

The Line-Profile Variations of θ^2 Tauri

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ABSTRACT. With a 5.4-hour time series of high-resolution CFHT spectra, the oscillations of the rapidly rotating δ Scuti star θ^2 Tauri (A7 IV + A5 V) are investigated. Line-profile variations are discovered and identified with the spectrum of the primary star of this binary system. Radial-velocity variations are derived from the data and analyzed to reveal an oscillation frequency near $13.7 \text{ cycles day}^{-1}$. Variations within the absorption profiles are analyzed with a Fourier-Doppler Imaging (FDI) technique to reveal that high-degree oscillations with a frequency of $16.1 \text{ cycles day}^{-1}$ and an apparent degree of about $\ell=8$ are also present in the star. Whereas the low-degree variations of θ^2 Tau have been shown to be consistent with p-modes of radial order $n=2$ or 3, the identification of the high-degree variations in terms of pressure modes requires confirmation with theoretical models.

1. INTRODUCING θ^2 TAURI

The δ Scuti star θ^2 Tauri (HR 1412) is a bright spectroscopic binary ($V_{tot}=3.41$) and a member of the Hyades cluster. Extensive photometric observations have shown the star to be multiperiodic with as many as five frequencies but the identification of these oscillations modes remains uncertain. In this paper, the oscillation modes of θ^2 Tau are investigated with a spectroscopic time-series from CFHT.

The binary nature of θ^2 Tau was first discovered by Moore (1908) and Frost (1909) but the first spectroscopic orbit for the system was derived by Plaskett (1915). Additional observations were obtained by Petrie (1940) and Ebbighausen (1959). The orbit was found to be highly eccentric ($e=0.750$) with an orbital period of $P=140.728$ days (Ebbighausen 1959), however the spectrum of the secondary star was not detected in these early investigations.

The system was finally resolved with lunar occultation observations by Peterson et al. (1981) which indicated that the components are separated by $\Delta V=1.10 \pm 0.05$ magnitudes and that the secondary star is only marginally bluer than the primary. Peterson et al. concluded that the primary is an A7 IV star with $V=3.75$ and $B-V=0.17$ and that the secondary is an A5 V star with $V=4.85$ and $B-V=0.16$. The mass ratio of the system was estimated to be $M_2/M_1=0.8$. Shortly thereafter, Breger et al. modeled the photometric properties of components using the *ubvy β* system and concluded that a magnitude difference between the components from $\Delta V=0$ to 1.5 magnitudes could be admitted.

With these observations in hand, Królikowska (1992) calculated evolutionary models of the binary-system compo-

nents in order to further constrain the models of the primary and secondary star. The distance modulus to the Hyades was used to estimate the luminosity of the components. The membership of the θ^2 Tau to the Hyades also constrained estimates of the chemical composition of the components. Królikowska concluded that the primary could be identified as an evolved star in the thick hydrogen-shell burning stage with mass $M=2.63 \pm 0.01 M_\odot$ and that the secondary was a main-sequence star with mass $M=2.23 \pm 0.01 M_\odot$. (Both stars lie within the instability strip.) However, these conclusions were subject to the assumption that overshooting in the convective core can be neglected. Significant overshooting could delay the evolution of the primary and the possibility that it too is a main sequence star could not be excluded in Królikowska's analysis.

Recently, the secondary spectrum of θ^2 Tau was identified in the investigations of the spectroscopic binary orbit by Peterson (1991) and Peterson et al. (1993). In the first of these papers, the spectrum of Procyon (F5 IV-V) was rotationally broadened and used as a template in a cross-correlation calculation which took into account the signatures of both the primary and secondary star. A projected rotational velocity of $v \sin i=80 \text{ km s}^{-1}$ was derived for the primary whereas the secondary was found to rotate with $v \sin i=150 \text{ km s}^{-1}$ (which explains why the spectrum of this star had not been easily detected in previous observations). The mass ratio of the components was determined to be $M_2/M_1=0.876$ in good agreement with earlier estimates. In the subsequent study, synthetic spectra were used as the templates for the cross-correlation calculation. A model which satisfied both the photometry and spectroscopy was derived with $T_{\text{eff}}=8400 \text{ K}$, $\log g=3.9$, and $v \sin i=65 \text{ km s}^{-1}$ for the primary and $T_{\text{eff}}=8400 \text{ K}$, $\log g=4.3$, and $v \sin i=170 \text{ km s}^{-1}$ for the secondary. The orbital parameters obtained from this investigation did not deviate much from previously established values.

