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## Ca II H AND K AND HYDROGEN-LINE VARIATIONS IN V471 TAURI (= BD +16°516)

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Spectroscopic and narrow-band photoelectric observations of the white dwarf eclipsing binary V471 Tau (= BD +16°516) are reported. Periodic fluctuations in Ca II H and K emission and H $\alpha$  absorption, and a wave-like distortion of the light curve mimic the characteristics of several well-observed RS CVn binaries. A probable correlation between maximum emission-line strength and wave minimum is shown to exist.

*Key words:* eclipsing binaries—white dwarfs—emission-line variations

### Introduction

The discovery of the eclipsing nature of BD +16°516 (= V471 Tauri) by Nelson and Young (1970) unleashed a brief flurry of excitement among observers and theorists. Not only was the opportunity for the determination of reliable physical data for a white dwarf anticipated, but early calculations indicated that the degenerate component was one of the hottest known (Hills 1971; Young and Nelson 1972). When ambiguities in the solution of the photometric light curve due to the very small value for the ratio of the radii ( $\sim 0.01$ ) became apparent, interest waned. Within the last few years, however, this system has again received attention because of the cooler component's striking similarities to many of the so-called RS Canum Venaticorum variables, which exhibit peculiar migrating wave-like light-curve distortions but do not contain degenerate components. V471 Tau is known to exhibit such a photometric distortion wave, migrating toward decreasing orbital phase with a period of about one year.

Nelson and Young (1976) have published a concise review of work that has been done to date on this system. Hall (1976) has presented a comprehensive discussion of the RS CVn variables. Some of the similarities of V471 Tau to this class of binaries were specifically mentioned.

Photoelectric *UBV*, *woby*, H $\alpha$ , and H $\beta$  photometry, and spectroscopic work conducted during the last three observing seasons at the Perkins and Lowell Observatories has revealed additional similarities between V471 Tau and several of the most active RS CVn variables (Oswalt 1978). Presented here are the results of the narrow-band photometry and spectroscopic work. Concurrent *UBV* and *woby* light curves obtained on all nights will be published elsewhere.

### Equipment and Observations

The spectrograms were obtained at the Perkins 1.8-

m telescope of the Ohio State and Ohio Wesleyan Universities in Flagstaff, Arizona, equipped with the Boller and Chivens single-stage image-tube spectrograph. All the exposures were made on unbaked IIA-D emulsion at a reciprocal dispersion of about 77 Å mm<sup>-1</sup> near the 4640 Å blaze wavelength of the grating.

The H $\beta$  photometry was obtained with the single-channel OSU "red" photometer attached to the 0.8-m telescope at Perkins Observatory in Delaware, Ohio. A refrigerated EMI 6256 S-11 photomultiplier operated in the pulse-counting mode was used. The H $\beta$  filter pair used closely matches the transmission characteristics defined by Crawford and Mander (1966).

A similar photometer was used for the H $\alpha$  observations. These were obtained with the 1.1-m and Perkins 1.8-m telescopes at Lowell Observatory in Flagstaff. Refrigerated EMI 9558 S-20 and ITT F4085 S-20 photomultipliers operated in the pulse-counting mode were used for the 1976 and 1977 observations, respectively. Bandpass half-widths for the narrow and wide filters are about 28 Å and 150 Å, respectively.

The primary comparison star was BD +17°638 (= HD 24040). A check star, BD +16°544, was monitored occasionally on several nights. No variations in either of these stars were noted.

An observing sequence SCVCS was followed throughout each night. On those nights when the check star was observed readings were taken at least once an hour. Integration times were integral multiples of ten seconds. Three or more such readings were averaged for an observation, depending on the count rates in a particular filter. The standard error of a single observation, as determined from the internal scatter of the comparison and variable star readings, was considerably better than  $\sim 0^m.015$  in all bandpasses for most nights. All data have been corrected for atmospheric extinction. Phases of all observations are calculated from the heliocentric linear ephemeris given by Young and Lanning (1975).

### Spectroscopic Results

During a separate observing program 17 image-tube spectrograms were obtained between 1975 October 6–11. Medium-density exposures ranged from three to seven minutes depending on sky conditions and were grouped mostly about phase 0.5 and eclipse for the purpose of detecting any transient spectral features during ingress and egress. These plates were examined in detail for spectral variations. At least during this time the emission components of Ca II H and K were strongly variable, *apparently* in synchronism with the orbital period. Maximum emission levels occurred near phase 0.5, with virtually zero emission during eclipse totality. Density tracings from the most uniformly exposed plates are shown in Figure 1.

