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V471 TAURI LIGHT CURVES AND SPOT MODELLING

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ABSTRACT

Reduced photoelectric photometry on V471 Tau was recovered from the 1976-1979 observing seasons. The data were used to create light curves of the eclipsing red dwarf plus white dwarf binary. A binary star program was used to model dark spots and calculate times of minima via differential corrections of parameters. Dark spots on the active red dwarf were required for all light curves modeled while subsequent data in the same observing season hint at spot evolution. The $O-C$ values from times of minima loosely follow the trend expected due to the light-travel time of a third body. The large errors in the timings may be due to the paucity of data during eclipses and ellipsoidal as well as spot distortions of the red dwarf outside eclipses.

Subject headings: binaries – binaries: close – individual stars: V471 Tau

1. INTRODUCTION

V471 Tauri (BD +16°516) is a detached eclipsing binary comprised of a tidally distorted, rapidly rotating ($P_{\rm rot} = P_{\rm orb}$) K2V red dwarf and a white dwarf in a circular 12.5 h orbit (Nelson & Young 1970). The system also has a distant brown dwarf companion discovered by means of a light-time effect in eclipse timings (Guinan & Ribas 2001; Ibanoglu et al. 2005).

The primary focus of this research was to analyze data that was collected in the 1970's that largely hasn't been examined until now. Many studies of this system have indicated period changes seen in the eclipse timings. With some eclipse photometry obtained in UBV, the changes in times of minima ($O-C$) could be corroborated.

Dark (i.e. cool) spot evolution on the red dwarf has been another studied aspect of V471 Tau. The best-fitting models tend to require dark spots to fit the observed light curves. These fits are essential for many kinds of studies, such as the connection between magnetic photospheric/chromospheric activities, solar-like cycles, and disentangling these activities from possible fluorescence caused by the white dwarf's far-ultraviolet radiation (Vaccaro & Wilson 2002). Most of the obtained light curves were best fit with two dark spots.

By solving for the HJD0's (Heliocentric Julian Date at time of minimum or T(min I)) and fitting light curves with dark spots, $O-C$'s were determined. Although on some nights there were not enough data around the eclipse area, the T(min I) could be obtained but with large errors. Plots for the most complete data sets are shown, including the best-fitting curve assuming a third-body perturbation (Guinan & Ribas 2001).

2. PARAMETERS

For spot modeling and eclipse fits, the parameters shown in Table 1 were used. The chosen ephemeris for the eclipsing pair was (Guinan & Ribas 2001):

$$T(min\ I) = HJED\ 2,440,610.06406 + 0.521183398E. \quad (1)$$

Other parameters such as temperatures, mass ratio, log g, and sizes were assumed (O'Brien et al. 2001; Vaccaro & Wilson 2002). A solar metallicity was assumed. The orbital eccentricity was assumed to be zero since the orbit is circular. These parameters were fixed so that the differential corrections (DC) routine (Wilson & Devinney 1971; Wilson 1979, 1990) in the binary star program PHOEBE, version 0.27 (Prsa & Zwitter 2005) was then simultaneously applied to the light curve data and velocities of O'Brien et al. (2001) to adjust gamma velocity, separation, and inclination while maintaining the stellar sizes. The end result, based on the assumptions above, was a consistent and fixed set of physical and orbital parameters, which then allowed for straight forward determinations of times of minimum and spot parameters.

