OCCULTATION OF THE T TAURI STAR RW AURIGAE A BY ITS TIDALLY DISRUPTED DISK

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ABSTRACT

RW Aur A is a classical T Tauri star, believed to have undergone a reconfiguration of its circumstellar environment as a consequence of a recent flyby of its stellar companion, RW Aur B. This interaction stripped away part of the circumstellar disk of RW Aur A, leaving a tidally disrupted “arm” and a short truncated circumstellar disk. We present photometric observations of the RW Aur system from the Kilodegree Extremely Little Telescope survey showing a long and deep dimming that occurred from 2010 September until 2011 March. The dimming has a depth of $\sim2$ mag, a duration of $\sim180$ days, and was confirmed by archival observations from American Association of Variable Star Observers. We suggest that this event is the result of a portion of the tidally disrupted disk occulting RW Aur A, specifically a fragment of the tidally disrupted arm. The calculated transverse linear velocity of the occultor is in excellent agreement with the measured relative radial velocity of the tidally disrupted arm. Using simple kinematic and geometric arguments, we show that the occultor cannot be a feature of the RW Aur A circumstellar disk, and we consider and discount other hypotheses. We also place constraints on the thickness and semimajor axis of the portion of the arm that occulted the star.

Key words: binaries: general – circumstellar matter – protoplanetary disks – stars: individual (RW Aur) – stars: pre-main sequence – stars: variables: T Tauri, Herbig Ae/Be

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

Classical T Tauri stars (CTTSs) are a type of active pre-main-sequence stars that show a large excess of infrared (IR) radiation and were first identified by the broad H$\alpha$ emission line widths in their spectra. The large IR flux in the spectra of CTTSs is normally attributed to thermal emission from their dusty circumstellar disks. A large excess of ultraviolet (UV) radiation is often observed and is believed to be a result of material in the disk being accreted onto the surface of the star, producing hot spots (Bertout et al. 1988). Irregular photometric variability that is characteristic of CTTSs has a typical amplitude of less than one magnitude and a timescale of days to weeks (Herbst et al. 1994). T Tauri stars are known to have significant magnetic activity, which can produce cool star spots and enhanced chromospheric emission. Weak-line T Tauri stars (WTTSs), which are typically found in the same star-forming clouds as CTTSs, were first distinguished from CTTSs by having very narrow H$\alpha$ emission widths (Walter 1986; Herbig & Bell 1988). They were then found to be bright X-ray emitters and show little to no UV or near-IR excess emission. These observational results are generally interpreted as indicating that WTTSs are no longer accreting and are either diskless or have disks with very little mass in the form of small, hot dust grains (Haisch et al. 2001). It is generally believed that CTTSs evolve into WTTSs when the disk is no longer a significant component of the system, as a result of accretion onto the star, planet formation, and dispersal.

From surveys, it appears that most nearby T Tauri stars are members of close binary systems (Ghez et al. 1993, 1997a; Leinert et al. 1993; Richichi et al. 1994; Simon et al. 1995). These companions can influence the stellar environment and affect the stellar properties determined for the primary star if not taken into account (Ghez et al. 1997b). Depending on the parameters of the companion star’s orbit, the companion can significantly disrupt the primary star’s circumstellar disk. Simulations show that a flyby of a stellar companion can tidally disrupt the circumstellar disk around a star, leaving behind a truncated, more compact disk and a long tidal arm feature trailing out from the disrupted material (Clarke & Pringle 1993).

Occultations of stars by their disks, though rare, provide a powerful tool for probing the structure of circumstellar disks. To date, only a few long-duration, deep eclipses of young stars have been discussed in the literature. Most such eclipses appear to be periodic, with the occultation attributed to a disk around a stellar companion or occultation of a star by its own disk. One well-known example of this is $\epsilon$ Aur, an F0 giant that experiences long and deep eclipses every 27.1 yr. The eclipse has a duration of almost two years and a depth of 0.8–1.0 mag (Carroll et al. 1991). The eclipse is attributed to a companion star with its own circumstellar disk (Kloppenborg et al. 2010). KH 15D is another system, discovered in 1995, which experiences complex eclipsing events with changing properties (Kearns & Herbst 1998). That system consists of a non-eclipsing binary star pair that is repeatedly occulted on the binary orbital period by the sharp edge of the circumbinary disk. Long-term secular changes in the occultations are caused by the slow precession of the circumbinary disk across our line of sight (Chiang & Murray-Clay 2004; Winn et al. 2004). There are a few other examples of periodically occulting systems (see, e.g., Bouvier et al. 2007; Plavchan et al. 2008; Grinin et al. 2008).

Some young stars experience occultations that are not periodic (or at least not known to be). In 2007, a pre-main-sequence star (2MASS J14074792-3945427) exhibited a long and
extremely deep occultation (Mamajek et al. 2012). This eclipse was observed by the Wide Angle Search for Planets (SuperWASP) photometric transit survey (Butters et al. 2010) and the ASAS photometric survey (Pojmanski 2002). The eclipse lasted \( \sim 54 \) days and had a \( \sim 4 \) mag maximum depth. The cause of the eclipse is thought to be a circumplanetary disk, in the process of formation, analogous to the rings around Saturn. Photometric variability was seen during the eclipse and attributed to gaps in the large ring system around the hypothesized planet (Mamajek et al. 2012).