The variability of θ^2 Tau due to stellar oscillations was first reported by Horan (1977) and Horan (1979) who iden-

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tified a frequency near 14 cycles day⁻¹ based on photometric observations. Further studies by Duerbeck (1978) confirmed the variability. Later, Antonello and Mantegazza (1982) found θ^2 Tau to be multi-periodic with several closely spaced frequencies (i.e., at 13.22, 12.37, 16.02, and 12.04 cycles day⁻¹). In order to fully resolve all the frequencies of oscillations, a campaign to obtain multi-site photometric observations of θ^2 Tau was orchestrated by Breger et al. (1987). Unprecedented coverage of the star was obtained during several weeks of observation to produce a frequency spectrum that was relatively free of one-day aliases. Four frequencies of oscillation were identified in this study at 13.22970, 13.48090, 13.69362, and 14.31756 cycles day⁻¹. However, the authors were not able to unambiguously identify the oscillation modes from these frequencies alone. Calculations of the light-time delay due to the binary orbit revealed that at least most of the variability seen in θ^2 Tau must originate with the primary.

A second multi-site campaign was initiated by Breger et al. (1989) in order to investigate the persistence of the previously identified frequencies and to search for additional variations. Once again superb coverage was obtained, this time with multi-color observations being made at one site. Frequencies consistent with those which were previously identified were derived from the data (at 13.229653, 13.480733, 13.693596, and 14.317637 cycles day⁻¹) with one additional variation discovered at 14.614537 cycles day⁻¹ but again reliable mode identifications could not be made, especially without the availability of specific theoretical models to describe the expected frequency spectrum for θ^2 Tau. Meanwhile, an independent study by Kovács and Paparó (1989) confirmed the frequencies identified by Breger et al. (1989).

2. THE 1990 CFHT OBSERVATIONS

A 5.41 hour time series of θ^2 Tau was obtained at CFHT on 1990 October 4 UT (HJD 2448168). The data consisted of 52 high-resolution ($R=40000$) Reticon spectra obtained with ~ 300 second integration times. This translates to a Nyquist frequency of 230 cycles day⁻¹ and a resolution of 4.44 cycles day⁻¹. The spectral region from 4460 to 4530 Å was chosen for observation in order to monitor the variations in the $\lambda 4501.278$ Ti II, $\lambda 4508.289$ Fe II, and $\lambda 4515.342$ Fe II profiles which suffer from relatively little blending with neighboring absorption lines. A mid-exposure meter which monitored the starlight flux was used to determine the time of each observation to within 5 seconds. Thorium-Argon calibration spectra were obtained about every hour during the night and several spectra of an incandescent lamp were obtained following the end of the series with signal levels which matched that of the observations. The data were processed using IRAF.⁵

Using standard techniques (e.g., Walker et al. 1985), the Reticon data were corrected for zero-point and pixel-to-pixel

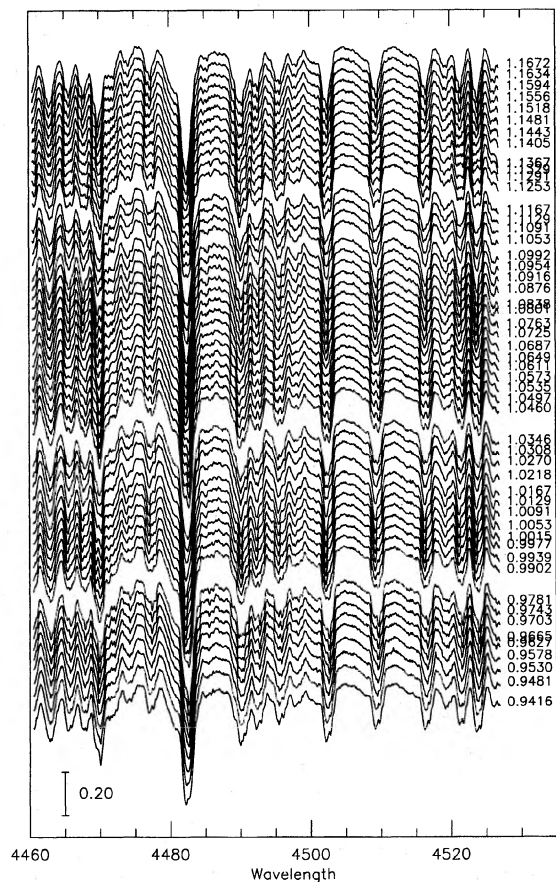


FIG. 1—The time series of θ^2 Tau spectra exhibits variations within the absorption line profiles. Numbers on the right-hand side of the figure represent times of observation relative to HJD 2448168. The bar indicates the intensity scale relative to a continuum of unity.

variations. Wavelength calibration of the spectra was performed using a time-weighted average of the dispersion relations derived from the Th-Ar spectra obtained preceding and succeeding the stellar exposures. Corrections for the heliocentric velocity were made to the spectra (without interpolating the data) and cosmic-ray features were removed by examining each spectrum and assigning corrected intensities to the affected pixels. In the observed spectral region, blending between neighboring (rotationally broadened) absorption lines leaves little indication of the true continuum level. Therefore, in these reductions a somewhat arbitrary choice of the continuum was assigned to the time series. With the mean spectrum normalized to the chosen level, the normalization of individual spectra was performed by dividing each spectrum by the mean, then fitting a low-order polynomial to the residuals, and dividing each of the original spectra by the fitted functions. The resulting time-series of θ^2 Tau spectra is illustrated in Fig. 1. Variations within the absorption line profiles can be clearly seen.