More complete phase coverage was obtained during the period 1976 January 1–6. These 14 spectra covered about 80% of the 12.5-hour orbital period. Ten exposures taken on January 5 provided continuous coverage between phase  $\sim 0.5$  and eclipse. The same periodic variability in Ca II H and K emission was evident: maximum near phase 0.5, minimum near eclipse. Two plates in particular taken during ingress showed a distinct strong double-emission core in the K line. No other obvious emission features are present in this collection of spectra, except O I  $\lambda 5577$  due to the night sky.

### Narrow-Band Photometry

A search for absorption-line changes was made and H $\beta$  seemed to be marginally variable (Fig. 2). Consequently, H $\beta$  photometry was undertaken during the following season with the 0.8-m telescope at Perkins Observatory. These observations are presented in Table I. The instrumental H $\beta$  index is defined conventionally:

$$\beta' = -2.5 \log F(\text{H}\beta)_n / F(\text{H}\beta)_w,$$

where  $F(\text{H}\beta)_n$  and  $F(\text{H}\beta)_w$  are the observed fluxes through the narrow and wide H $\beta$  filters, respectively. The concurrent  $V$  and  $\beta'$  observations are presented in Figure 3. The migrating nature of the wave is clearly evident in such composite  $V$  light curves, however no periodic variability above the noise greater than about 0<sup>m</sup>02 in  $\beta'$  was detected.

It was presumed that any real periodic variations in H $\beta$  would be accompanied by larger fluctuations in H $\alpha$ . Later in the same season H $\alpha$  photometry was begun at the Lowell 1.1-m and Perkins 1.8-m telescopes. These data are listed in Table II, where an instrumental H $\alpha$  index is defined in a manner similar to  $\beta'$ :

$$\alpha' = -2.5 \log F(\text{H}\alpha)_n / F(\text{H}\alpha)_w.$$

Figure 4a presents the  $V$  light curve for these four nights. It is virtually identical in appearance to those

obtained in the wide bandpass H $\alpha$  filter. Immediately below this is a plot of the behavior of  $\alpha'$  with phase for comparison (Fig. 4b). The 1976 observations indicate  $\sim 0^m06$  variation in  $\alpha'$ ; a "dip" in H $\alpha$  flux (increase in  $\alpha'$ ) occurs at about phase 0.0 in Figure 4b. This may be interpreted to arise from the same mechanism producing the fluctuations in Ca II H and K emission. It can be supposed that a small emission component partially filled in the H $\alpha$  absorption line outside eclipse. Short-exposure, high-dispersion line profiles would be required to confirm this. Interestingly, Lanning and Etzel (1976) have reported the detection of H $\alpha$  emission in V471 Tau on at least one occasion.

It was not apparent from the 1976 observations that the variations in H $\alpha$  had anything at all to do with the photometric distortion wave, since wave maximum occurred about 1/4 cycle before the "dip" in H $\alpha$  flux (maximum  $\alpha'$ ), and wave minimum about 0.6 earlier in phase than the "dip". Besides, minimum H and K emission and H $\alpha$  flux appeared to occur during eclipse totality. Rather, some sort of excitation due to the hot companion outside eclipse seemed probable. Another interesting feature of the 1976  $V$  light curve was that observations made during wave minimum seemed to exhibit considerably more scatter than elsewhere in the light curve, even though the individual ten-second readings averaged to obtain each observation were consistent to better than 1%.

Additional H $\alpha$  observations were obtained at Lowell Observatory during December 1977. These are presented along with the 1976 data in Table II, plotted versus phase with the 1976 data in Figure 4c, and plotted separately in Figure 4d. The first new nights in 1977 were of generally lower photometric quality than the previous year, however  $\alpha'$  values for the comparison and check stars were found to be virtually independent of the small changes in sky transparency which affected the long-term stability of individual filter readings. This is evident by the comparable intrinsic scatter in Figures 4b and 4d.

