The Mysterious Dimmings of the T Tauri Star V1334 Tau

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Abstract

We present the discovery of two extended ~0.12 mag dimming events of the weak-lined T Tauri star V1334. The start of the first event was missed but came to an end in late 2003, and the second began in 2009 February, and continues as of 2016 November. Since the egress of the current event has not yet been observed, it suggests a period of >13 years if this event is periodic. Spectroscopic observations suggest the presence of a small inner disk, although the spectral energy distribution shows no infrared excess. We explore the possibility that the dimming events are caused by an orbiting body (e.g., a disk warp or dust trap), enhanced disk winds, hydrodynamical fluctuations of the inner disk, or a significant increase in the magnetic field flux at the surface of the star. We also find a ~0.32 day periodic photometric signal that persists throughout the 2009 dimming which appears to not be due to ellipsoidal variations from a close stellar companion. High-precision photometric observations of V1334 Tau during K2 campaign 13, combined with simultaneous photometric and spectroscopic observations from the ground, will provide crucial information about the photometric variability and its origin.

1. Introduction

The circumstellar environments of young stellar objects (YSOs) are complex because a large number of processes drive their evolution. The observed properties of YSOs involve accretion onto the star, dispersion by stellar winds and radiation, magnetic fields, outflows, and in many cases stellar companions. Many of these characteristics can manifest themselves through disk substructures, gradients, and other disk properties that could reveal the mechanisms that influence planet formation. Although high spatial resolution imaging and interferometry can now resolve the circumstellar environment of some young stars, we are not yet able to probe the innermost region for most stars (<10 au) where a large fraction of the exoplanets reside.

First classified by Herbst et al. ([1994]), YSOs are known to vary in the optical as a result of material accreting onto the stellar surface and/or circumstellar extinction. This variability can be in duration, depth, and periodicity. Some YSOs showing non-periodic, large (>1 mag) and long (months to years) dimmings and are referred to as UX Orionis stars (UXors). Proposed causes are over-dense regions in the nearly edge-on circumstellar disk surrounding the host star (Wenzel [1969];

Grinin 1988; Voshchinnikov 1989; Grinin et al. 1998; Grady et al. 2000, p. 613), hydrodynamical fluctuations of the inner disk (Dullemond et al. 2003), or strong disk winds (Petrov & Kozack 2007).

Shorter duration (days to weeks) photometric variability of YSOs has been seen in both the optical and infrared but the cause is unclear. This variability could be caused by accretion of circumstellar material onto the stellar surface causing hot spots, circumstellar extinction, or orbiting dust clumps (Herbst et al. 1994; Stassun & Wood 1999; Bouvier et al. 2007). These stars are typically referred to as "dippers," and although the variability is shorter in duration, the dimming can have a depth of up to $\sim$1 mag. Dippers have a lower amplitude in the infrared than the optical, supporting the interpretation that they are caused by circumstellar dust obscuration (Cody et al. 2014).

A unique way to study protoplanetary formation and evolution is to observe YSOs that exhibit significant large dimming events ($>$10% depth and months to years in duration) caused by a portion of the star's circumstellar disk. While these events are quite rare, they provide a powerful tool for studying the circumstellar environment of YSOs. Using high-cadence photometric observations from the Kilodegree Extremely Little Telescope (KELT, Pepper et al. 2007, 2012), we have been conducting the Disk Eclipse Search with KELT (DESK) survey to identify and characterize these rare systems (Rodriguez et al. 2016a). The DESK survey has discovered and analyzed previously unknown disk eclipsing events around the stars RW Aurigae (Rodriguez et al. 2013, 2016b), V409 Tau and AA Tau (Rodriguez et al. 2015), TYC 2505-672-1 (Rodriguez et al. 2016d), and DM Ori (Rodriguez et al. 2016c).

Interestingly, not all of these discoveries are YSOs. TYC 2505-672-1 is an evolved M giant being eclipsed every $\sim$69 years by a companion with a disk. This system is very similar to the archetype ϵ Aurigae, an F-giant being eclipsed every $\sim$27 years by a small star embedded in a circumstellar disk (Carroll et al. 1991). Interferometric observations by Georgia State University's Center for High Angular Resolution Astronomy (CHARA) during the last eclipse of ϵ Aur confirmed this interpretation by imaging the companion and disk crossing the star (Kloppenborg et al. 2010). These evolved systems still have remnant circumstellar material in their systems. Since these discoveries are all at different ages and stages of disk evolution, each system provides information about different stages of protoplanetary formation and evolution, which may in turn provide insight into the large diversity of exoplanetary systems.

In this paper, we present new photometric and spectroscopic observations for the Weak-lined T Tauri Star (WTTS) V1334 Tau. Here we find two dimming events of V1334 Tau, one that ended in late 2003 and another that began in 2009 and extends to the present date. The known characteristics of the V1334 Tau system are described in Section 2. The photometric observations are presented in Section 3. We present our estimate of the stellar parameters of V1334 Tau A in Section 4. We describe the spectroscopic analysis and the long-term photometric variability in Section 5, discuss possible dimming mechanisms in Section 6, and summarize our results in Section 7.

2. The V1334 Tau System

V1334 Tau was previously identified as a Weak-lined T Tauri Star (WTTS) with a K1 spectral type by Wichmann et al. (1996)

using observations from the *ROSAT* All-Sky-Survey (Zimmermann et al. 1993) combined with optical spectra. More recently, V1334 Tau was reclassified as a G2 star (Nguyen et al. 2012). Wichmann et al. (2000) determined that V1334 Tau has a radius of 2.73 $R_\odot$, a mass of 2.05 $M_\odot$, and an age of 3.83×10^6 year. V1334 Tau has a proper motion of $\mu_\alpha = 8.7 \pm 0.8$ and $\mu_\delta = -24.7 \pm 0.7$ mas yr^{-1}, which is in agreement with the known motion of the Taurus–Aurigae association ($\mu_\alpha = 7.2$ and $\mu_\delta = -20.9$, Bertout & Genova 2006). Using speckle observations, Kohler & Leinert (1998) identified a close companion to V1334 Tau (1.″631, $\Delta K = 3.42$). A near-IR high-spatial-resolution survey for low-mass companions in Taurus by (Daemgen et al. 2015) found two additional nearby companion candidates at 0.″106 with a $\Delta K = 1.68 \pm 0.05$ and 6.″969 with a $\Delta K = 12.5 \pm 0.3$.

3. Observations

Over the past decade multiple ground-based photometric surveys have observed V1334 Tau. None of the photometric observations resolve the fainter components in the system. All the follow-up photometry shown in Figure 1 is available in machine-readable form in the online journal.