Such systems provide insight into the nature of protoplanetary and circumstellar environments and can be used as tools to probe the structure and composition of circumstellar disks. In this paper we present new observations of the bright system, RW Aur, indicating a long and deep occultation (Figure 1) somewhat similar to the one seen by Mamajek et al. (2012). We interpret the event as an occultation of RW Aur A by a portion of its tidally disrupted disk.

The paper is organized as follows. We introduce the known characteristics of the RW Aurigae system in Section 2, illustrating the complex stellar environment. In Section 3, we describe the photometric observations, and then discuss the photometric properties of the data in Section 4. In Section 5, we present several interpretations of the light curve and discuss their plausibility. We summarize our results and conclusions in Section 6.

5 From Aleks Scholtz, A huge eclipse in the young star RW Aur. http://dx.doi.org/10.6084/m9.figshare.92169. Retrieved 21:01, 2013 May 13 (GMT).
(Ghez et al. 1997b; Woitas et al. 2001). It is a late K star (K6 ± 1; White & Hillenbrand 2004) with V ~ 13.7 (White & Ghez 2001). Ghez et al. (1993) found faint K-band emission 0′.12 from RW Aur B and interpreted this to be a third stellar component to the system, RW Aur C. Other authors have also claimed the presence of a third component in the system, but clear evidence is lacking. Furthermore, later observations failed to confirm the third component (Ghez et al. 1997b).

The RW Aur system has been found to vary in many observational characteristics. Beck & Simon (2001) found that the RW Aur system showed peak-to-peak variations of 2–3 mag on timescales of months using Harvard photographic observations from 1899 to 1952 (see Figure 3 of Beck & Simon 2001). The standard deviation of these variations is ~0.7 mag. Petrov et al. (2001) observed periodic variability in the radial velocity of RW Aur A of 2.77 days, as well as periodicity in the $U-V$ and $B-V$ colors of 2.64 days. The combined RW Aur system shows an overall non-periodic, photometric variability that Herbst et al. (1994) determined arises from the A component. The erratic variability has been attributed by different authors to the accretion of the disk onto the star or circumstellar extinction from strong disk winds (Herbst et al. 1994; Petrov & Kozack 2007). These are discussed in more detail in Section 4.1.

Cabrit et al. (2006) conducted millimeter observations of the RW Aur system using the IRAM Plateau de Bure Interferometer (1.3 mm, 2.66 mm). They find in the 1.3 mm observations that RW Aur A has an outer truncated circumstellar disk extending out 41–57 AU in radius, inclined by 45°–60° to our line of sight, and what appears to be a large, tidally disrupted trailing “arm” that is wrapped around the star (see Figure 1a from Cabrit et al. 2006). This arm-like feature has a three-dimensional length of ~600 AU and is almost certainly the result of a recent stellar flyby of RW Aur B (Cabrit et al. 2006). This flyby also caused the RW Aur A disk to be truncated near the periastron separation. While a large portion of the arm is redshifted, indicating it is wrapped around and behind the A component, there is a small portion that is connected to the northeast side of the RW Aur A disk which is blueshifted by up to 3.1 km s$^{-1}$ relative to the star. This feature resembles the destructive outcome of a coplanar eccentric flyby similar to simulations from Clarke & Pringle (1993), where all material outside the periastron distance is fully disrupted and drawn out into a coherent tail in the direction of the companion’s orbit. The RW Aur system therefore provides an excellent example of a T Tauri disk that has experienced a recent dynamical disruption.

3. PHOTOMETRIC OBSERVATIONS

Several photometric surveys have observed RW Aur over both short and long timescales going back to 1899. The light-curve data are shown in Figures 1 and 3.

3.1. Archival Data

The SuperWASP is a wide-field photometric survey designed to detect transiting extrasolar planets over a large fraction of the sky. SuperWASP observed RW Aur for one shortened season in 2004 and then two later seasons in 2006 and 2007. The SuperWASP public archive data are described in detail in Butters et al. (2010). The SuperWASP observations have a cadence of a few minutes in the V band and do not resolve the RW Aur system, thus the light curve incorporates light from all system components. The median error for SuperWASP is ~0.01 mag.

The American Association of Variable Star Observers (AAVSO) is a non-profit organization dedicated to the goal of understanding variable stars. The AAVSO archive contains observations of RW Aur going back to 1937, with the observations increasing in cadence around 1954. The AAVSO data consist of V-band and visual observations. Only some of the AAVSO data have corresponding uncertainties reported.

Wesleyan University’s Van Vleck Observatory has monitored many known T Tauri stars with the 0.6 meter Perkin Telescope. The resulting observations are included in a public archive of $UBVRI$ photometry. RW Aur A was observed from 1965 January until 1994 October, with varying frequency. A detailed description of the archive is provided in Herbst et al. (1994).

The AC and AM photographic plate series at the Harvard College Observatory have observations of RW Aur from 1899 to 1952, resulting in 162 observations. The photographic observations were obtained using the 1.5 inch Cooke lens, corresponding to a plate scale of 600$′$ mm$^{-1}$. The $B$-band magnitudes were estimated by analyzing over 150 archival plates and comparing them to the known $B$ magnitudes of nearby stars (not shown in Figure 1; see Figure 3 of Beck & Simon 2001).

3.2. KELT-North

The Kilodegree Extremely Little Telescope (KELT-North) is an ongoing survey, searching for transiting planets around bright stars ($V = 8–10$). KELT-North uses a Mamiya 645 80 mm f/1.9 lens, and has a 42 mm aperture and a large field of view (26′ × 26′) with a plate scale of 23″ pixel$^{-1}$ (Pepper et al. 2007).