TABLE 1
PARAMETERS USED IN PHOEBE

Parameter	Value
Model	Detached binary
HJD0	2440610.06406
Period	0.521183398
Primary Radius	0.010
Secondary Radius	.950
Semimajor Axis	3.29496
Mass Ratio	1.10714
Inclination	77.50000
Gamma Velocity	45.03400
Primary Temperature	32400
Secondary Temperature	5000
Primary Potential	308.79944
Secondary Potential	4.85000
Primary log g	8.30000
Secondary log g	4.45000
Primary Metallicity	0.00000
Secondary Metallicity	0.00000
Orbital Eccentricity	0.00000
Primary Synchronicity	1.00000
Secondary Synchronicity	1.00000
Primary Star Albedo	1.00000
Secondary Star Albedo	0.60000
Primary Gravity Brightening	1.00000
Secondary Gravity Brightening	0.30000

3. ANALYSIS

Data input was a big part of the work. The source for the light curves was approximately 30 nights of single-channel

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TABLE 2
MODELED SPOTS FOR THE NIGHTS BETWEEN 1976 AND 1979.

Date (UT)	Lat[a]	Long	Rad	Temp
10/02/76	0.5	3.0	0.9	0.8
	0.8	5.6	0.8	0.7
11/20/76	0.65	2.7	0.65	0.8
	0.3	0.7	0.9	0.7
12/01/76	0.9	0.47	0.42	0.8
	0.5	2.4	0.57	0.8
12/08/77	0.275	1.75	0.72	0.8
	0.3	4.5	0.398	0.8
10/30/79	0.3	3.31	0.67	0.75
	0.7854	5.7	0.24	0.76
11/18/79	0.3	3.2	0.4	0.75
	0.7854	5.7	0.24	0.76
12/19/79	0.7854	3.7	0.4	0.8
	0.6	0.7	0.39	0.8

[a]Parameters latitute, longitude and radius are in radians

photometric data obtained between 1976 through 1979 at Lowell and Perkins observatories (Oswalt 1978 1979). The photometry had been previously reduced by a FORTRAN program called DIFFPHOT (Oswalt, private communication). The fundamental arithmetic task for this program is to compute

$$\Delta m' = 2.5 \log \left(\frac{object - sky}{comparison - sky} \right) \qquad (2)$$

where $\Delta m'$ is the differential magnitude estimate for the time the variable star was observed, and *object*, *comparison*, and *sky* are their corresponding photoelectric counts. The comparison star for the observations was BD +17°638 (= HD 24040).

DIFFPHOT also converted UT times to HJD, which were confirmed accurate to 1 second via IRAF. UT was accurate to 1 second as well (Oswalt, private communication). Johnson and Strömgren UBV/uby measurements (corrected for extinction) were chosen from the outputs of this program. To be more specific, HJD and $\Delta m'$ (also called $V - C$ or Variable minus Comparison) were the only sets of numbers needed.

The use of PHOEBE was the next step. Data for each night were treated separately. In this program, all of the parameters shown in Table 1 were fixed and plots of synthetic and experimental light curves in each band were compared. Luminosity for the primary star was scaled to fit the light-curve data.

3.1. *Dark spots*

Dark-spot modeling was essential for light-curve fitting. Unfortunately, some data couldn't be used because of poor sampling or weather effects. For the nights that spot modeling was possible, two dark spots were simulated in each light curve. The modeled spots are shown in Table 2.

The differential correction routine adjusted some of these parameters. Although these light curves seem to fit nicely, it is important to note that this doesn't mean that these were the actual spots present during this period. There were many ways for these light curves to fit and we chose the simplest configurations. Spot latitude is a primary uniqueness problem since a mirror image of a northern configuration would produce the same results as a southern spot instead. However, spots did need to be mid latitudes, and bright spots did not fit all the pass bands as nicely as dark spots.

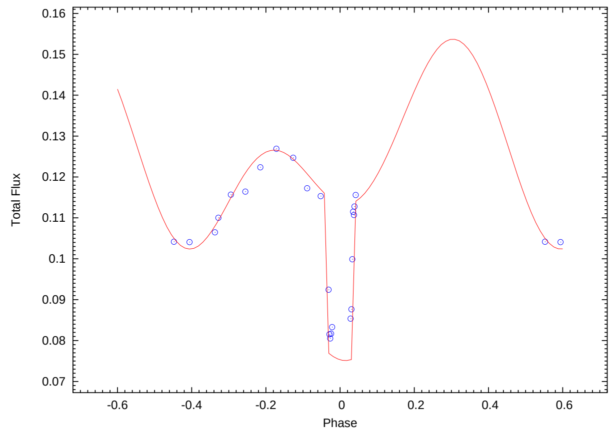

FIG. 1.— Light-curve fit for the night of 10/02/76. These data were taken using the Johnson U filter. This was one of the few nights with eclipse data.