The 1977 observations indicate that either the "dip" in H $\alpha$  flux was much broader than was apparent during the previous year, or that it had migrated toward decreasing orbital phase. Observations scheduled during the 1978 season should help decide between these alternatives. If the latter possibility is correct this shift is in the same sense as that observed for the distortion wave in the broad-band light curves. In addition, the "dip" in H $\alpha$  flux still would have occurred about 1/4 cycle past wave maximum. It is not obvious why such a phase lag might occur, but some sort of aspect effect is suggested. The incomplete phase coverage of the 1977 data makes it difficult to judge whether the mean

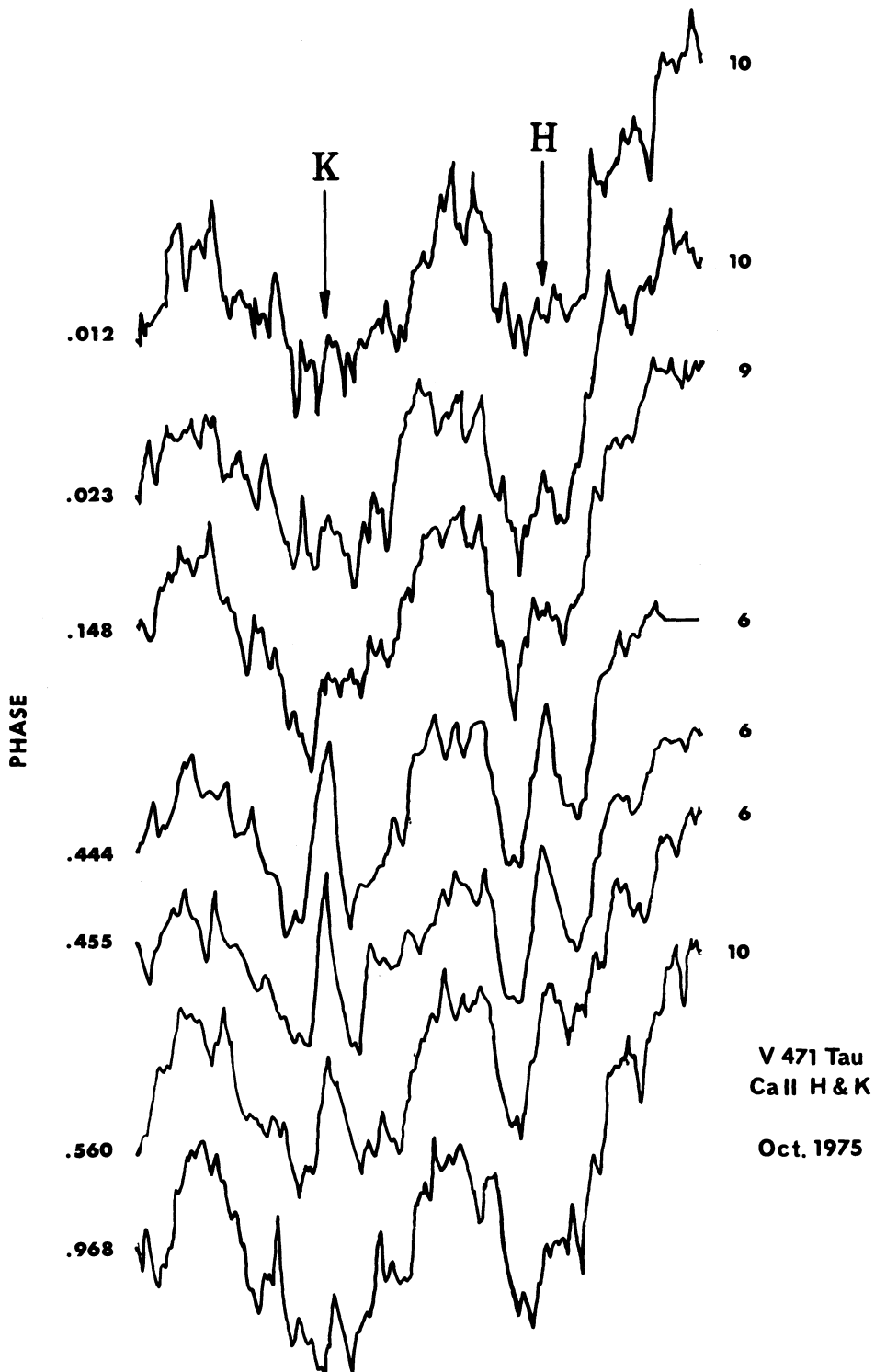


FIG. 1—Density tracings of spectrograms showing the behavior of Ca II H and K emission with orbital phase in V471 Tau during October 1975. Numbers along right side are UT day of exposures. Density scale is arbitrary but similar for all tracings.

systematic  $\alpha'$  changed between the two seasons although the “dip” appears to be  $\sim 0^m.03$  shallower than in 1976.

Minimum  $H\alpha$  flux (maximum  $\alpha'$ ) seems to occur at or near the base of the descending branch of wave

maximum, immediately before the most level portion of the light curve. The peak of the broad asymmetrical  $H\alpha$  flux maximum ( $\alpha'$  minimum) evidently corresponded with wave minimum in November 1976.