3.1. KELT

With the primary goal of discovering transiting planets around bright host stars ($8 < V < 11$), the KELT project is a ground-based photometric survey covering $>$70% of the entire sky on a 10–20 minute cadence (Pepper et al. 2007, 2012). The project consists of two telescopes, KELT-North in Sonoita, AZ, and KELT-South in Sutherland, South Africa. Each telescope has a Mamiya 645-series wide-angle lens with a 42 mm aperture and a 80 mm focal length ($f/1.9$), and observes in a broad R-band filter. The telescopes have a $26° \times 26°$ field-of-view (FOV), and a 23″ pixel scale. V1334 Tau is located in KELT-North field 03 (field center at $\alpha = 3^h58^m12^s$, $\delta = 31°39'56.″16$). The KELT-North telescope observed V1334 Tau from UT 2006 October 26 to UT 2013 March 13, obtaining 9186 observations after processing. For a detailed description of the KELT data acquisition and reduction process, see Siverd et al. (2012). The median per-point error is 0.005 mag.

3.2. All-Sky Automated Survey for SuperNovae (ASAS-SN)

Designed to discover nearby supernovae, the All-Sky Automated Survey for SuperNovae (ASAS-SN) is photometrically monitoring the observable sky every two days down to $V \sim 17$ (Shappee et al. 2014). The survey has two sites, Cerro Tololo InterAmerican Observatory (CTIO) in Chile and Mount Haleakala in Hawaii. Each site is hosted by the Las Cumbres Observatory Global Telescope Network (Brown et al. 2013) and has two units with four 14 cm Nikon telephoto lenses and a 2K $\times$ 2K thinned CCD, with a 4.5 $\times$ 4.5 degree FOV and a 7.″8 pixel scale. V1334 Tau was observed 532 times from UT 2012 January 20 until UT 2016 October 14. The median per-point error is 0.004 mag.

3.3. SuperWASP

The Wide Angle Search for Planets (SuperWASP) is a high-cadence photometric survey designed to detect transiting exoplanets. Observing in a broad filter (centered at 550 nm), the survey has two observing locations, one at the Roque de los
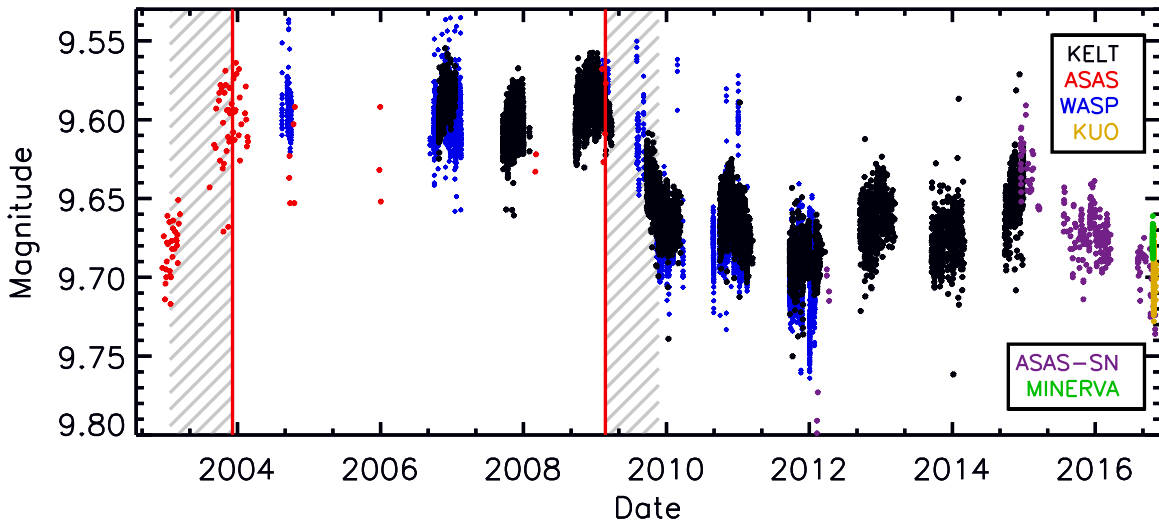
Figure 1. The KELT (black), ASAS (red), WASP (blue), ASAS-SN (purple), KUO (yellow), and MINERVA (green) photometric observations of V1334 Tau from 2002 until late 2016. Only the *V*-band observations from KUO and MINERVA are shown. The red vertical lines represent the estimated end of the pre-2004 events and the start of the 2009 event. The gray shaded region represents the estimated egress/ingress for each event described in Section 5. The intercalibration of the data sources is described in Section 5. The ASAS-SN, KELT, KUO, and MINERVA photometry shown in this figure is available as the data behind the figure. The data used to create this figure are available.

Muchachos Observatory on La Palma (WASP-North) and the other located at the South African Astronomical Observatory (WASP-South). With eight cameras at each location, each using a 200 mm $f/1.8$ lens and a 2048×2048 pixel CCD, SuperWASP is able to monitor large portions of the sky at a very high cadence (minutes). Each camera has a $7°.8 \times 7°.8$ FOV, and a $13″.7$ pixel scale. V1334 Tau was observed in two separate seasons in the publicly released observations: UT 2004 august 15 to UT 2004 September 30 and UT 2006 September 11 until UT 2007 February 15.[25] All observations from WASP prior to 2006 are unfiltered, and after 2006 the observations are in a broad *V*-band filter. A 3σ clipping around the median was performed to remove large outliers. V1334 Tau was also observed from UT 2009 February 08 until UT 2012 January 29. Since the data reduction of the public SuperWASP data was performed differently than the more recent WASP observations, so the two data sets were kept separate throughout the analysis described here. Additionally, we binned the second SuperWASP data set in 1 hr bins and calculated the standard deviation of each bin. All data points within bins which had a standard deviation greater than 2% were then discarded. After processing and cleaning, 14,339 observations remained and were used in this work. The median per-point error is 0.009 mag for the public observations and 0.003 mag for the recent observations.

3.4. All-Sky Automated Survey (ASAS)

Designed to discover and catalog variable stars over the entire sky, the All-Sky Automated Survey (ASAS) observes all stars brighter than $V = 14$. For a detailed description of the observing strategy and data reduction, see Pojmanski (1997). ASAS uses two locations, Las Campanas, Chile and Haleakala, Maui. Each location observed in the *V* and *I* bands simultaneously using two wide-field Minolta 200/2.8 APOG telephoto lenses with a $2K \times 2K$ Apogee CCD. Each telescope has a $8°.8 \times 8°.8$ FOV. ASAS observed V1334 Tau in the *V*-band from UT 2002

December 13 until UT 2009 February 25. 93 observations were obtained over this period. The median per-point error is 0.034 mag.

3.5. MINERVA

The MINERVA Project has four 0.7 m PlaneWave CDK-700 telescopes located on Mt. Hopkins, AZ, at the Fred L. Whipple Observatory, capable of both millimag photometry and precision radial velocity measurements (Swift et al. 2015). On the night of UT 2016 October 21, two telescopes simultaneously observed V1334 Tau using an Andor iKON-L 2048×2048 detector with a $20′.9 \times 20′.9$ FOV and a plate scale of $0″.6$ pixel^{-1}. One telescope observed in the V-band with 200 exposures and achieved a per-point rms scatter of 0.0009 mag. The other observed in the B band with 140 exposures and achieved a per-point rms scatter of 0.0015 mag.