The observations at CFHT were obtained during the phase of θ^2 Tau's orbit when the system was near perihelion allowing the greatest possible velocity separation between the two components. Note that because the system is highly ec-

⁵IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

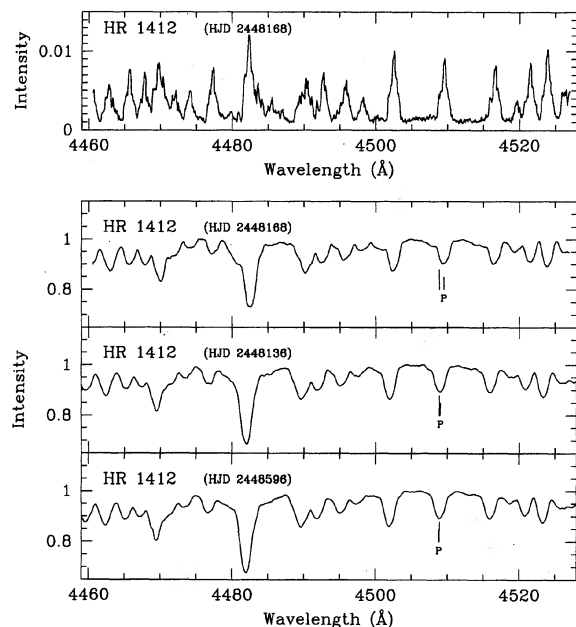


FIG. 2—The mean spectrum from CFHT (HJD 2448168) is compared with spectra obtained at DAO during two different phases of the binary orbit (HJD 2448136 and HJD 2448596). The position of the primary spectrum is indicated by the label 'P' relative to the systemic velocity for the star in each of these spectra. The presence of the secondary spectrum can be identified by comparing the observations. At the top of the figure, the absolute mean deviation for the time series obtained at CFHT is shown. Note that the increased amplitude due to variations is confined to within the rotationally broadened profiles of the primary.

centric, this window of opportunity is just a couple of days. In Fig. 2, the mean spectrum obtained during the 1990 CFHT observations is plotted together with spectra obtained using the 1.2-m telescope at the Dominion Astrophysical Observatory (DAO) (with $R=18000$) at two different epochs (HJD 2448136 and HJD 2448596). The spectrum of the secondary star can be identified in the CFHT data on the blue edge of the line profiles of the primary by comparing the observations. Its presence is especially evident in the strong Mg II-Fe I blend at $\lambda 4482$. The positions of the Doppler-shifted $\lambda 4508$ Fe II line of the primary relative to the systemic velocity of the system is indicated by the symbol 'P' in each of these spectra. The projected rotational broadening of the primary was measured by fitting rotationally broadened synthetic profiles to the $\lambda 4501$ (Ti II) and $\lambda 4508$ (Fe II) lines to give $v \sin i = 75 \text{ km s}^{-1}$. The position and projected rotational broadening of the secondary was not determined, however the estimates derived by Peterson (1991) were at least found to be consistent with the observations.

The top panel of Fig. 2 shows the absolute mean deviation of the continuum normalized time series of spectra obtained at CFHT (i.e., $\sum |data_i - \text{mean}|$). Notice that the regions of line-profile variability are confined within the limits of profiles of the primary star. There is no evidence of variability on the blueward side of these lines where the secondary spectrum is located. It can be concluded, therefore, that the oscillations giving rise to the line-profile variations must originate from oscillations of the primary star as inferred by

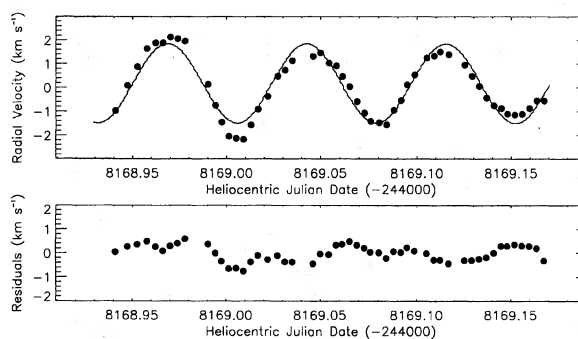


FIG. 3—Radial-velocity variations were measured using a cross-correlation technique with the mean spectrum as the template. A sinusoidal fit with a single frequency of $13.7 \text{ cycles day}^{-1}$ was made to the data and is shown as the solid curve in the figure. Non-negligible residuals obtained after removing the variation at this frequency suggest that multiple frequencies are present.