RW Aur is located in KELT-North Field 04, which is centered on ($σ = 5^h 54^m 14.466, δ = +31° 44′ 37″$). KELT-North observed this field from 2006 October 10 to 2012 September 23, obtaining 8001 images. The data were reduced using a heavily modified version of the ISIS software package, described further in Section 1 of Siverd et al. (2012).$^6$ The observations are in a broad $R$-band filter, with a ~15 minute cadence, and the typical error is less than 0.04 mag. The KELT-North observations also fail to resolve the RW Aur system. The KELT-North data are presented in Table 1.

4. RESULTS: VARIABILITY BEFORE AND DURING THE DIMMING EVENT

Here we discuss the variability characteristics of the deep dimming event. We also describe the general photometric variability of RW Aur A. In Section 5 we discuss the dimming in the context of an interpretation in which the star has been occulted by a portion of its tidally disrupted disk. We focus our analysis on four data sets: KELT-North, AAVSO, SuperWASP, and Wesleyan (Van Vleck).

4.1. Pre-dimming Variability

CTTSs can have erratic photometric variations on the timescale of a few days (Herbst et al. 1994). The light curve for RW Aur shows this photometric variability, and it is observed in all four data sets (Figure 1). The variability seen in the four data sets for RW Aur has a peak-to-peak amplitude of 1–2 mag, on the timescale of days to weeks, with a standard deviation of ~0.4 mag.

Two possible explanations for the non-coherent photometric variability are circumstellar extinction and varying accretion.

$^6$ Much of the software is publicly available at the following address: http://verdis.phy.vanderbilt.edu.
which the photometric variability of RW Aur A is principally a 1–1.5 mag brightening and then re-dimming toward the end which occurs with a characteristic timescale of 10 days, is apparent during the dimming (Figure 3). The peak-to-peak depth of the fading is \( \sim 4 \) mag and has a sustained duration of many months. Therefore, the dimming event has a much deeper and longer duration than the out-of-event stochastic variations that present a peak-to-peak amplitude of 1–2 mag and a standard deviation of \( \sim 0.4 \) mag on shorter timescales.

During the dimming, the system’s brightness decreases to \( V \sim 12.5 \) (Figure 3). For reference, the B component by itself was previously measured to be \( V \sim 13.7 \) (Ghez et al. 1997b). Assuming that the dimming is only due to a decrease in the brightness of the A component, we calculate that the \( V \) magnitude of the A component, during the dimming event, is \( \sim 12.9 \). That corresponds to a decrease in flux of the A component of 91%, making it \( \sim 1.5 \) times brighter than the B component during the 2010–2011 event. The large-amplitude non-periodic short-timescale variability that is so ubiquitous outside the 2010–2011 dimming appears to significantly diminish but is still present. This is expected if the short-term variability, originating from the A component, is subjected to significant dilution from the combined system with the B component during the dimming. This supports the interpretation that the A component is the source of the non-periodic variability. At the same time, we do observe structure during the dimming, in particular a 1–1.5 mag brightening and then re-dimming toward the end which occurs with a characteristic timescale of \( \sim 10 \) days, very similar to the main ingress timescale. Below we discuss the possibility that this structure during the dimming may imply substructure in the occulting body.

RW Aur A was serendipitously monitored spectroscopically during October through December of 2010 by Chou et al. (2013). Although the authors were unaware of the 2010–2011 dimming, their spectroscopic observations by chance coincide precisely with the first half of the deep dimming event, including most of the ingress and the point of maximum depth. Their analysis of 14 different emission lines tracing accretion, infall, and outflow is broadly consistent with both the nature of the line profiles and the short-timescale variability observed by others many years before (see references in Chou et al. 2013). In addition, their observed correlations between the various emission lines are consistent with a largely steady magnetospheric accretion model over the course of the observations. They do infer variations in

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### 4.2. 2010–2011 Dimming

In late 2010 September the light curve of the RW Aur system became fainter, dropping from a median brightness of \( V = 10.4 \) to \( V = 12.5 \) mag (Figure 1). This decrease lasted for \( \sim 180 \) days, ending in late 2011 March. A good deal of structure and variability, on similar timescales as the ingress and egress, 10–30 days, is apparent during the dimming (Figure 3). The peak-to-peak depth of the fading is \( \sim 4 \) mag and has a sustained duration of many months. Therefore, the dimming event has a much deeper and longer duration than the out-of-event stochastic variations that present a peak-to-peak amplitude of 1–2 mag and a standard deviation of \( \sim 0.4 \) mag on shorter timescales.

### Table 1: KELT-North Photometric Observations of RW Auriga

| BJD TDB | KELT V Mag | Poisson Errors |
|---------|------------|----------------|
| 2454035.812879 | 10.326 | 0.008 |
| 2454035.817902 | 10.327 | 0.008 |
| 2454035.822123 | 10.324 | 0.008 |
| 2454035.826745 | 10.319 | 0.008 |
| 2454035.831367 | 10.311 | 0.008 |
| 2454035.835989 | 10.294 | 0.007 |
| 2454035.840612 | 10.286 | 0.007 |
| 2454035.845235 | 10.281 | 0.007 |
| 2454035.849855 | 10.286 | 0.007 |
| 2454035.854477 | 10.283 | 0.007 |

