The Peculiar Periodic YSO WL 4 in ρ Ophiuchus

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Abstract. We present the discovery of 130.87 day periodic near-infrared flux variability for the Class II T Tauri star WL 4 (= 2MASS J16271848-2429059, ISO-Oph 128). Our data are from the 2MASS Calibration Point Source Working Database, and constitute 1580 observations in J, H and K_s of a field in ρ Ophiuchus used to calibrate the 2MASS All-Sky Survey. We identify a light curve for WL 4 with eclipse amplitudes of $\sim$0.4 mag lasting more than one-quarter the period, and color variations in J-H and H-K_s of $\sim$0.1 mag. The long period cannot be explained by stellar rotation. We propose that WL 4 is a triple YSO system, with an inner binary orbital period of 130.87 days. We posulate that we are observing each component of the inner binary alternately being eclipsed by a circum-binary disk with respect to our line of sight. This system will be useful in investigating terrestrial zone YSO disk properties and dynamics at $\sim$1 Myr.

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INTRODUCTION

ρ Ophiuchus (ρ Oph) is a $\sim$135 pc star-forming region containing several hundred $\sim$1 Myr YSOs [3, 7]. Photometric variability is a common property of YSOs, and several large-sky and targeted variability studies of YSOs have been undertaken in the near-infrared [e.g., 1, 4]. With the Two Micron All-Sky Survey (2MASS) Calibration Point Source Working Database [Cal-PSWDB, 12], we are carrying out a program to study the near-IR variability of YSOs in ρ Oph as a probe of stellar and circumstellar disk evolution.

WL 4 is a previously unremarkable $\sim$1 Myr Class II T Tauri star in ρ Oph. We present the discovery of long-term periodic variability that we attribute to eclipses by a circum-binary disk around WL 4.

OBSERVATIONS

2MASS imaged the entire sky in three near infrared bands between 1997 and 2001. Photometric calibration for 2MASS was accomplished using hourly observations of 35 selected calibration fields. The calibration fields were observed and reduced with the same strategy used for the main survey. One of these fields in ρ Oph covers a region 8.5′ wide in R.A. by 60′ long in dec. In 3 $\sim$6 month visibility windows spanning 901 days, 1582 independent scans were made of the field in ρ Oph, including 1580 detections of WL 4.

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ANALYSIS AND RESULTS

For WL 4, periodic variability is apparent in the unphased data, alternating between bright and faint states. We identify a period of 130.87±0.40 days using both the Lomb-Scargle periodogram and the period-searching algorithm of Plavchan et al. [9]. The phased light curve is shown in Figure 1a. For JD=2450000.0, the corresponding phase in Figure 1a is 0.33. While a ∼65 day period is consistent with the 2MASS results, our best physical model for the system requires that this is an alias of the true period. The period is too long to be associated with a ∼1 Myr YSO stellar rotation period [11].

MODEL

The long period of the near-infrared variability necessitates a binary companion, and the SED indicates the presence a primordial disk (Figure 1b). We denote the binary components WL 4a and WL4b, and the companion resolved in Ratzka et al. [10] as WL 4c. All three components are unresolved with 2MASS and *Spitzer*. The observed IRAC variability implies a circum-binary disk around WL 4ab, but part of the infrared excess could be associated with a disk around WL 4c. To explain the shape of the light curve, we postulate that a component of the WL 4ab binary goes into obscuration and re-emerges from behind a circum-binary disk every 65.44 days. The binary must be inclined with respect to the disk, and the disk relatively close to edge-on with respect to our line of sight.

We can solve for the brightnesses of the three components using the total stellar luminosity derived from the SED fit, the magnitude depth of the faint state from one component being obscured, and the flux ratio observed during a predicted bright state in Ratzka et al. [10]. We find that WL 4 is comprised of three approximately equal brightness 0.6 $L_\odot$ YSOs. The symmetry between the brightnesses of WL 4a and WL 4b implies that the binary period is 130.87 and not 65.44 days. Our model predicts that WL 4a and WL 4b alternate being obscured by the circum-binary disk. The estimated stellar masses (0.40 $M_\odot$) imply a binary separation of 0.47 AU, or ∼50 stellar radii (2.0 $R_\odot$).