The incomplete 1977 observations seem to indicate

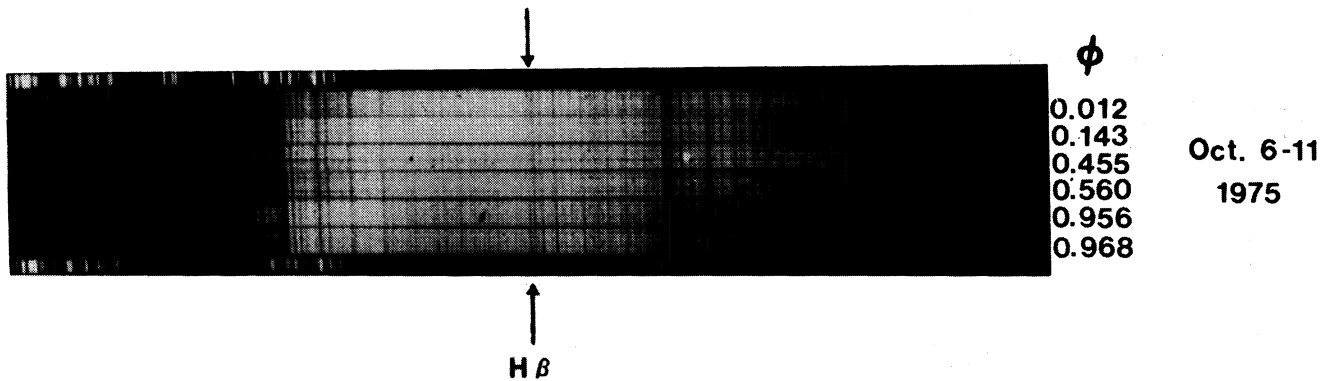


FIG. 2—H $\beta$  absorption-line variations in V471 Tau during October 1975. Emission lines near yellow end of spectrum (right) are due to night sky.

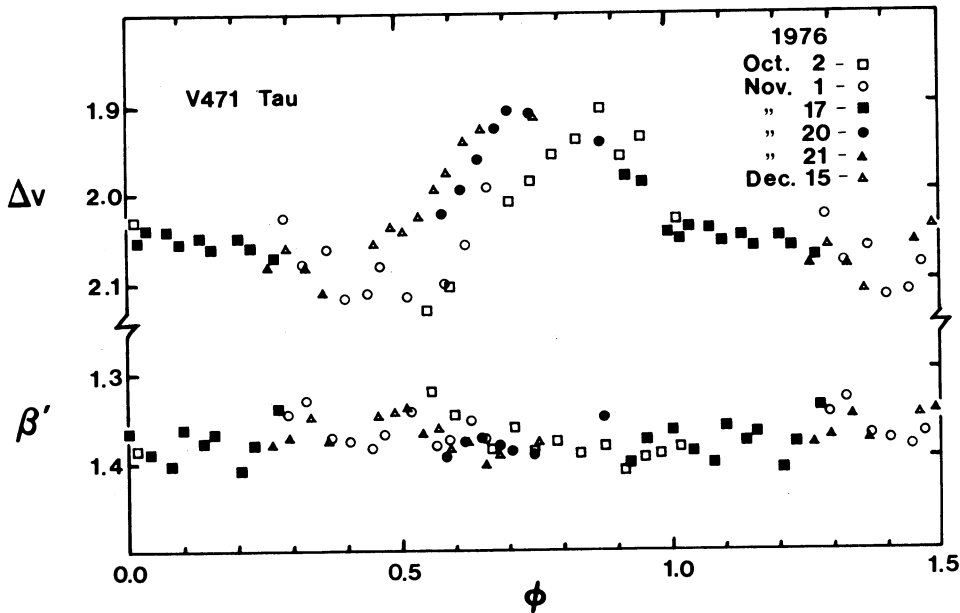


FIG. 3—Photometric behavior of V471 Tau in 1976: Differential V magnitudes (top), and  $\beta'$  observations (bottom). Standard error of a single observation is comparable to symbol size.

that the phase of maximum H $\alpha$  emission does not always coincide with wave minimum, however. This suggests that rather long-lived emitting regions may migrate in longitude with respect to the darkened areas presumed responsible for the distortion wave minimum. Such behavior is that which might be expected from large-scale prominence activity arising from the active regions, particularly if differential rotation is taking place as supposed in the RS CVn variables (Hall 1972). There exists strong circumstantial evidence for such chromospheric events in several of these binaries (Weiler 1978*b*) and in V471 Tau (Young and Lanning 1975; Young 1976). This interpretation may shed some light on the conflicting phase correlations between emission-line strengths and the distortion wave observed in some

of these stars (Droppo and Milone 1976). At any rate, it appears that the variations in H $\alpha$  are related to the distortion wave in the same sense that Weiler (1978*a*) found for Ca II H and K emission in several RS CVn variables, and not exclusively the result of excitation by the hot companion.