Notes:
- \(^a\) Relative KELT instrumental magnitude corrected to Johnson \( V \) magnitude. Absolute accuracy to \( \sim 0.2 \) mag. Relative accuracy to \( \sim 0.04 \).
- \(^b\) Poisson errors to instrumental KELT magnitudes. True per-point magnitude errors must fold in 0.036 mag systematic errors.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

onto the surface of the star. Herbst et al. (1994) argued convincingly that the non-coherent variability is caused by irregular accretion onto the surface of RW Aur A, creating hot spots that rotate into and out of view. Herbst et al. (1994) performed an analysis of the \( UBVRI \) photometric observations, finding that the photometric variations are roughly divided evenly (with relatively large amplitude) between positive and negative excursions relative to a well-defined median level. This is a defining characteristic of accretion-driven variability, as opposed to circumstellar obscuration-driven variability, which tends to produce mainly dimming of the star, or flare-driven variability, which tends to produce mainly brightening events. Importantly, the \( \text{H} \alpha \) flux appears to be correlated with the brightness of the star at all wavelengths (Herbst et al. 1982). This is very strong evidence in favor of an interpretation in which the photometric variability of RW Aur A is principally connected to variations in its accretion rate. Petrov & Kozack (2007) and Grinin et al. (2004) suggest that the photometric variability is the result of a strong disk wind lifting material from the disk across the star causing circumstellar extinction. Such disk winds are a known feature of CTTs but at odds with the accretion variability interpretation of Herbst et al. (1994).

Some accreting stars can show periodic modulations in their light curves due to hot accretion spots on the stellar surface rotating in and out of view on the stellar period. To look for such periodicity, we use a Lomb–Scargle periodogram as presented in Lomb (1976), Scargle (1982), and Press & Rybicki (1989). This Lomb–Scargle method performs spectral analysis on unevenly sampled time series data and allows us to effectively identify weak periodic signals. We performed this analysis on the KELT, AAVSO, SuperWASP, and Wesleyan photometric data.

We do not see any significant periodicity in the full KELT-North RW Aur light curve, nor in the KELT-North light curve with the dimming in late 2010 removed aside from the 1 day diurnal sampling effect. The AAVSO and SuperWASP light curves also do not show any periodic signal. We do, however, confirm a \( \sim 2.7 \) day periodic variability seen by Petrov & Kozack (2007) in the Wesleyan University \( (B-V) \) and \( (U-B) \) curves. The KELT and SuperWASP light curves each exhibit a small peak between 2.69 and 2.72 days. Though not individually statistically significant, their presence does lend additional credence to this signal. A periodicity at twice this value \( \sim 5.5 \) days has been reported as the rotation period of the star (Petrov et al. 2001; Gahm et al. 1999). We are unable to identify this periodicity in the individual \( U, B, \) or \( V \) Wesleyan University light curves (Figure 2), which could be the result of the rotational modulation signal being masked by the stochastic accretion variability.

While the periodicity analysis does not shed much new light on the physical origin of the variability, the overall available evidence appears to favor an interpretation in which the photometric variability is tied to variations in the accretion rate. Spectroscopic monitoring observations obtained during the deep dimming event corroborate this interpretation also, as discussed in the next section.
Figure 2. The resulting periodograms from the Lomb–Scargle analysis of the AAVSO, KELT-North, SuperWASP, and Van Vleck photometric data. The vertical dashed line represents a 2.7 day periodicity that has been previously reported as half the rotation period of the star. We recover this period in the Wesleyan $U - B$ light-curve data. The features seen at 1.0 c/d are the (high-frequency) aliases of long-term variation caused by diurnal sampling.

Figure 3. KELT-North (black) and AAVSO (blue) light curves zoomed in on the eclipse. In gray dashed highlights is the estimated ingress of 20 days, and the two red vertical lines mark the estimated eclipse duration. The KELT observation has an error of 0.04 mag, while most AAVSO data do not have reported errors. The faintest points observed during the dimming are near the observational limit of KELT.

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

the magnetospheric accretion of the order of 20%, comparable to previous accretion variability measurements for RW Aur A and with the accretion variability interpretation for the general photometric variability of the system (Herbst et al. 1994). More fundamentally, these serendipitous spectroscopic observations suggest that the accretion behavior of RW Aur A was not connected with the source of the pronounced photometric dimming event.

It is clear that a dimming this large is not present prior to 2010 in the combined light curves from KELT-North, AAVSO, Van
Vleck, and SuperWASP. Although there is substantial variation seen in the full light curve across 60+ yr (Figure 1), we observe no comparable events in duration or depth. We verify that by examining time spans in the full data set that might appear to represent similar eclipses, but a detailed look shows that those events clearly do not resemble the deep long and coherent event in 2010 to 2011. Since we can place a lower limit on the duration of the fading to be \( \sim 180 \) days from the KELT and AAVSO light curves, we searched for a gap in the combined light curve, large enough that a similar previous event may have occurred but have been missed. We examine the RW Aur light curve, using all four data sets, and find no gap in the observations greater than 180 days since 1961. Prior to 1961, the only photometric observations of this target are the Harvard photographic observations and a much sparser set of AAVSO observations. Those data span the years 1899 to 1961, with frequent gaps of 200+ days. We can therefore conclude that if the 2010–2011 event repeats, it would have a minimum period of \( \sim 50 \) yr.