3.2. *The $O - C$ Diagram*

Eclipse data were also taken during this period. The Johnson UBV filters were used to collect this data. From all the eclipses, the cleanest were taken into consideration. We wanted to compare our observed timing results against those expected from the light-travel-time effect caused by the suspected brown dwarf tertiary component (Guinan & Ribas 2001). Their plot of the best-fitting curve assuming a third-body perturbation was re-created. The time delay or advance of the eclipse timings caused by the influence of a third body can be expressed as

$$\Delta T = \frac{a_{12} \sin i_3}{c} \left[\frac{1 - e_3^2}{1 + e_3 \cos \nu_3} \sin(\nu_3 + \omega) + e_3 \sin \omega \right] \qquad (3)$$

where a_{12} is the orbital semimajor axis of the eclipsing pair around the barycenter, i_3 and e_3 are the inclination and the eccentricity of the third-body orbit, respectively, c is the speed of light, ω is the argument of the periastron, and ν_3 is the true anomaly of the third body as it moves around the barycenter (i.e., the function of time). The orbital inclination i_3 is measured relative to the plane of the sky.

Experimental $O - C$ values were derived from equation (1). First, an HJD near an observed eclipse was chosen and substituted into equation (1) for T(min I) and used to determine E (number of cycles). E was then rounded to the nearest integer as the expected number of orbits and placed back into equation (1) to get the true calculated T(min I). Applying DC to refine the HJD0 on every selected night, a new HJD0 was found, i.e. the observed T(min I). Subtracting the observed T(min I) from the calculated yields $O - C$ in decimal days, which was then converted to seconds.

4. RESULTS

Fitting spots was not an easy task. The simulated dark spots were created in such way that the computed light-curves would best fit all of the observed UBV data available on a given night. There was not complete coverage of all pass bands in some cases. The U and V light curves were fit first when available because these data spanned several eclipses (FIGURES 1, 2, 3). Most of the spots were fit in the B band since it's the middle band (FIGURES 4, 5, 6).

Dark spots were modeled with and without eclipse data included. The nights that had eclipse data provided O-C data

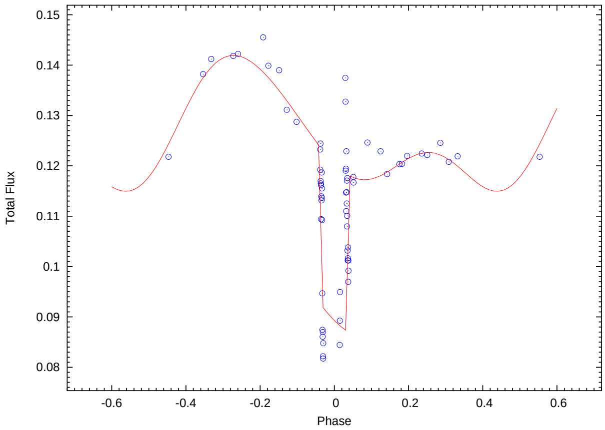

FIG. 2.— Night of 12/01/76. The Johnson U filter was applied. Although this night had more data points than any other night in the eclipse area, O-C's were difficult to calculate because of possible flares or atmospheric conditions.