### The Light Curve Variations

No unique model has yet been presented which explains the peculiarities of the light-curve distortion wave exhibited by V471 Tau, although like the RS CVn binaries, several characteristics of the system can be explained very simply by relatively dark regions rotating with the surface of the cooler component: variability of eclipse depths, changes in wave amplitude,

TABLE I

| H $\beta$ Observations of V471 Tauri |       |          |
|--------------------------------------|-------|----------|
| Julian Date<br>(2,440,000+)          | Phase | $\beta'$ |
| 3053.665                             | 0.560 | 1.323    |
| 3053.686                             | 0.601 | 1.349    |
| 3053.721                             | 0.668 | 1.388    |
| 3053.743                             | 0.710 | 1.363    |
| 3053.763                             | 0.749 | 1.392    |
| 3053.784                             | 0.789 | 1.380    |
| 3053.807                             | 0.833 | 1.393    |
| 3053.831                             | 0.878 | 1.384    |
| 3053.850                             | 0.916 | 1.412    |
| 3053.869                             | 0.952 | 1.397    |
| 3053.885                             | 0.982 | 1.394    |
| 3053.903                             | 0.018 | 1.386    |
| 3083.755                             | 0.294 | 1.348    |
| 3083.772                             | 0.328 | 1.332    |
| 3083.796                             | 0.373 | 1.374    |
| 3083.814                             | 0.407 | 1.378    |
| 3083.835                             | 0.448 | 1.386    |
| 3083.847                             | 0.472 | 1.371    |
| 3083.873                             | 0.522 | 1.345    |
| 3083.897                             | 0.566 | 1.383    |
| 3083.910                             | 0.591 | 1.377    |
| 3083.931                             | 0.632 | 1.356    |
| 3083.944                             | 0.656 | 1.376    |
| 3099.718                             | 0.924 | 1.404    |
| 3099.735                             | 0.955 | 1.378    |
| 3099.759                             | 0.002 | 1.368    |
| 3099.780                             | 0.041 | 1.391    |
| 3099.799                             | 0.078 | 1.405    |
| 3099.811                             | 0.101 | 1.365    |
| 3099.830                             | 0.138 | 1.380    |
| 3099.841                             | 0.159 | 1.370    |
| 3099.866                             | 0.207 | 1.411    |
| 3099.879                             | 0.231 | 1.382    |
| 3099.902                             | 0.276 | 1.342    |
| 3102.670                             | 0.586 | 1.396    |
| 3102.687                             | 0.620 | 1.379    |
| 3102.704                             | 0.652 | 1.375    |
| 3102.721                             | 0.684 | 1.384    |
| 3102.733                             | 0.707 | 1.390    |
| 3102.754                             | 0.747 | 1.394    |
| 3102.821                             | 0.877 | 1.352    |
| 3103.545                             | 0.265 | 1.382    |
| 3103.561                             | 0.297 | 1.375    |
| 3103.581                             | 0.335 | 1.352    |
| 3103.597                             | 0.366 | 1.379    |
| 3127.621                             | 0.460 | 1.350    |
| 3127.637                             | 0.491 | 1.347    |
| 3127.649                             | 0.514 | 1.342    |
| 3127.663                             | 0.542 | 1.371    |
| 3127.678                             | 0.571 | 1.364    |

TABLE I (Continued)

| Julian Date<br>(2,440,000+) | Phase | $\beta'$ |
|-----------------------------|-------|----------|
| 3127.691                    | 0.594 | 1.388    |
| 3127.707                    | 0.626 | 1.379    |
| 3127.724                    | 0.658 | 1.406    |
| 3127.737                    | 0.683 | 1.395    |
| 3127.775                    | 0.757 | 1.381    |

migration of the wave, and, to a certain extent, apparent changes in period. That the wave-like variations are intrinsic to the cooler component is quite certain: the 1977 light curves show clear continuation of the wave during eclipse of the hot companion.