5. INTERPRETATION AND DISCUSSION

5.1. Favored Interpretation: Occultation by the RW Aur A Tidally Disrupted Disk

In this section we present what we regard as the most plausible interpretation of the 2010–2011 dimming event, namely, an occultation of RW Aur A by a fragment of the tidal arm that resulted from its disrupted circumstellar disk. This known feature of the circumstellar environment provides the necessary ingredients of a large opaque body, with a sharp edge moving perpendicular to the line of sight, to be able to naturally explain many of the features of the observations. We explore alternate interpretations in Section 5.2, but here we investigate the necessary properties of the occulting body and discuss how well these properties agree with those observed for RW Aur A’s tidally stripped arm.

We calculate the key characteristics of the occultor by modeling the dimming as an occultation of RW Aur A by a large body which possesses a sharp edge that is oriented perpendicular to the direction of motion. From the photometric observations, we are able to determine three important features about the occultor: transverse velocity, semimajor axis, and width. From the light curves, we estimate the ingress to be between 10 and 30 days and the total duration to be about 180 days. As a result of the cadence and gaps in observing between the KELT-North data and AAVSO, the values determined for these two parameters are based on a visual inspection of the light curves. We choose to define the end of the dimming event to be after the two large variations at \( \sim 5600 \) and \( \sim 5640 \) (JD–2,450,000; Figure 3) since this type of variability is not seen anywhere in the light curve outside the dimming event and thus can be attributed to the mechanism responsible for the event. We also observe that the variations during the dimming (including the substructure near the end of the event) all share the same characteristic timescale of the ingress/egress (10–30 days).

Using the known mass and age of RW Aur A (1.3–1.4 \( M_\odot \), Ghez et al. 1997b; Woitas et al. 2001), we refer to the Dartmouth Stellar Evolution Program’s young stellar models to find that the radius should be between 1.5 and 1.7 \( R_\odot \) (Dotter et al. 2008). These specific models give a log\( (T_{\text{eff}}) \) of 3.67–3.70 that is consistent with the effective temperature determined for RW Aur A by Liu & Shang (2012). For our calculations, we adopt a mass of 1.35 \( \pm 0.135 M_\odot \) (error estimate for isochrone fitting) and a stellar radius of 1.6 \( \pm 0.32 R_\odot \) (conservative error estimate for the stellar evolution models).

We use the stellar radius and the minimum timescale of the ingress and characteristic variation seen during the occultation (10 days) to calculate the maximum transverse velocity of the occultor to be \( 2(1.6 R_\odot)/10 \) days = 2.58 \pm 0.52 km s\(^{-1}\). Furthermore, the calculated velocity of the occultor and the total observed duration of the occultation yield a physical width of the occulting body of 2.58 km s\(^{-1}\) \times 180 days = 0.27 \pm 0.05 AU. Assuming Keplerian motion and a circular orbit, a velocity of 2.58 km s\(^{-1}\) implies a semimajor axis of 180.5 \pm 28.9 AU:

\[
\frac{1.35 M_\odot G \text{(10 days)}^2}{4(1.6 R_\odot)^2} \sim 180.5 \text{ AU}. \tag{1}
\]

Using instead the estimated maximum ingress timescale (30 days), we calculate a minimum transverse velocity of 0.86 \pm 0.17 km s\(^{-1}\), semimajor axis of 1624.7 \pm 260.1 AU, and occulter width of 0.089 \pm 0.02 AU. At 180 AU, the occultor would be more than three times as far from RW Aur A as the maximum estimated extent of the circumstellar disk (57 AU; see Section 2). Unless the occultor is moving at an extremely oblique angle, these values should be roughly accurate to within a factor of a few.

Cabrit et al. (2006) conducted millimeter observations of the RW Aur system and found that the system appears to have undergone a complex interaction with its companion, RW Aur B, that resulted in a short truncated circumstellar disk around RW Aur A (inclined by 45°–60°) and a large (600 AU along the spine) tidally disrupted arm that wraps around behind the A component (see Section 2). The arm is believed to be mostly wrapped behind the A component, although a small portion appears to be in front. The portion of the arm in front of the A component has a blueshifted velocity relative to RW Aur A of \( \lesssim 3.1 \) km s\(^{-1}\), which is similar to our calculation of the occultor’s transverse velocity. The 0.86 km s\(^{-1}\) velocity, for the 30 day ingress calculation, is also consistent since Cabrit et al. (2006) measured a range of blueshifted velocities in their millimeter observations.

The observations of the tidal feature are consistent with the simulations of a coplanar stellar interaction conducted by Clarke & Pringle (1993). There is no indication that the orbit and disk plane are not in the same plane, which is the most probable configuration. Bisikalo et al. (2012) found that the orbit of the binary is retrograde to the orbit of the circumstellar disk around RW Aur A. The simulations by Clarke & Pringle (1993) for a co-planar, retrograde interaction not only produce a tidal arm but also show that the interaction disrupts a significant amount of material out of the disk plane. Therefore, it is plausible that material was disrupted out of the disk plane into our line of sight even though the system is significantly inclined.

Although the distance between RW Aur A and the arm is unknown, simulations by Clarke & Pringle (1993) show that in an eccentric stellar interaction, the disrupted arm spirals outward from the primary component and its closest point would be outside the extent of the disk. Thus, our calculated semimajor axis of \( \sim 180 \) AU (or larger for 30 day ingress) is consistent with simulations of the hypothesized interaction. Without more information about the system configuration during the flyby, we have no definitive knowledge of the full three-dimensional direction of movement for the blueshifted component of the arm. We therefore expect that it is unlikely that the velocity vector is extremely oblique. Thus, we expect that the transverse velocity...
we calculate is within a factor of a few of the true velocity. Since our calculated velocity is quite similar to the radial velocity seen in the Cabrit et al. (2006) observations, that congruence supports the conclusion that the disrupted arm (likely a fragment of the full arm) and the occulter are the same body.

