accretion rate, hole size, inner disk inclination—could account for much of the variability that was seen. In the case of the periodic sources, it appears the obscuration of the star by a non-uniformly thick disk was the primary cause of the changes in brightness, but other factors were changing as well. In the quasi-periodic cases, the trajectory in the color–magnitude diagram which was perpendicular to reddening implies changes to the accretion rate and/or to the disk structure. Meanwhile, the long-term changes show some periods dominated by slow changes in the disk-accretion structure. It is clear that multiple processes are taking place in some sources. Nowhere is this clearer than in RWA 7, in which the trajectory in the color–magnitude diagram has an inflection point. While more detailed modeling in the future could be used to provide a better understand of each of the various type of variability, it is equally clear that differences in the state of each star and its disk system are sufficient that each YSO needs to be considered as a unique entity.

Finally, we briefly discussed the distribution of YSOs in the region combining the 96 sources in the samples from Paper I, Aspin et al. (2009), and the WISE candidates added here. We find that the WISE candidates within the monitoring field are co-located with the previously known YSOs, primarily in the L 1003–1004 clouds. The sources outside the field continue that, extending the active star formation to the extreme eastern end of Lynds 1004 and the extreme western end of Lynds 1003. Empirical modeling indicates the whole star-forming region is under 1 Myr in age, with at least one source, the highly absorbed and wildly variable RWA 2, is fitted with an age <0.1 Myr.

S.J.W. is supported by NASA contract NAS8-03060 (Chandra). T.S.R. was supported by grant 1348190 from the Spitzer Science Center. Thanks also to the NSF REU program for funding part of this research via NSF REU site grant 0757887. This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this sacred mountain.

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