Spotted star models such as those developed by Friedemann and Gürtler (1975) and Vogt (1975) predict a quasi-sinusoidal distortion wave if the darkened region extends over  $180^\circ$  in longitude, and flat maxima (minima) if less (more) than one hemisphere of the star is darkened. Some of the light curves of V471 Tau obtained by Ibanoglu (1976) and possibly Cester and Pucillo (1976) may be explained by the first situation. Frequently, however, V471 Tau exhibits a temporary constant light level between wave extrema. Moreover, this "reference" or "R-level" does not always bisect the wave; wave maximum often has a larger amplitude relative to this level than does wave minimum. Occasionally the situation is reversed. In addition, V471 Tau at times exhibits little evidence of a distortion wave at all (Oswalt 1978).

The published *V* light curves of V471 Tau which exhibit a well-defined R-level between wave maximum and minimum seem to share a common characteristic: the magnitude and color of this R-level seems to be fairly constant from season to season despite striking changes in the distortion wave on time-scales as short as several weeks. This is especially evident among those observations made over several seasons on the same or similar instrumental systems (Young and Nelson 1972; Ibanoglu 1976; Oswalt 1978). Such behavior suggests the occasional existence of a relatively spot-free hemisphere on the cool component. In this case the R-level would provide the most appropriate basis for determination of the photometric properties of the system, particularly when it coincides with the eclipse of the degenerate component.

It is interesting, though not unprecedented, that the above interpretation of the R-level would require co-existent bright and dark regions to explain the distortion wave maximum and minimum, respectively. Similar phenomena were suggested as an explanation for the light curve irregularities observed in AR Lacertae and YY Geminorum (Kron 1947, 1952). In addition, transient hot spots have been strongly indicated for the

TABLE II

TABLE II (Continued)

| H $\alpha$ Observations of V471 Tauri<br>1976 |       |           | Julian Date<br>(2,440,000+) | Phase | $\alpha'$ |
|---|-------|-----------|-----------------------------|-------|-----------|
| Julian Date<br>(2,440,000+)                   | Phase | $\alpha'$ |                             |       |           |
| 3107.728                                      | 0.291 | 1.486     | 3110.869                    | 0.319 | 1.479     |
| 3107.743                                      | 0.320 | 1.457     | 3110.876                    | 0.331 | 1.456     |
| 3107.756                                      | 0.346 | 1.462     | 3110.892                    | 0.362 | 1.468     |
| 3107.769                                      | 0.371 | 1.459     | 3110.902                    | 0.381 | 1.474     |
| 3107.786                                      | 0.403 | 1.487     | 3110.920                    | 0.416 | 1.441     |
| 3107.810                                      | 0.449 | 1.474     | 3110.941                    | 0.456 | 1.455     |
| 3107.825                                      | 0.479 | 1.471     | 3110.953                    | 0.480 | 1.466     |
| 3107.843                                      | 0.512 | 1.467     | 3110.969                    | 0.509 | 1.455     |
| 3107.854                                      | 0.534 | 1.460     | 3110.982                    | 0.534 | 1.452     |
| 3107.869                                      | 0.561 | 1.488     | 3111.001                    | 0.571 | 1.486     |
| 3107.885                                      | 0.592 | 1.464     | 3111.686                    | 0.886 | 1.487     |
| 3107.898                                      | 0.618 | 1.488     | 3111.698                    | 0.908 | 1.478     |
| 3107.914                                      | 0.648 | 1.476     | 3111.704                    | 0.919 | 1.514     |
| 3107.940                                      | 0.698 | 1.488     | 3111.712                    | 0.936 | 1.489     |
| 3107.956                                      | 0.729 | 1.493     | 3111.792                    | 0.089 | 1.518     |
| 3108.676                                      | 0.111 | 1.518     | 3111.801                    | 0.106 | 1.510     |
| 3108.687                                      | 0.132 | 1.488     | 3111.810                    | 0.124 | 1.465     |
| 3108.697                                      | 0.151 | 1.492     | 3111.823                    | 0.149 | 1.484     |
| 3108.709                                      | 0.174 | 1.501     | 3111.832                    | 0.166 | 1.506     |
| 3108.719                                      | 0.193 | 1.483     | 3111.844                    | 0.190 | 1.496     |
| 3108.730                                      | 0.213 | 1.481     | 3111.853                    | 0.206 | 1.486     |
| 3108.734                                      | 0.222 | 1.475     | 3111.865                    | 0.230 | 1.521     |
| 3108.818                                      | 0.382 | 1.477     | 3111.874                    | 0.247 | 1.490     |
| 3108.827                                      | 0.401 | 1.488     | 3111.888                    | 0.273 | 1.493     |
| 3108.834                                      | 0.414 | 1.487     | 3111.894                    | 0.285 | 1.459     |
| 3108.842                                      | 0.429 | 1.478     | 3111.916                    | 0.327 | 1.456     |
| 3108.857                                      | 0.458 | 1.474     | 3111.932                    | 0.358 | 1.459     |
| 3108.867                                      | 0.477 | 1.480     | 3111.945                    | 0.382 | 1.476     |
| 3108.880                                      | 0.501 | 1.470     | 3111.954                    | 0.400 | 1.445     |
| 3108.889                                      | 0.520 | 1.467     | 3111.967                    | 0.426 | 1.448     |
| 3108.899                                      | 0.539 | 1.477     | 3111.987                    | 0.463 | 1.511     |
| 3108.911                                      | 0.560 | 1.481     | 3111.999                    | 0.486 | 1.474     |
| 3108.922                                      | 0.583 | 1.472     | 3112.010                    | 0.508 | 1.470     |
| 3108.932                                      | 0.601 | 1.487     | 3112.022                    | 0.531 | 1.489     |
| 3108.943                                      | 0.624 | 1.479     |                             |       |           |
| 3108.950                                      | 0.636 | 1.508     | 3481.748                    | 0.928 | 1.551     |
| 3108.961                                      | 0.658 | 1.478     | 3481.768                    | 0.965 | 1.506     |
| 3110.667                                      | 0.930 | 1.506     | 3481.778                    | 0.984 | 1.506     |
| 3110.678                                      | 0.952 | 1.513     | 3481.812                    | 0.050 | 1.542     |
| 3110.692                                      | 0.979 | 1.514     | 3481.882                    | 0.185 | 1.512     |
| 3110.702                                      | 0.999 | 1.526     | 3482.675                    | 0.705 | 1.481     |
| 3110.705                                      | 0.004 | 1.526     | 3482.686                    | 0.726 | 1.497     |
| 3110.714                                      | 0.020 | 1.517     | 3482.700                    | 0.755 | 1.481     |
| 3110.716                                      | 0.025 | 1.468     | 3482.721                    | 0.795 | 1.525     |
| 3110.726                                      | 0.043 | 1.530     | 3482.752                    | 0.854 | 1.555     |
| 3110.786                                      | 0.160 | 1.475     | 3482.775                    | 0.898 | 1.546     |
| 3110.804                                      | 0.193 | 1.461     | 3482.824                    | 0.992 | 1.527     |
| 3110.823                                      | 0.230 | 1.450     | 3482.879                    | 0.097 | 1.510     |
| 3110.836                                      | 0.254 | 1.432     | 3482.908                    | 0.153 | 1.516     |
| 3110.847                                      | 0.277 | 1.489     | 3482.929                    | 0.193 | 1.522     |