3.6. Kutztown University Observatory (KUO)

Using the 0.61 m Ritchey–Chrétien optical telescope at the KUO in Kutztown, Pennsylvania, V1334 Tau was observed in the *B* and *V*-bands on UT 2016 October 26, UT 2016 November 05 and 07. The observing setup uses a 3072×2048 CCD that has a $19′.5 \times 13′.0$ FOV with a $0″.38$ pixel^{-1}. Standard aperture photometry was used, and the instrumental flux was color-corrected using several Landolt standard fields. In total, KUO obtained 160 *B*-band and 186 *V*-band observations. The median per point a per-point rms is 0.0007 mag in the *B*-band and 0.0006 *V*-band.

3.7. Spectroscopic Follow-up

We obtained spectroscopic observations of V1334 Tau with the Tillinghast Reflector Echelle Spectrograph (TRES) on the 1.5 m telescope at the Fred Lawrence Whipple Observatory, on Mount Hopkins, Arizona, USA from UT 2016 October to December. We obtained nineteen 10 minute exposures over the span of the two months, with fourteen observations occurring on UT 2016 December 09 and 10. The spectra were obtained at

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[25] http://exoplanetarchive.ipac.caltech.edu/

a resolution of $\lambda/\Delta\lambda \equiv R = 44000$ over the wavelength range of 3900–9100 Å. The spectra are consistent with a $\sim$5500 K dwarf and our estimate from Section 4, rotationally broadened by 77.6, km s^{-1}. We estimate the absolute radial velocity of the V1334 Tau system to be $\sim$19 km s^{-1} which is in agreement for the known absolute radial velocity of the Taurus–Auriga association (15 km s^{-1}, Bertout & Genova 2006). The TRES observations show no large ($>$1 km s^{-1}) radial velocity changes.

4. Determination of Stellar Parameters

In order to determine the stellar parameters of V1334 Tau, we use MINESweeper, a newly developed Bayesian approach to determining stellar parameters. A full description of MINESweeper is given in P. A. Cargile et al. (2017, in preparation); here we provide a brief summary of the method. MINESweeper uses nested importance sampling to determine posterior probability distributions for physical parameters inferred from stellar evolution models. MINESweeper uses a modified version of the nestle.py code[26] to perform multi-nested ellipsoid sampling based on the algorithm described in Feroz et al. (2009). Multi-nested sampling is uniquely suited to the problem of modeling parameters from stellar evolution models due to its ability to efficiently sample the multi-modal likelihood surfaces, frequently found when modeling stars with stellar isochrones. MINESweeper uses the most recent release of the MIST stellar evolution models (Choi et al. 2016), and an optimized interpolation schema based on the recommendations of Dotter et al. (2008). MINESweeper can use both photometric and spectroscopic measurements as well as a wide range of prior probability distributions. The MINESweeper inference results in posterior probability distributions for the fundamental MIST model parameters: equal evolutionary points (EEP), input stellar metallicity, and stellar age. Using these posterior distributions, MINESweeper then generates posterior distributions for any other stellar parameters predicted by the MIST models such as the mass, radius, T_{eff}, luminosity, and surface abundances.

We use MINESweeper to infer the physical properties (e.g., mass, radius, age, etc.) of V1334 Tau, as well as its distance and extinction (A_V). We modeled all the available broadband optical and IR photometry (see Table 1) except the *GALEX* UV and APASS photometry. We are hesitant to include the *GALEX* data due to the likely presence of chromospheric emission in such a young rapidly rotating star. The APASS data were not included due to our past experience with unaccounted for zero-point offsets seen in this survey's photometry (P. A. Cargile et al. 2017, in preparation). We applied a Gaussian distance prior centered at 140 pc with a FWHM of 40 pc (Torres et al. 2007, 2009), and a uniform age prior (0–50 Myr).

The spectral energy distribution (SED) for V1334 Tau does not have an infrared (IR) excess indicative of a circumstellar disk (see Figure 2), but there is an excess in the ultra-violet (UV) when compared to the MIST stellar SED model. In Figure 3, we show the posterior probability distributions for the age, mass, radius, distance, and A_V. Our inferred distance and age agrees with standard estimates for solar-type stars in the Taurus star-forming region, $\sim$130 ± 25 pc (Torres et al. 2007, 2009) and $\sim$1 Myr (Briceño et al. 2002; Luhman et al. 2003)—suggesting that V1334 Tau appears to be a bona

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[26] http://kbarbary.github.io/nestle/

fide member of this stellar association. Our models suggest that the mass of V1334 Tau is lower than that proposed by Wichmann et al. (2000) but within 1σ (see Table 2 for our determined stellar parameters).

5. Results

In this section, we examine the available photometry. We explore different interpretations for the long-duration dimming events observed in Section 7. All photometric observations displayed in Figure 1 are in the *V*-band (ASAS, ASAS-SN, KUO, and MINERVA) or a broader filter (KELT and WASP). To place all photometric data on the same scale, we use the KUO observations as the photometric standard and apply a vertical offset to each data set to align them where they overlap. We do not otherwise correct for the filter differences.

5.1. Out-of-dimming Variability

We searched for periodic variability in the high-cadence KELT data prior to and during the 2009 dimming using the Lomb–Scargle (LS) periodicity search algorithm (Lomb 1976; Scargle 1982) in the VARTOOLS analysis package (Hartman & Bakos 2016). For the each season of KELT data, we find a 0.3214 day period with an average peak-to-peak amplitude of $\sim$2% (see Figure 4). This periodic signal is clearly changing in amplitude and phase over the 9 years of observations. We find the same $\sim$0.32 day periodicity in every season except the 2008–2009 observing season where the source faded. Additionally, the targeted observations by MINERVA and KUO are consistent with this periodicity. There is no color evolution over the short duration of these targeted observations. During the 2009 dimming, the $\sim$0.32 day periodicity is recovered but at a lower signal-to-noise ratio. The periodicity is likely caused by processes near the star. If the 0.32 day periodicity is the rotation period of the star, then this would imply a rotational velocity of $\sim$347 ± 57 km s^{-1} for a stellar radius of $2.619^{+0.597}_{-0.304}$ $R_\odot$, compared to a break up period of 0.39 ± 0.13 days. Given our uncertainty in the stellar radius, V1334 Tau A could be rotating near break up velocity. We explore the possibility that V1334 Tau is a rapidly rotating star close to a pole-on orientation in Section 6. Another possibility is that the $\sim$0.32 day period is the orbital period of some circumstellar material that periodically obscures the star at a semimajor axis of $\sim$2.3$R_\star$.