DISCUSSION

We list supporting evidence for our model:

- Dust luminosities and temperatures are sufficient to justify the shadowing model.
- Variability is detected from 1–8 μm.
- Lack of a significant component of hot ∼1000 K dust.
- Lack of strong accretion signatures in Natta et al. [8].
- Duration of faint state is too long to be produced by a stable circum-primary disk eclipse.
- Similarities to KH-15D [14, 6].

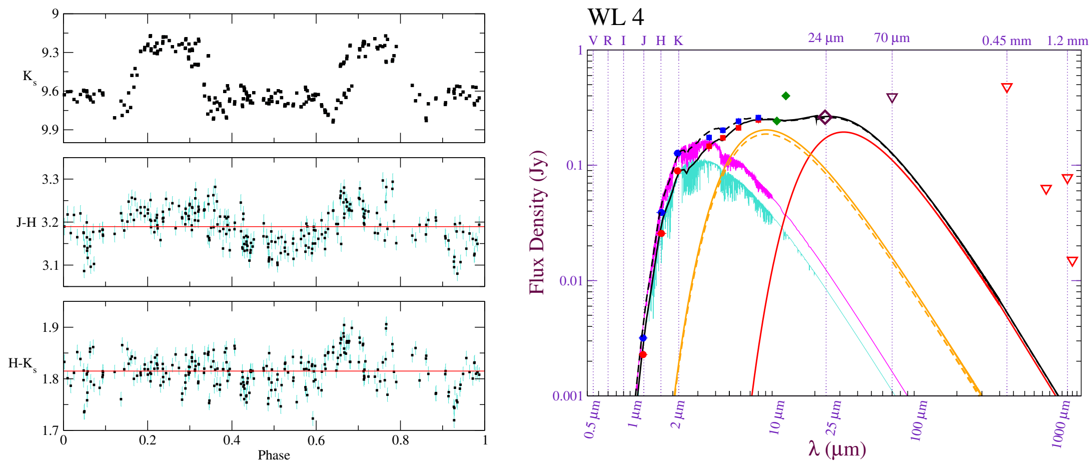

FIGURE 1. (a) Left: Top Panel - K_s band Cal-PSWDB light curve data in black for WL 4. Middle Panel: J-H Cal-PSWDB color curve. Bottom Panel: H-K_s Cal-PSWDB color curve. Data are folded to a period of 130.87 days, and plotted as a function of period phase. Each group of six scans from a single hourly calibration observation are co-added, and 1-σ error bars are shown in teal. (b) Right: Spectral Energy Distribution for WL 4. DATA: Red circles - 2MASS flux densities in the faint state; blue circles - 2MASS flux densities in the bright state; red squares - c2d IRAC flux densities in the faint state; blue squares - c2d IRAC flux densities in the bright state; green diamonds - 10.8 and 12.5μm measurements [3]; purple diamond - c2d MIPS 24 μm flux density; purple triangle - c2d MIPS 70 μm flux density upper limit; red triangles - sub-mm flux density upper limits [2, 13]. MODEL: solid red line - cold dust component; solid orange line - hot dust component in the faint state; dashed orange line - hot dust component in the bright state; cyan line - reddened synthetic spectra for the two WL 4 components un-obscured in the faint state; magenta line - reddened synthetic spectra for the three WL 4 components un-obscured in the bright state; black solid line - sum of stellar components, hot dust and cold dust spectra in faint state; black dashed line - sum of stellar components, hot dust and cold dust spectra in bright state.

The change in the hot dust luminosity indicates possible dynamical interaction or disk "warping," or simply changing illumination/heating. The transition between bright and faint states, including the "kinks" in the light curve at phases of 0.14, 0.36, 0.63 and 0.86, last ~13 days apiece. We speculate that the "kinks" could be due to disk substructure such as a puffed up or over-dense inner edge. The hot dust temperature is consistent with the stable inner orbital radius of ~2–3 times the binary semi-major axis [5].

CONCLUSIONS

We have identified periodic variability for the YSO WL 4 in ρ Oph that is likely due to alternating eclipses of two different components of a binary system by a circum-binary disk. WL 4 is a unique and valuable probe of YSO terrestrial zone disk evolution.

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