TABLE II (Continued)

| Julian Date<br>(2,440,000+) | 1977<br>Phase | $\alpha'$ |
|-----------------------------|---------------|-----------|
| 3482.958                    | 0.249         | 1.506     |
| 3483.624                    | 0.527         | 1.505     |
| 3483.634                    | 0.546         | 1.498     |
| 3483.649                    | 0.575         | 1.507     |
| 3483.658                    | 0.593         | 1.488     |
| 3483.669                    | 0.613         | 1.484     |
| 3483.683                    | 0.641         | 1.503     |
| 3483.694                    | 0.662         | 1.508     |
| 3483.708                    | 0.689         | 1.511     |
| 3483.722                    | 0.716         | 1.514     |
| 3483.731                    | 0.732         | 1.514     |
| 3483.744                    | 0.758         | 1.543     |
| 3483.772                    | 0.810         | 1.539     |
| 3483.806                    | 0.876         | 1.560     |
| 3483.815                    | 0.894         | 1.546     |
| 3483.826                    | 0.915         | 1.514     |
| 3483.836                    | 0.934         | 1.564     |
| 3483.851                    | 0.963         | 1.560     |
| 3483.861                    | 0.982         | 1.536     |
| 3483.866                    | 0.992         | 1.542     |
| 3483.878                    | 0.015         | 1.532     |
| 3483.883                    | 0.024         | 1.542     |
| 3483.894                    | 0.044         | 1.530     |
| 3483.906                    | 0.069         | 1.547     |
| 3483.917                    | 0.090         | 1.541     |
| 3483.927                    | 0.109         | 1.515     |
| 3483.936                    | 0.125         | 1.546     |
| 3483.961                    | 0.174         | 1.481     |

flare star BY Draconis (Fix and Spangler 1976).

The absence of strong Balmer emission and flare activity would seem to imply that the cool component of V471 Tau displays a somewhat less-active chromo-

spheric network than either the most active RS CVn variables or flare stars. Continuing observations are planned for V471 Tau, and hopefully a more complete model of this interesting system can eventually be constructed.