However, the observed periodicity is persistent over the entire KELT data set, making it unlikely to be related to accretion processes. Additionally, if there is a significant amount of orbiting disk material right at the surface of the star, we would expect to see an IR excess in the SED analysis. The 14 spectra of V1334 Tau on UT 2016 December 09 and 10 show no significant large radial velocity variability ruling out the possibility of a close stellar binary. The orbital semi-amplitude from the TRES observations is 338 ± 56 m s^{-1}, when a photometric ephemeris with a period 0.3124 days is imposed. The velocity residuals from a circular orbit have an rms of 433 m s^{-1}. The rms of all the RV measurements is 1.3 km s^{-1}. Using our determined stellar mass of 1.67 $M_\odot$ and a period of 0.3214 days, we get an upper mass limit of a companion to be $<$2 M_J (rms = 433 m s^{-1}) or $<$6.2 M_J (rms = 1.3 km s^{-1}). The upcoming K2 campaign 13 observations of V1334 Tau should provide additional information on the nature of this short-period variability.

Table 1
Stellar Properties and Photometric Measurements of V1334 Tau Obtained from the Literature

Parameter	Description	Value	Source	Reference(s)
Names		V1334 Tau		
		HD 290380		
		TYC 1839-643-1		
		2MASS J04445445+2717454		
α_{J2000}	R.A.	04:44:54.454	Tycho-2	Høg et al. (2000)
δ_{J2000}	Decl.	+27:17:45.23	Tycho-2	Høg et al. (2000)
B_T	Tycho B_T magnitude	10.909 ± 0.061	Tycho-2	Høg et al. (2000)
V_T	Tycho V_T magnitude	9.895 ± 0.038	Tycho-2	Høg et al. (2000)
FUV	Far UV magnitudes	20.05	*GALEX*	Gómez de Castro et al. (2015)
NUV	Near UV magnitudes	15.63	*GALEX*	Gómez de Castro et al. (2015)
V	Johnson V	9.612 ± 0.04	APASS	Henden et al. (2016)
B	Johnson B	10.511 ± 0.063	APASS	Henden et al. (2016)
g'	Sloan g'	10.312 ± 0.045	APASS	Henden et al. (2016)
r'	Sloan r'	9.361 ± 0.06	APASS	Henden et al. (2016)
i'	Sloan i'	8.923 ± 0.05	APASS	Henden et al. (2016)
J	2MASS magnitude	7.734 ± 0.02	2MASS	Cutri et al. (2003)
H	2MASS magnitude	7.281 ± 0.04	2MASS	Cutri et al. (2003)
K_s	2MASS magnitude	7.154 ± 0.02	2MASS	Cutri et al. (2003)
WISE1	*WISE* passband	7.017 ± 0.033	*WISE*	Cutri et al. (2012)
WISE2	*WISE* passband	7.060 ± 0.018	*WISE*	Cutri et al. (2012)
WISE3	*WISE* passband	7.048 ± 0.018	*WISE*	Cutri et al. (2012)
WISE4	*WISE* passband	7.058 ± 0.108	*WISE*	Cutri et al. (2012)
μ_α	Proper Motion in R.A. (mas yr^{-1})	8.7 ± 0.8	NOMAD	Zacharias et al. (2004)
μ_δ	Proper Motion in Decl. (mas yr^{-1})	-24.7 ± 0.7	NOMAD	Zacharias et al. (2004)
RV	Systemic radial velocity (km s^{-1})	~19	this work	
U^*	Space motion (km s^{-1})	-12.1 ± 0.6		this work
V	Space motion (km s^{-1})	24.3 ± 1.6		this work
W	Space motion (km s^{-1})	16.2 ± 2.4		this work

Note. The photometry shown is used in Section 4 to determine the stellar parameters. U^* is positive in the direction of the Galactic Center. UVW analysis suggests a 98.4% chance of V1334 Tau being in the thin disk according to the classification system of Bensby et al. (2003). The UVW kinematics used the peculiar velocity of the Sun with respect local standard rest from Coşkunoğlu et al. (2011). The UVW analysis and distance from Section 4 are consistent with this being a member of the Taurus–Aurigae association.

5.2. Pre-2004 Dimming

In UT 2002 December, V1334 Tau was in its "minimum" state, at a $V \sim 9.7$ mag. The system took ~280 days to return to its quiescent brightness of ~9.6 mag. Unfortunately, there are no available photometric observations of V1334 Tau prior to UT 2002 December, so there is no constraint on the dimming duration. We only know that the dimming must be longer than the time between the start of the ASAS observations and the end of the observed brightening—i.e., greater than ~320 days.

5.3. 2009 Dimming

During late 2009 February, the V1334 Tau system began to fade from its median magnitude of $V \sim 9.59$ mag. We estimate that the ingress of the dimming takes ~273 days and that the event has a maximum depth of ~0.12 mag ($V \sim 9.71$, the maximum depth occurred during the 2012 and 2016 observing seasons). This ingress timescale is very similar to the estimated timescale to brighten in 2002–2003. The dimming lasts through the end of the data analyzed here on UT 2016 November 07,

leading to a lower limit on the dimming duration of >2802 days. If we assume that the two dimming events are similar, the time between events is >13 years. Multi-band observations from MINERVA and KUO show no $B - V$ color trend over the course of an ~6 hr observing night.

With the combined high-cadence observations from KELT and WASP during the 2009 dimming, we are able to study the photometric variability during the event. If this is indeed an occultation, the additional brightening and dimming events seen during the large dimming (on a similar timescale as the initial dimming) suggests that we are observing sub-structure in the occulting body. After the ingress, the system stays at a constant brightness of ~9.66 mag through the remainder of the 2009–2010 observing season and the first half of the 2010–2011 season. At JD ~ 2455502, V1334 Tau begins to dim again, down to a brightness of ~9.69 mag. At the start of the 2011–2012 observing season, V1334 Tau is near its minimum brightness of ~9.71 mag. Since the end of this additional dimming occurred during the 2011 seasonal observing gap, we can only place an upper limit of ~325 days
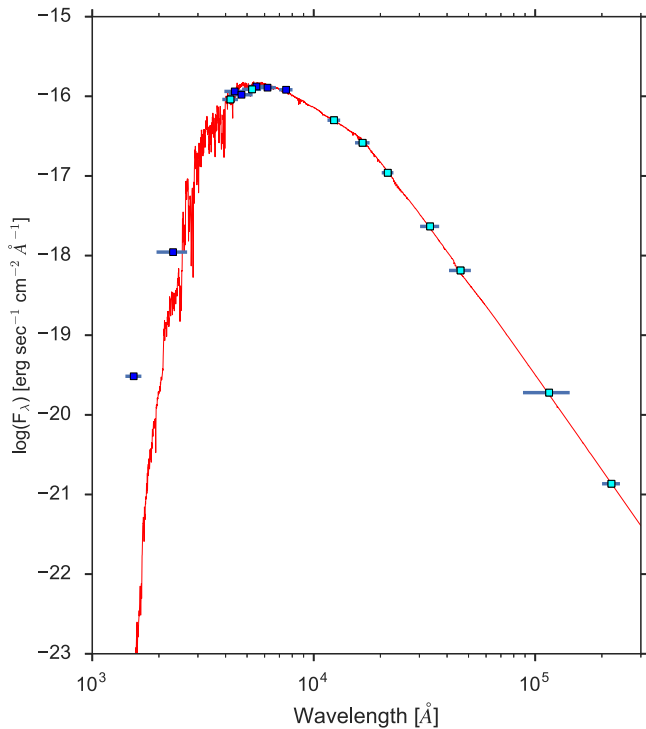
Figure 2. Spectral energy distribution of V1334 Tau along with a model using the most probable stellar parameters from our MINES*weeper* analysis. The light blue points show the Tycho-2 B_T, V_T, 2MASS J, H, K_s, and WISE 1–4 photometric observations included in the fit. The dark blue points are the *GALEX* and APASS photometry that were not used in the fit. The UV excess is likely due to chromospheric activity.