The occultation displays a large maximum depth (~2 mag) and a long duration (180–210 days), with some substructure occurring on a timescale similar to the ingress, 10–30 days (Figure 3). There are large-amplitude variations observed near the end of the dimming (5590–5650 JD UTC-2,450,000). These features appear to repeatedly brighten from the maximum dimming depth to the median out of occultation magnitude, suggesting that the occulter has substructure and potentially gaps. The faintest points during the occultation are near the edge of KELT’s detectability, compromising our ability to characterize any short-period variability during the dimming. Within this interpretation, the brightness variations seen during the occultation are due to the substructure of the tidal arm fragment.

Having made several simple assumptions (sharp leading edge, Keplerian motion, etc.), our calculated properties of the occulter are consistent with the observed properties of the tidal arm from Cabrit et al. (2006). The distance between RW Aur A and the occcluding body derived in this section (~180 AU) is comparable to the separation between the RW Aur A and RW Aur B components (~200 AU). This location implies that the occcluding body cannot be a circumbinary object and is probably a fragment of one of the components of the system. Therefore, we believe that the best explanation for the occultation mechanism, producing the 2010–2011 occultation, is that a fragment of the tidally disrupted arm crossed in front of RW Aur A.

5.2. Alternate Explanations

We have presented evidence for an interpretation in which the deep, long-duration dimming of RW Aur A is due to occultation by its tidally disrupted circumstellar disk. We now explore alternate explanations for these observations.

5.2.1. Occultation by Stellar Companion

We can rule out the possibility that the occulter is comparable in size to RW Aur A because the combined ingress/egress timescale would need to be similar to the entire duration of the dimming. If the cause of this event was the result of an eclipse of the A component by a large unseen stellar companion, this would require the companion to have extreme stellar parameters. We can model the system as a large stellar disk passing in front of a smaller one (RW Aur A). This allows us to use the same calculations as in Section 5 for the velocity, semimajor axis, and diameter (projected width) of the occcluding star. The same calculations apply because the eclipsing star’s leading edge would be perpendicular to its tangential motion. The occcluding star would thus need to be moving at ~2.5 km s⁻¹ and have a diameter of ~0.27 AU, corresponding to a radius of ~58 R⊙, a giant star. The star would also need to be dark and cause the large variations at the end of the dimming (Figure 3). From these observed and calculated characteristics, we are confident the occulter is not an unseen stellar companion.

5.2.2. Alternate Stellar Parameters of RW Aur A

We address the assumptions in our calculations of the occulter distance from RW Aur A. In Section 5 we determined that the occcluding body must be more than three times as far from the star as the outer edge of the known circumstellar disk. Since that calculation is based on our determination of the linear velocity of the occulter, which in turn depends on the radius of the star, we ask whether our stellar radius estimate (1.6 R⊙) could be incorrect. Given the observed maximum extent of the disk of 57 AU (Cabrit et al. 2006) and assuming Keplerian motion, we calculate that RW Aur A would need a radius of at least ~2.75 R⊙ for the occulter to be located at the edge of the disk.

However, a star with a radius 2.75 R⊙ would be much more intrinsically luminous. A star with a radius of 2.75 R⊙, log(T eff) of 3.684, and apparent magnitude of V = 10.4 would be at a distance of ~218 pc, which is much larger than the measured distance to RW Aur of ~140 pc (Wichmann et al. 1998). Furthermore, according to the Dotter et al. (2008) stellar models, a radius of 2.75 R⊙ implies a stellar age of ~9.5 × 10⁵ yr. RW Aur is part of the Taurus-Auriga association, where star formation is thought to have first occurred on the outer edge and progressed inward. The youngest estimated age for the Taurus-Auriga stellar association is ~1 Myr for the center of the association; however, RW Aur is located on the outer edge of the region, where star formation is believed to have occurred much earlier and corresponds to an age closer to 10 Myr (Palla & Stahler 2002). Since a radius of 2.75 R⊙ is not consistent with either the apparent magnitude or age of RW Aur A, it is not likely that the estimated radius is incorrect.

5.2.3. Occultation from Outer Edge of RW Aur A’s Circumstellar Disk

We explore the possibility that a large feature at the edge of the circumstellar disk around RW Aur A has occulted the star. Even though the disk is inclined to our line of sight, pre-transitional disks are not uniformly flat and tend to flare as a function of semimajor axis. An example of this is clearly seen in Espaillat et al. (2010), which shows that the height of the disk is 13.8 AU at a semimajor axis of 71 AU but only 0.009 AU at 0.1 AU from the star.

To determine the plausibility of a feature at the edge of the RW Aur A circumstellar disk causing the occultation seen in late 2010, we model the feature to be in a Keplerian orbit, at the farthest estimated extent of the disk (57 AU), and calculate the additional height required to cross the face of the star. For our model, we consider a conservative disk inclination from Cabrit et al. (2006) for RW Aur A of 60° and a flared disk height of 15 AU above the mid-plane at the outer edge. We assume that the disk flares out linearly to 15 AU. The flared disk height we use is an extreme example of what is seen in other disks (Espaillat et al. 2010). Using geometric arguments, we calculate that the necessary increase in height for a feature at the disk edge to occult the star is 15.5 AU in addition to the extreme flaring already assumed for the disk (Figure 4).