It is a pleasure to thank Dr. Nathaniel White who generously lent his time and photoelectric equipment during the 1976 and 1977 observing runs at Lowell Observatory. Dr. Terry Roark kindly obtained the image-tube spectra concurrently with the author's 1976 photometry. Several helpful and informative discussions with Dr. Gerald Newsom and comments by an anonymous referee are also gratefully acknowledged.

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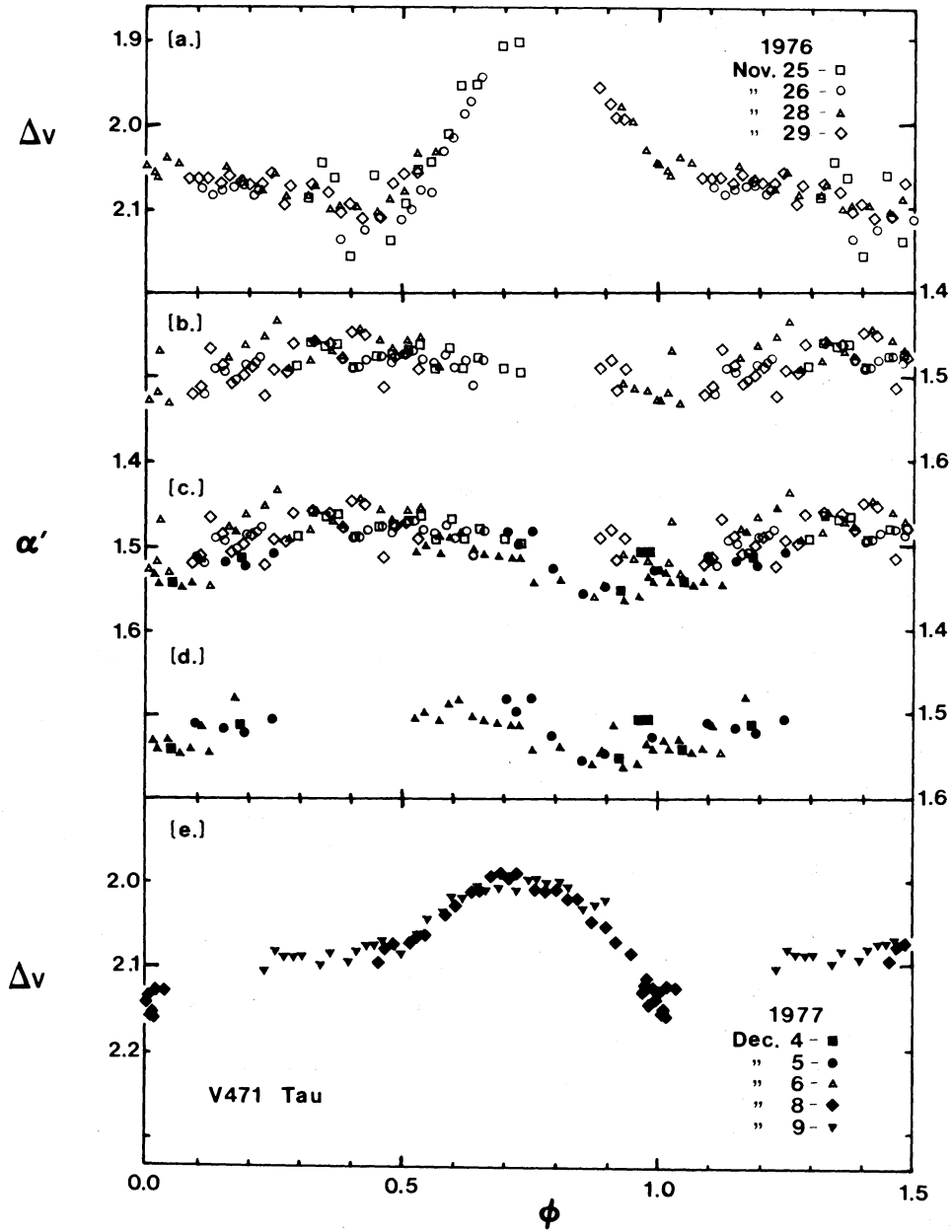


FIG. 4—Photometric observations of V471 Tau: (a) 1976 V light curve, (b) 1976  $\alpha'$  variations, (c) composite 1976-77  $\alpha'$  plot, (d) 1977  $\alpha'$  variations, (e) 1977 V light curve. Symbol size is comparable to standard error of a single observation. In all plots open symbols represent 1976 observations, solid symbols those made in 1977.