on its duration. After V1334 Tau brightens to ∼9.65 in 2012, it remains at a depth of ∼9.69 mag for the following season. Following the 2013/2014 season, V1334 Tau brightens over the course of the entire season from ∼9.69 mag to ∼9.64 mag. Following this peak in brightness, the following two seasons of ASAS-SN, KUO, and MINERVA data suggest that V1334 Tau faded back to the maximum depth of ∼9.71 mag. Interestingly, the timescales of these variations are similar to the estimated ingress timescale in 2009. However, our ability to draw any conclusions is limited by the seasonal observing gaps. We discuss the possibility that the observed structure of the dimming may be caused by a change in the opacity of the occulting feature in Section 7.

5.4. Spectroscopic Analysis

To check for photospheric features on the stellar disk, we derived line broadening profiles using a least-squares deconvolution (LSD) of the TRES spectra (following Zhou et al. 2016). Indentations and protrusions in the broadening profile map the presence of spots, faculae, and pulsation on the stellar surface. The broadening profiles show large-scale variations over the course of hours. Figure 5 shows the time series of the spectra gathered over 2016 December 09 and 10, phased to the 0.3214 day photometric modulation period (see Section 5.1). We find that the broadening profiles do not phase well with the photometric period, suggesting that there is no persistent spot crossing the star, and that the variability is possibly due to non-radial pulsations on the star. In addition, we find no evidence of line blending indicative of a binary stellar companion orbiting the primary star.

We also find a double-peaked Hα emission line, which may be an indication of an accretion disk (See Figure 5). The Hα feature has an equivalent width of ∼5 Å, which could be taken to mean that the star still possesses an inner accretion disk (Mohanty et al. 2005). The relatively high equivalent width also suggests that V1334 Tau should be reclassified as a Classical T Tauri Star (CTTS) (>3 Å, White & Basri 2003). Given our mass estimates, the peak Hα emission corresponds to a distance of >0.16 au from the star, assuming we are observing a Keplerian velocity for a possible inner disk. However, it is also possible that the Hα feature could be from cooler, neutral H I that is falling onto the star or disk winds. No other Balmer lines are found in emission, nor do we find other common accretion signatures, such as the He I 5876 Å and He I 6670 Å lines in emission. We see the Ca II H and K lines with core emission, and equivalent widths of 1.5 Å and 2.6 Å respectively, perhaps indicative of the strong chromospheric activity expected for T Tauri stars. Lithium absorption at 6708 Å is also present, with an equivalent width of 0.25 Å, consistent with the absence of depletion expected for a solar-type star with an age of 2 Myr (Soderblom et al. 1993). The sodium Na I D feature has a depth and width consistent with a stellar absorption line, along with a superimposed narrow feature due to the interstellar medium. Unlike RW Aur (Facchini et al. 2016), we do not see a time varying P Cygni profile in the Na lines, which would suggest the existence of a strong disk wind. However, we do not have a spectroscopic observation of V1334 Tau prior to the large dimming, limiting our interpretation.

6. Interpretation and Discussion

With only two incompletely sampled dimming events, we are unable to determine whether this phenomenon is periodic in nature. However, the egress/ingress timescales from each event are consistent. In similar systems with dimming events, such as V409 Tau and DM Ori, the dimmings are believed to be periodic (Rodriguez et al. 2015, 2016c). In this section we explore the possibility that the dimmings of V1334 Tau are caused by an orbiting body (e.g., a disk warp or dust trap), enhanced disk winds, hydrodynamical fluctuations of the inner disk, or a significant increase in the magnetic field flux at the surface of the star.

6.1. Occultation by Orbiting Body

To determine the key properties of the occulting feature, we model the observed dimmings as an occultation of the host star by a large body in Keplerian motion. The leading edge of the occulting body can be perpendicular to its direction of motion ($\theta = 90$, sharp edge) or can be inclined ("wedge-shaped," see Figure 9 from Rodriguez et al. 2015). The estimated ingress time of the 2009 dimming, where we have the best photometric coverage, is ∼273 days. The ingress timescale gives us an estimate of the occulting body's transverse velocity, $V_T \sim 2R_\star/(T_{\mathrm{ingress}} \sin\theta)$. For $R_\star = 2.62\,R_\odot$, we get a minimum velocity of ∼155.1 m s^{-1}. The full duration of the 2009 dimming is >2803 days. Using our estimated transverse velocity and the duration timescale, we estimate that the occulting body must be >0.25 au in width. If we assume that the occulting body is in Keplerian motion, the ingress timescale also provides an estimate of the orbital semimajor axis (see Equation (1) from Rodriguez et al. 2016c). However, using
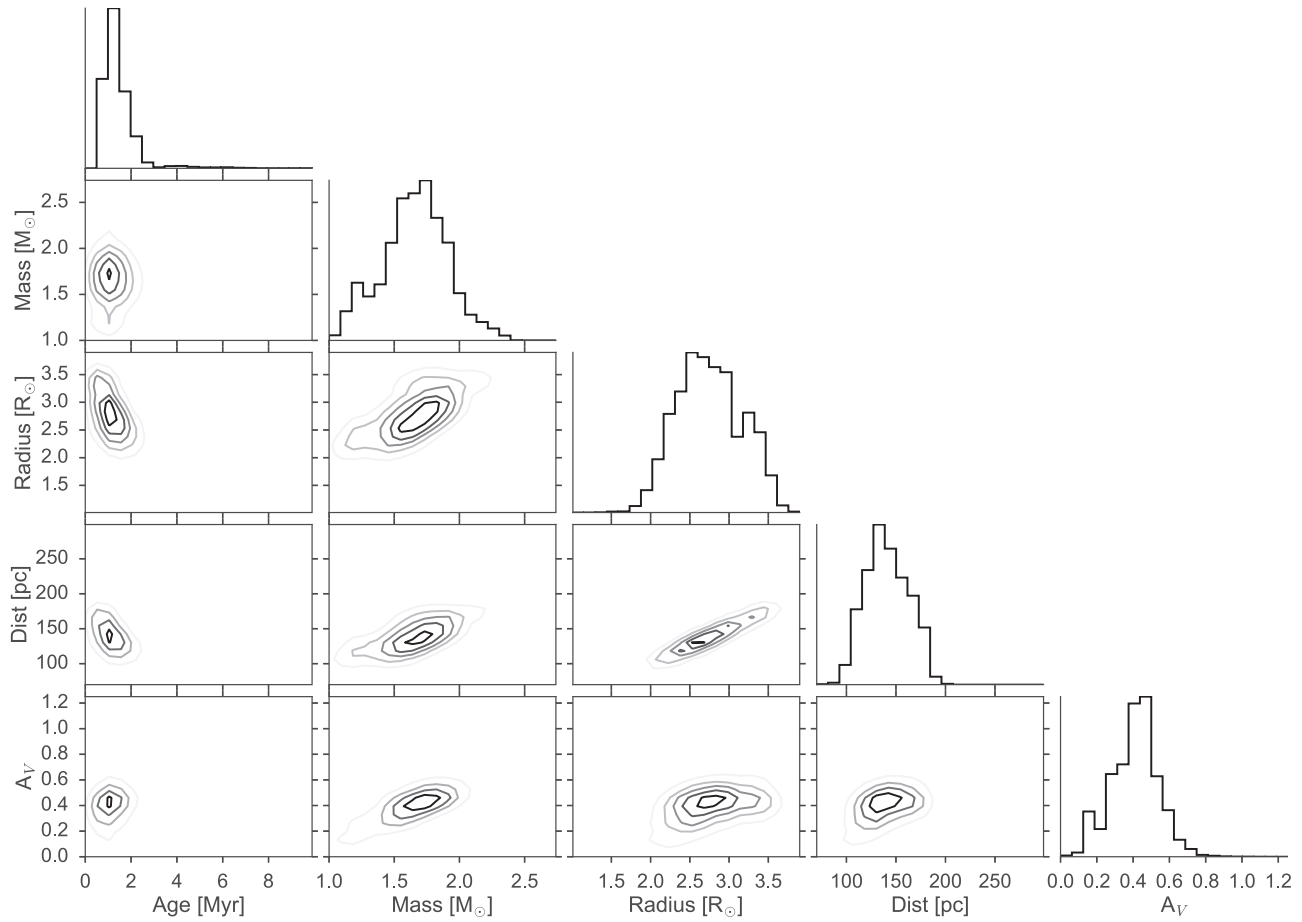
Figure 3. Posterior probability distributions of the stellar parameters for V1334 Tau based on our MINES*weeper* analysis. The parameters in Table 2 are the maximum posterior probabilities of these posteriors along with their 68% confidence intervals.