Using instead the argument of Keplerian motion, a feature at the edge of the disk would have an orbital velocity of ~4.66 km s⁻¹, corresponding to a width of ~0.49 AU. This results in the postulated feature with a projected height and width of ~15 AU and ~0.5 AU, respectively. A feature with these dimensions would be so tall and thin as to be highly implausible.

5.2.4. A Warp in the Inner Circumstellar Disk

RW Aur A appears to have undergone a close interaction with its companion, RW Aur B, in the recent past. Here we consider the plausibility that a warp in the inner part of the RW Aur A disk, caused by the flyby, could cause the dimming
seen in 2010–2011. The models by Clarke & Pringle (1993) for a retrograde, co-planar orbit show that even though all disk material outside periastrom is fully disrupted, the interaction has little effect on the disk interior to this. Therefore, the Clarke & Pringle (1993) simulations predict that an interaction of this type would not warp or twist the innermost part of the disk. Other mechanisms such as a misaligned magnetic field, stellar radiation, or planetary companions could cause a warp. The longevity of a warped circumstellar disk is dependent on the mechanism that causes it.

A misaligned magnetic field, where disk material is funneled onto the stellar surface, would show variations on the timescale of days to a few weeks (e.g., AA Tau; Bouvier et al. 2003) because this is the Keplerian timescale in the disk at a distance of a few stellar radii, which is the extent of the star-disk magnetic interaction. The magnetic misalignment effect, such as is seen around AA Tau, could not result in the 180 day dimming of RW Aur A.

If the warp is caused by the presence of planetary companions, the stability of the warp should be related to the stability of the planets’ orbit and therefore the warp should last many orbital periods (Burrows et al. 1995; Mouillet et al. 1997). Armitage & Pringle (1997) showed that radiation-induced warping is possible in high-luminosity stars ($L_\star \geq 10 L_\odot$) as long as the central star’s intrinsic luminosity is much higher than what is created by accretion from the disk. This was an alternate explanation for the warp seen in the disk around β Pictoris (Armitage & Pringle 1997).

To explore the possibility that the occultation is caused by a warp, we adjust our interpretation from Section 5.1 and now model the occulter as an opaque body with a sharp leading edge moving across the face of the star at an oblique angle. The obliquity of the leading edge allows the occulter to move at a higher velocity, thus potentially placing it closer to the star. To determine whether a warp is plausible or not, we must determine two key characteristics, the additional height required to cross into our line of sight and the width of the warp. As we place a warp closer to the star, the orbital velocity increases, which as a result would increase the calculated occulter width (Figure 5). For a warp to be plausible, it would likely need a larger width than height. Assuming the same scenario as in the previous sub-section, where the disk flares out linearly to a height of 15 AU, we determine through geometric arguments that the only location where the calculated width of the occulter is larger than the line-of-sight height is at a distance from the star of \( \leq 11 \) AU.

This would require the leading edge of the occulter to cross at a highly oblique angle, \( \leq 15^\circ \) relative to the direction of motion. This semimajor axis for the feature corresponds to an orbital period of \( \leq 31 \) yr, well within our window of observations, and so we should have observed it to repeat. It does not seem plausible that the presence of planets could create and dissipate a warp in less than one orbital period, especially since a planet-induced warp should be stable for longer than its orbital period.

The accretion rate is too high and luminosity of RW Aur is too low for it to cause a radiation-induced warp in its inner disk. Also, the stability of the warp by induced radiation would be very long and should have been observed more than once in 50+ yr of constant observation. In both potential disk warping mechanisms (planetary companions and stellar radiation), the lifetime of the warp would be much longer than the orbital timescale and would have been observed more than once. Therefore, we do not believe that a warp is a likely interpretation of the 2010–2011 dimming.

Finally, we examine the possibility that the circumstellar disk around RW Aur A has eclipsed the star once due to a large precession of the disk. From our calculations, we are confident that the occulter is not located inside the disk around RW Aur A (minimum semimajor axis of \( \sim 180 \) AU compared to the maximum radius of the disk, 57 AU; Cabrit et al. 2006). We have determined that due to the inclination of the disk, any warp would need to be extremely large to cross our line of sight. This would also require an extreme precession of the circumstellar disk to force it into our line of sight. Thus, precession is not a plausible explanation.

Given the extreme disk distortions required by these scenarios, we can conclude that the circumstellar disk around RW Aur A is not a likely explanation for the 2010–2011 dimming.

5.2.5. UXor Variation

UX Orionis stars are a class of pre-main-sequence stars, typically Herbig Ae/Be objects, that experience large dimming events, sometimes described as Agol-type minima, in the V band of up to 3 mag, lasting on timescales of days to months. These events manifest as sudden drops in the visual brightness followed by a slow recovery. The minima events are aperiodic but recurring and not known as one-time phenomena. During these minima events, as the light decreases, the star becomes redder, then bluer, and the polarization increases. High dust column densities cause the initial dimming and reddening of light, while the bluing during minima and polarization is caused by an increase in the scattered light (Grinin et al. 1998; Waters & Waelkens 1998).
Some UXor stars such as SV Cep show long-term periodicities in their light curves on timescales of years (Rostopchina et al. 1999). Even though UXor stars are usually early-type, there are a few known late-type stars that display UXor variations, such as the late K stars UY Aurigae (Ménard & Bastien 1987), AA Tau (Bouvier et al. 1999), and the M2 star DF Tau (Chelli et al. 1999). Also, even though one of the explanations for the deep minima in UXor stars requires the disk to be edge on, the variations typically occur in pre-main-sequence stars that are surrounded by circumstellar disks at an inclination of 45°–68° (Natta & Whitney 2000).