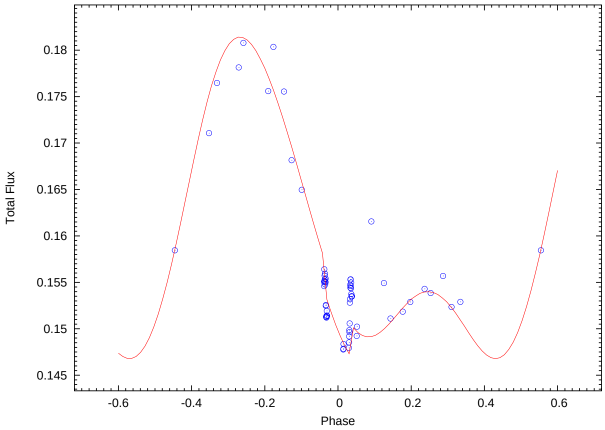

FIG. 3.— Light-curve fit for the night of 12/01/76. This different set of data points come from the Johnson V filter. Since it's the same night as the one shown in FIGURE 2, the same problems might have been experienced.

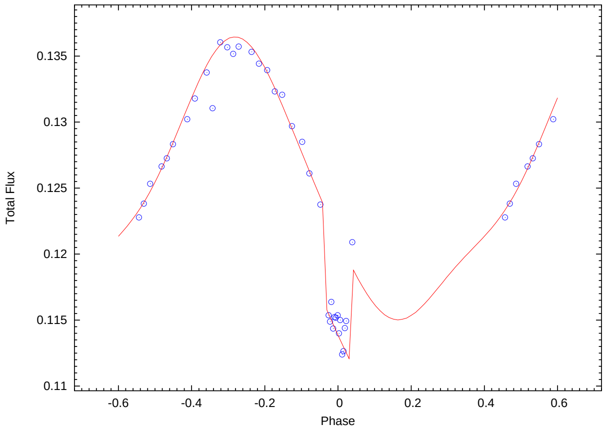

FIG. 4.— Light-curve fit for the night of 12/08/77. The Johnson B filter was chosen as the most helpful for fitting curves during this night. Eclipse data wasn't that accurate since it didn't represent the beginning and end of the eclipse.

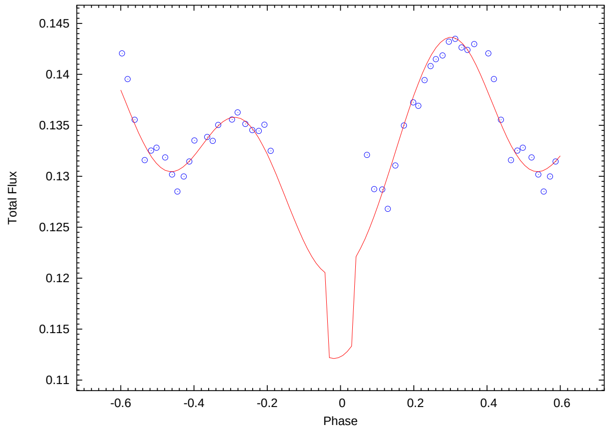

FIG. 5.— Dark spots model for the night of 10/30/79. Two spots were simulated without eclipse data since the Johnson B band didn't cover that portion of the light-curve.

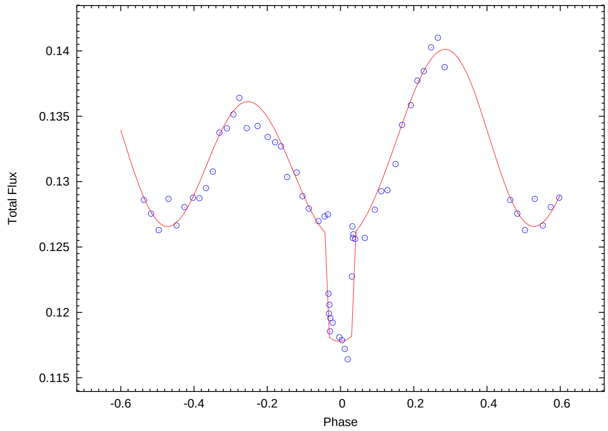

FIG. 6.— Dark spots model for the night of 11/18/79. The Johnson B filter data is represented.