Table 2
Determined Stellar Parameters for V1334 Tau A and
68% Confidence Interval Values

Parameter	Description	Determined Value
Age	Stellar Age	1^{+1}_{-1} Myr
$M_\star$	Stellar Mass	$1.674^{+0.229}_{-0.279}$ $M_\odot$
$R_\star$	Stellar Radius	$2.619^{+0.597}_{-0.304}$ $R_\odot$
$\log(L_\star)$	Log Stellar Luminosity	$0.658^{+0.103}_{-0.214}$ $L_\odot$
$T_{\rm eff}$	Effective Temperature	5015^{+93}_{-154} K
$\log(g)$	Surface Gravity	$3.767^{+0.114}_{-0.085}$ cgs
[Fe/H]$_{\rm initial}$	Metallicity at formation	$-0.116^{+0.081}_{-0.164}$
[Fe/H]$_{\rm surface}$	Surface Metallicty	$-0.077^{+0.083}_{-0.171}$
Distance	...	132^{+32}_{-14} pc
A_v	Extinction	$0.438^{+0.092}_{-0.160}$ mag

these estimated parameters, the occulting body would be unrealistically far from the host star (at ~62,000 au), ruling this interpretation out.

Unfortunately, there is no measurement of the size of the circumstellar disk around V1334 Tau A. We know from Kohler & Leinert (1998) and Daemgen et al. (2015) that there are two nearby companions to V1334 Tau A: V1334 Tau B (1″631) and C (0″106). Therefore, we can constrain the occulting feature to be within the projected separation of the B component, 1″631 (215 au for $d = 132$ pc). Assuming the occulting feature is at the projected separation of V1334 Tau B,

it would require a transverse velocity of ~2.6 km s^{-1} and be ~4.2 au in width. Also, constraining the occulter to 219 au would suggest a wedge-angle of <3°4. From our analysis of the TRES spectra, we estimate that the peak emission of the double-peaked Hα emission corresponds to a distance of >0.16 au. Assuming the occulting feature is associated with an inner disk and at a semimajor axis of 0.16 au would imply that it is moving at ~98 km s^{-1} and have a leading edge angle of 0°06. In this scenario, the duration of the occultation requires multiple orbits (≳160) of the same material across our line-of-sight to cause the dimming event that began in 2009. This could be explained if the entire inner disk has precessed into our line-of-sight, but this does not seem plausible. We can also place the occulting body at the distance of the C component (14 au for $d = 132$ pc). This would suggest a transverse velocity of ~10.3 km s^{-1}, a ~16.7 au wide occulter, and a leading edge angle of 0°86. The width would be ~19% of the entire orbit at 14 au, assuming Keplerian motion. At 14 au, an orbital period would be ~40 years. It is possible that the close-in nearby companion is associated with the observed dimming events.