RW Aur A would be one of the rare late-type stars showing UXor variability. There are some apparent similarities in the long-term light curve of the UXor star SV Cep when compared with our observations of RW Aur A. Both SV Cep and RW Aur A show minima lasting 100–400 days and long-term changes in the median baseline (Rostopchina et al. 1999). Even in the extreme case of SV Cep, which experiences rare deep minima, it still shows three events in 36 yr (Rostopchina et al. 1999). We have examined the entire 50+ year light curve of RW Aur and find nothing resembling the depth and duration of the 2010–2011 dimming. Thus, if RW Aur A is a UXor star, it would have the longest time lapse between minima known.

An explanation of UXor minima is that they are the result of hydrodynamical fluctuations in either the inner rim or outer edge of the star’s circumstellar disk (Dullemond et al. 2003). Taking a conservative disk inclination for RW Aur A of 60° (see Figure 4), we determined in Section 5.2.3 that a feature at the edge of the RW Aur A disk, even with an extremely flared disk, would have to protrude an additional 15.5 AU from the disk to cross the star. A 15.5 AU protrusion is far larger than any known hydrodynamical fluctuations of a circumstellar disk. Therefore, we explore the possibility that the disk of RW Aur A has a puffed-up inner rim causing the occultation. Dullemond et al. (2003) determined that the height of the inner rim would be $H_{\text{rim}} \sim 0.2 R_{\text{am}}$ with a hydrodynamical fluctuation of $\sim 0.1 R_{\text{am}}$. We use the conservative inner radius of the RW Aur A disk of $0.103 \pm 0.005$ AU from Eisner et al. (2007). This results in a maximum puffed-up inner rim height of 0.031 AU. Using the same inclination of the RW Aur disk, this would result in a relative height of 0.027 AU to our line of sight. At 0.103 AU from the star, in a disk inclined by 60°, the height necessary to cross our line of sight is 0.0555 AU. Even using the most conservative values, the required height to cause extinction is still twice the maximum puffed-up height of the inner rim for the RW Aur A disk. Moreover, this puffing would need to have occurred only once for some unknown reason. However, the accretion rate onto the star during the occultation did not change appreciably (see Section 4.2). Thus, it is unlikely that the dimming observed is the result of circumstellar extinction from a hydrodynamically puffed-up inner disk rim.

Unfortunately, we do not have any color or polarization observations of the system during the large dimming event and therefore cannot look for the reddening during the beginning of the dimming or color reversal and increased polarization of the light at the maximum depth. These types of observations would allow us to definitively determine if the 2010–2011 event is a UXor minimum. However, when comparing our observations to known UXor stars, if the 2010–2011 dimming was a UXor minimum, it should have occurred more than once in the 50+ yr of consistent observations. Also, RW Aur A does not fit the typical profile of a UXor star, and therefore we do not believe it to be a new UX Orionis star.

6. SUMMARY AND CONCLUSIONS

The new observations of the RW Aur system from KELT-North show that a long ($\sim 180$ days) deep ($\sim 2$ mag) dimming occurred in late 2010 to early 2011. The event is also visible in the AAVSO archive, which contains photometric observations of RW Aur.

We have determined that the most plausible explanation for this event is that a fragment of the arm from the tidally disrupted circumstellar disk, thought to be caused by a recent flyby of the B component, crossed the face of the A component. The observations from Cabrit et al. (2006) show a tidally disrupted “arm” feature, 600 AU long, that is connected at the northeast position of the A component and wraps around behind the star toward the B component. We calculate a maximum linear velocity of the occulter of 2.58 km s$^{-1}$, consistent with the maximum blueshifted velocity, relative to RW Aur A, of the tidally disrupted arm, $\sim 3.1$ km s$^{-1}$ (Cabrit et al. 2006). Assuming Keplerian motion, the occulter is located at a distance of $\sim 180$ AU from RW Aur A, which is over twice the maximum radius of the observed circumstellar disk, but could still be located in this tidal feature.

The simulations performed by Clarke & Pringle (1993) predict that the tidally disrupted arm, produced from a close stellar flyby of a companion, would have a relative width of 0.05 the periastron distance. Cabrit et al. (2006) calculated that the periastron distance, during the recent flyby of RW Aur B, would have been 100–140 AU. From our maximum linear velocity, we calculate the thickness of the arm fragment to be 0.27 AU ($\sim 0.003$ the periastron distance). Evidently the tidal arm has remained fairly coherent despite the tidal disruption event. These observations may indicate that we are witnessing the leading edge of the tidally disrupted arm occulting the star, and that future occultations may arise from other portions of the tidal arm. Therefore, we encourage observers to obtain multi-filter photometric observations of RW Aur in hopes of better characterizing future occultations of the star. These results also motivate additional detailed simulations to extend the early work of Clarke & Pringle (1993) along with a reexamining of the spectra taken by Chou et al. (2013) that coincide with the first half of the dimming event, including the point of maximum depth. Since the authors of Chou et al. (2013) were unaware of the dimming event, a comparison of their results with out-of-occultation observations may show spectroscopic signatures of the occulting body. This rare observation provides insight into the dynamics of protoplanetary environments in binary star systems.

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