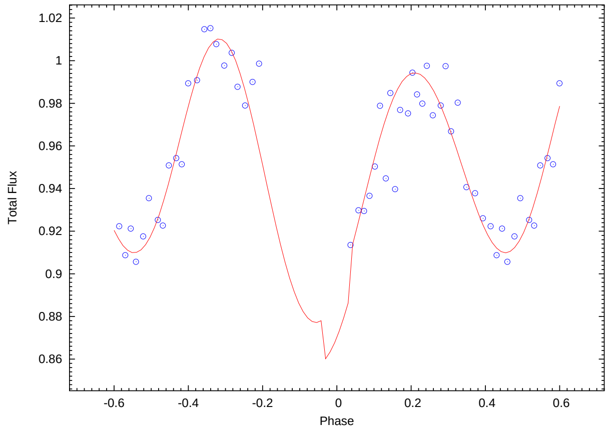

FIG. 7.— Scattered data for the night of 12/19/79. This time, the Johnson V band didn't have eclipse data.

TABLE 3
$O-C$ RESULTS

HJD	$O-C$ (s)	σ (s)
2443053.892885	-11.1	8.8
2443113.829394	25.1	43.3
2443485.954645	51.4	90.5
2444195.805377	-39.9	12.9
2444226.554697	-83.1	6.1

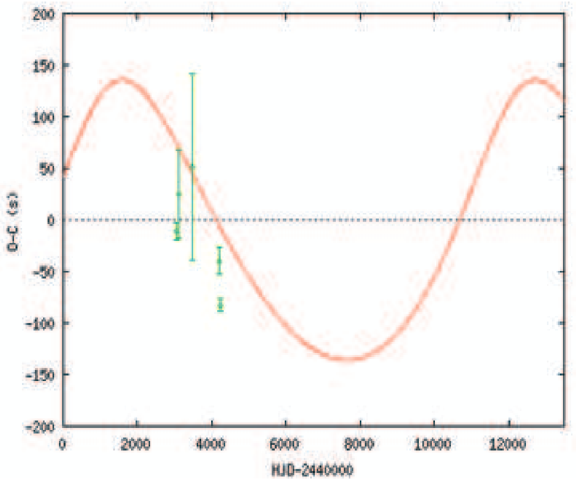

FIG. 8.— Comparison between light-travel time and the five calculated O-C's. The green dots are the O-C's numbers and the error bars represent the standard deviations.

using equation (1). Table 3 displays these results, which are shown along with their individual error bars in Figure 8.

The $O-C$ diagram was calculated using the eclipse data only. This means that any data point that was outside eclipse was not taken into consideration when fitting the HJD0 in PHOEBE.

5. CONCLUSIONS

Light-curve fits for V471 Tauri can be done with two dark spots. Unfortunately, there wasn't enough data to analyze spot evolution. From the fits one can conclude that the temperatures of the spots remain fairly constant (between 3,500 K and 4,000 K). Spot modeling also showed that DC in PHOEBE doesn't work very well with spot parameters. Adjustments in these parameters were done manually for better fits and hence no errors were determined. It has been indicated that newer versions of PHOEBE deal with spots better (Prsa, private communication).

The $O-C$ data couldn't be accurately determined. Determining new HJD0s for nights that had eclipse data mixed up with outside-eclipse data gave large standard deviations. The DC routine appears to give better results when more data points are fit for HJD0 instead of considering the more important eclipse data. It seems for most nights there weren't enough data points around the eclipse area. The systematic offset below the $O-C$ curve may be a result of UT vs. ephemeris time (ET). It was unclear if the data had been corrected for this time difference but there was a 50 second offset indicated in the output as ET-UT. Adding these corrections to our $O-C$ values would place our data more closely around the curve in figure 8. However, since we couldn't confirm this from the output available, we did not apply these corrections.

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