Fortunately, we observed two separate dimmings, one pre-2004 and one beginning in 2009. Since the egress from the pre-2004 dimming and the ingress of the 2009 dimming are similar in duration, it is plausible that we are seeing a periodic occultation with a period of >13 years. For a stellar mass of 1.67 $M_\odot$, this period would suggest that the occulting feature is located ≳6.6 au from the host star. Using the same wedge-
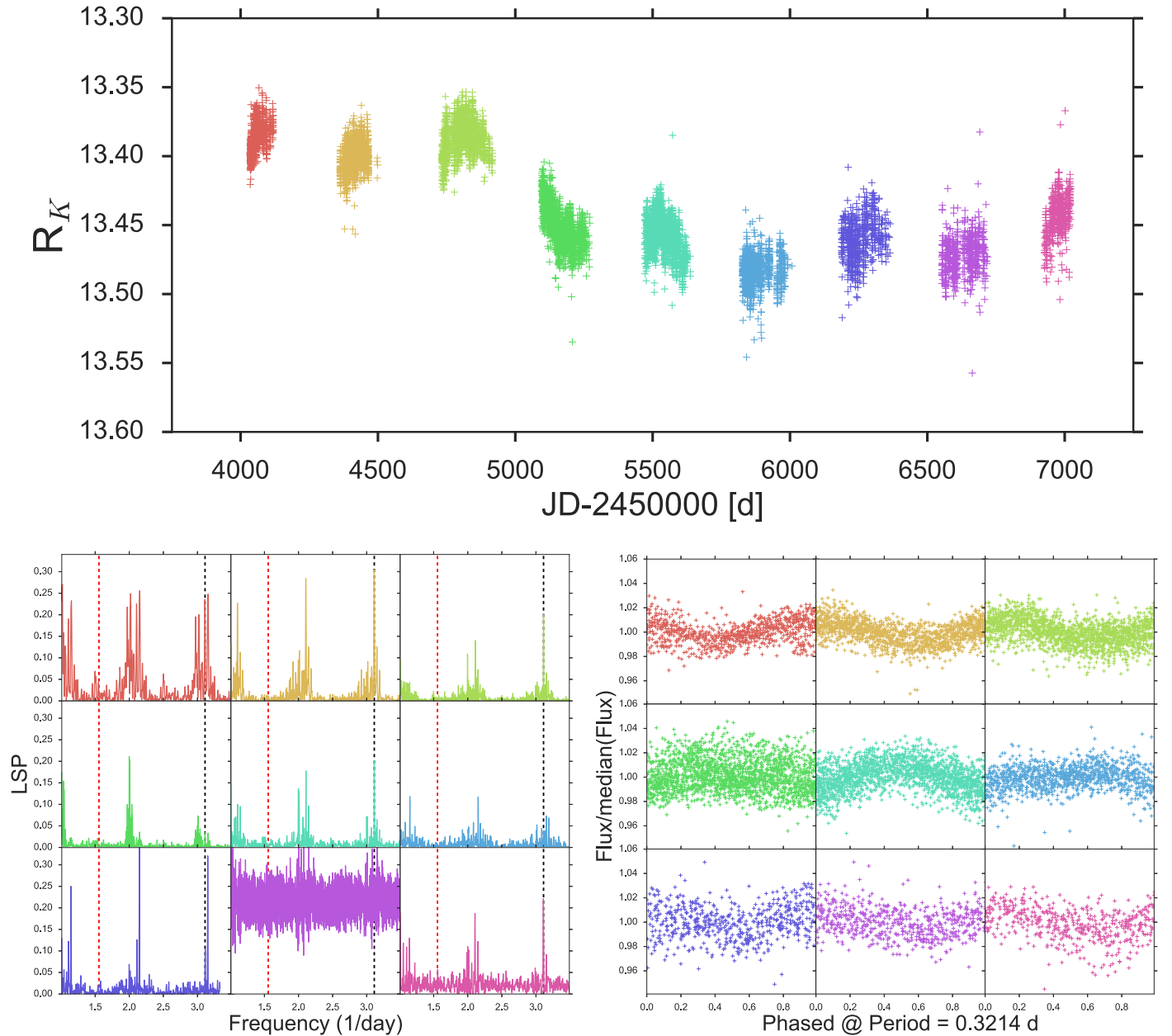
Figure 4. (Top) The 9 year light curve of V1334 Tau color coded by observing season. (Bottom left) The LS periodograms for each KELT season. The vertical lines correspond to the 0.32 day period estimate (black) and twice that period (red). (Bottom right) Each season of KELT data phase-folded to the 0.32 day period. Note that the phase and amplitude of the 0.32 day signal is changing over the nine observing seasons from KELT.

shaped model, the leading edge of the occulting body would have a highly inclined leading edge angle of $\sim0°6$, almost parallel to its direction of motion. This would also suggest that the occulter is moving at $\sim15\,\mathrm{km\,s^{-1}}$ and be $\geqslant24$ au in width, which is >59% of the entire orbit.

Observations from the Atacama Large Millimeter/submillimeter Array (ALMA) and the *Hubble Space Telescope* (*HST*) have shown that transitional disks can have large asymmetries (Pérez et al. 2014; Stark et al. 2014). Specifically, *HST* observations of MP Mus have shown that the eastern side of its disk is three times brighter than its western side (Schneider et al. 2014). The young star Oph IRS 48 has a large asymmetric dust structure that extends across almost one third of the entire disk ring (van der Marel et al. 2013). Therefore, if V1334 Tau has an edge-on, asymmetric disk, the large dimming could be caused by a dust trap in the disk crossing our line-of-sight,

leading to a periodic dimming. Future millimeter mapping of the V1334 Tau system should determine the plausibility of this interpretation. However, no detectable IR excess out to 20 μm would suggest a very low mass, nearly transparent circumstellar disk, making this interpretation unlikely.

6.2. Inner Disk Obscuration

An alternate explanation for the UXor phenomena is hydrodynamical fluctuations of the inner disk rim. Dullemond et al. (2003) determined that the inner disk rim would have a scale height of $\sim0.2\,R_{\mathrm{rim}}$ and fluctuate by $\pm\sim0.1\,R_{\mathrm{rim}}$. Using 0.16 au as an estimate of the inner disk radius, this would suggest a maximum fluctuation of the inner rim height to be ~0.048 au. In addition to the hydrodynamical fluctuation, the inner disk of a YSO can be warped and perturbed by a
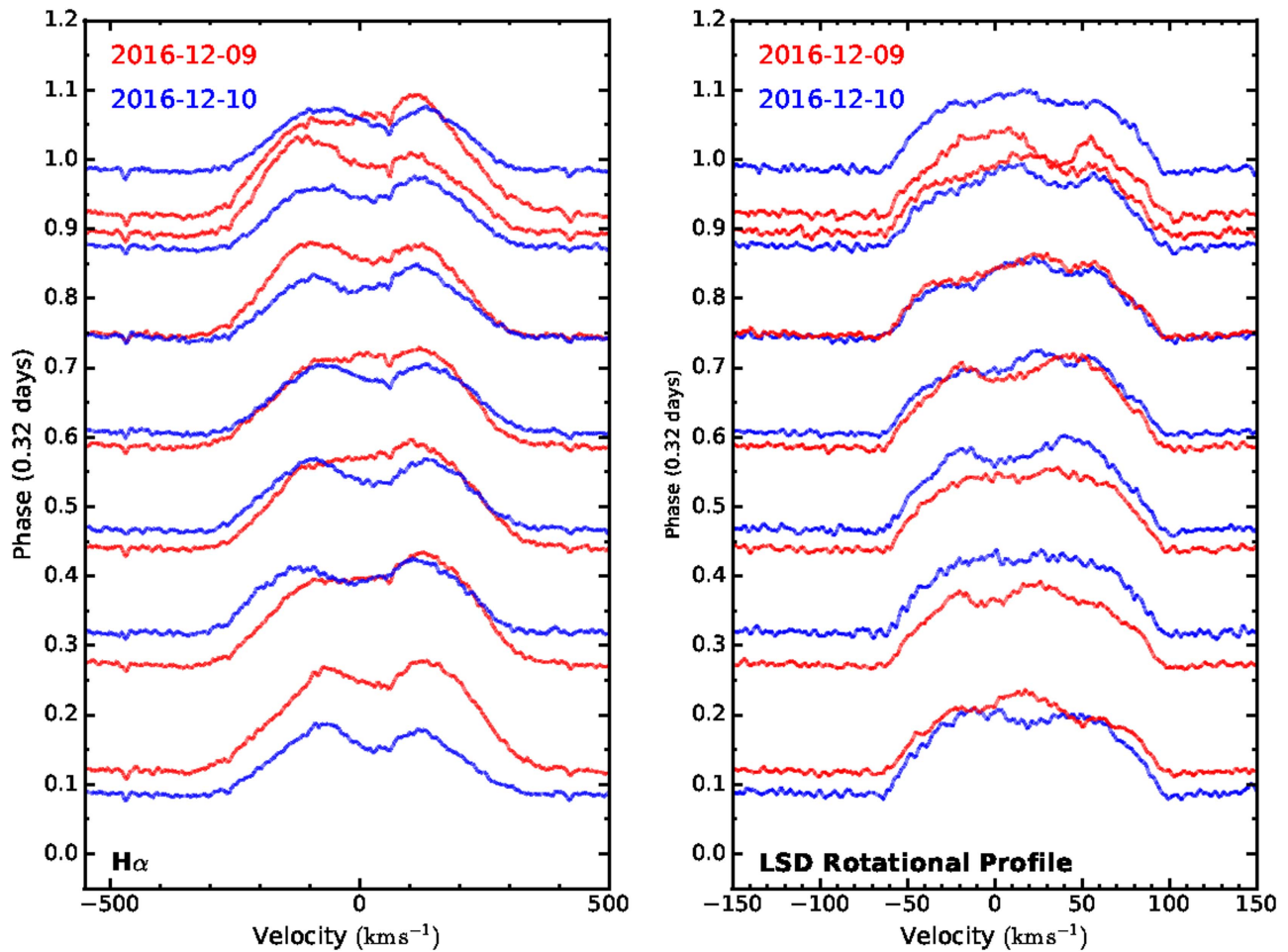
Figure 5. The Hα spectral line profiles of V1334 Tau show dramatic variations over the course of hours. Left: the double-peaked Hα line profile for the TRES observations on UT 2016 December 09 (Red) and 10 (Blue) phased to the 0.32 day photometric modulation period (see Section 5.1). Note that the line profile changes significantly over the span of the observations. Right: rotational broadening profiles derived from each TRES spectrum, derived via a least-squares deconvolution process and again phased to the 0.32 day period.

misaligned close companion (Facchini et al. 2013, 2014). Without a constraint on the inner disk inclination, we are unable to test the feasibility of this interpretation. However, this scenario has been proposed as the cause of the observed dimming events of RW Aur (Facchini et al. 2016).

In any case, the variability during the dimming suggests an opacity change in the occulting feature. Another interpretation for the extended dimming is that a screen of hot dust can be created in the inner disk and pushed across our line-of-sight by high disk winds (Petrov et al. 2015). However, we find no evidence for high or enhanced disk winds in the TRES spectra, making this scenario unlikely. Future millimeter mapping of the disk around V1334 Tau and radial velocity monitoring for a short-period companion will better constrain these scenarios.

6.3. Increased Magnetic Field Flux

Another possible explanation of the dimming events seen in V1334 Tau is they are a result of significant increase in the magnetic field flux at the surface of the star. According to the MIST stellar evolution models, the interior structure of V1334 Tau is predicted to be fully convective. Current magneto-hydrodynamic stellar structure models of fully convective dwarfs suggest that these stars are able to support stable (>1000 days), large-scale dipolar fields (>1 kilogauss) despite

rotating rapidly, resulting in the formation of large groupings of dark polar starspots blanketing a significant fraction of the stellar photosphere (Yadav et al. 2015). The formation of long-lived polar spots may result in multi-year dimming events similar to the ones seen here, particularly if we are viewing this star nearly pole-on. The high amount of Hα emission and the excess NUV and FUV *GALEX* flux observed in the star's SED suggest that V1334 Tau is magnetically active. Future observations should clarify if the dimming we observe is connected to magnetic activity. This includes stellar color information in and out of dimming events, mapping the stellar magnetic fields using Zeeman–Doppler imaging, and modeling the upcoming K2 high-precision light curves.

6.4. Similar Systems

There are only a dozen or so objects known to show this type of phenomenon. The duration of the V1334 Tau dimming events strongly resembles the long-term dimming of the archetype AA Tau (Bouvier et al. 2013). Although similar in duration, the dimming event in AA Tau shows a much larger depth of ~2 mag. Other systems like V409 Tau, DM Ori, and RW Aur have shown similar dimmings (again at much larger depths), and are interpreted as either a periodically obscuring feature in the circumstellar disk, high disk winds, or inner disk

instabilities (Rodriguez et al. 2013, 2015, 2016b, 2016c; Petrov et al. 2015; Facchini et al. 2016). It is possible that the dimming mechanisms for all these systems are related.

7. Summary and Conclusions

The complex circumstellar environment of YSOs can directly influence planetary formation and architecture. Unfortunately, it is not clear how each process or feature of a circumstellar disk (accretion, winds, warps, and companions) affects the planet forming process. From studying these processes for a large sample of YSOs at different ages, we may gain insight into the role each feature has on planet formation.

Here, we have discovered two dimming events in the WLTS V1334 Tau. The first fading occurred prior to 2004, where we observe a ∼0.1 mag dimming over ∼300 days. The second event started in 2009 and is yet to end. The photometric observations show a coherent dimming of ∼0.12 mag, an ingress dimming timescale of ∼273 days, and a duration of >2803 days. From applying a simple model where the dimming is caused by an occultation of V1334 Tau A by a large semi-opaque body that has an inclined leading edge, we determined that the occulting body would have to be moving at ∼14.2 km s^{-1}, have a semimajor axis of ∼6.56 au, and be ∼24.3 au in width. Assuming a circular orbit, this would suggest that the occulting feature is quite large, as the width is ∼59% of its entire orbit. This could be explained by an asymmetric disk or dust trap occulting the star in a nearly edge-on orientated disk. Although we see no IR excess, the double-peaked Hα line seen in the TRES spectra suggests the presence of orbiting material. It is possible that the occulting body may be a warp or perturbation in the surrounding disk, but this would require a close to edge-on geometry. It is possible that we are seeing a fluctuation in the inner disk structure or that winds have pushed material from the disk plane across our line-of-sight (Natta & Whitney 2000; Nelson et al. 2000; Petrov et al. 2015). However, we find no evidence for high disk winds in our TRES spectra. We also find a ∼0.32 day periodicity in the KELT photometry that persists through the 2009 dimming. The specific cause of this periodicity is unclear but it is consistent with orbiting material only a few stellar radii from the star.

Understanding the observed extended dimmings of V1334 Tau over the past ∼15 years requires the continued photometric monitoring of the system. As a start, V1334 Tau will be observed in the upcoming K2 campaign 13 (spring 2017). Simultaneous multi-band photometric and spectroscopic observations leading up to and coinciding with the K2 observations may provide new information to distinguish between potential dimming mechanisms. Future millimeter mapping of the V1334 Tau system should detect and measure the inclination of the possible circumstellar disk. Since V1334 Tau is a visual binary, millimeter mapping may also show evidence of a stellar encounter, similar to what has been seen in RW Aur (Cabrit et al. 2006). Upcoming large surveys like the *Transiting Exoplanet Survey Satellite* (Ricker et al. 2015), the Large Synoptic Survey Telescope (LSST Science Collaboration et al. 2009), and the PLAnetary Transits and Oscillations of stars (PLATO, Catala et al. 2010) mission should increase our sample of these unique systems, allowing us to statistically address the variety in the depth and timescales of these dimming events.

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