Breger et al. (1987). The width of the deviations (at $\lambda 4501$ and $\lambda 4508$) due to line-profile variability was used as an independent measure of the projected rotational broadening and gave $v \sin i = 65 \text{ km s}^{-1}$. This value is in better agreement with that obtained by Peterson et al. (1993) than is the value derived from line-profile fitting.

3. RADIAL-VELOCITY VARIATIONS

The radial-velocity variations of θ^2 Tau were determined using the IRAF cross-correlation routine (Tonry and Davis 1979) with the entire mean spectrum acting as the template. The IRAF routine measures the pixel shift between each spectrum in the series and the template by finding the value which corresponds to the maximum of the correlation function. These displacements were converted into velocities evaluated at 4500 Å .

The radial-velocity curve for θ^2 Tau is illustrated in Fig. 3. It has been fitted by a sinusoidal variation with a single frequency of $13.7 \text{ cycles day}^{-1}$ using the program PERDET (Breger 1980). Residuals after subtracting variations at this frequency are non-negligible and reflect the fact that more than one frequency is present in the star. Better agreement was obtained by fitting the data with two frequencies at $13.4 \text{ cycles day}^{-1}$ and $10.6 \text{ cycles day}^{-1}$ but the series is probably too short to warrant serious consideration of these frequencies.

4. LINE-PROFILE VARIATIONS

The variations within the line profiles of θ^2 Tau are illustrated in the time series shown in Fig. 4. The line profile displayed in this figure is actually an average of the $\lambda 4501$, $\lambda 4508$, and $\lambda 4515$ profiles which has been constructed in order to increase the signal-to-noise of the data. The residual variations formed after subtracting the mean profile are plotted on the right-hand side of the figure. The labels beside each spectrum represent the central time of observation in days relative to HJD 2448168. The line-profile variations in θ^2 Tau differ from those seen in other δ Scuti stars (e.g., κ^2 Boo, 21 Mon, σ^1 Eri, ν UMa; Walker et al. 1987) where

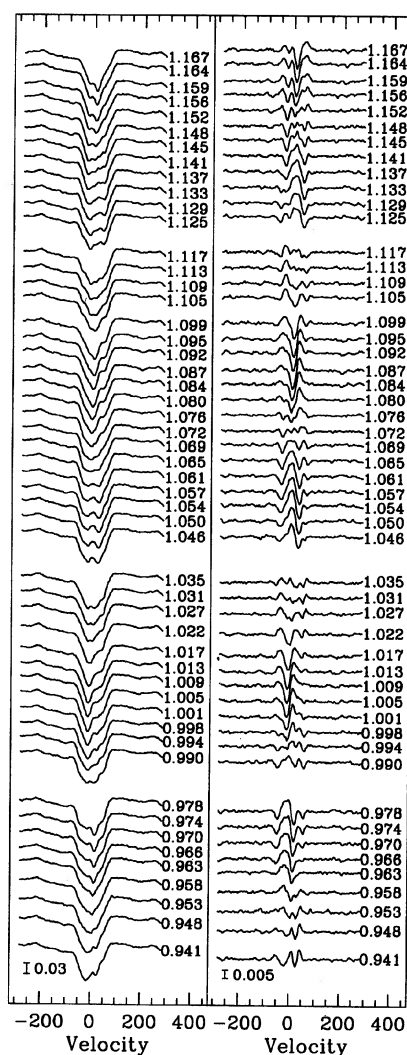


FIG. 4—The line-profile variations are illustrated as an average of three profiles (left). The variations are more clearly seen in the series of residuals calculated by subtracting the mean profile from each observed spectrum (right). The numbers on the right-hand-side represent times of observation relative to HJD 2448168. The bars indicate intensity relative to a continuum of unity.

an obvious progression of features travelling from blue to red across the profiles could be seen. Figure 4 shows a pattern of rising and falling residuals with very little motion through the profile. This type of behavior could possibly be caused by beating between the different oscillation modes.

The observations were analyzed using the method of Fourier-Doppler Imaging (Kennelly et al. 1992). Variations within the line profile were transformed as a function of time and Doppler space into their Fourier components allowing both the frequency and the mode of oscillation to be simultaneously resolved. For this calculation, $v \sin i = 65 \text{ km s}^{-1}$ was adopted. The resulting amplitude spectrum is illustrated in Fig. 5. The amplitudes are measured as a fraction of the continuum level. Using the method of Bootstrap Resampling (Press et al. 1992), the 99% confidence level was calculated

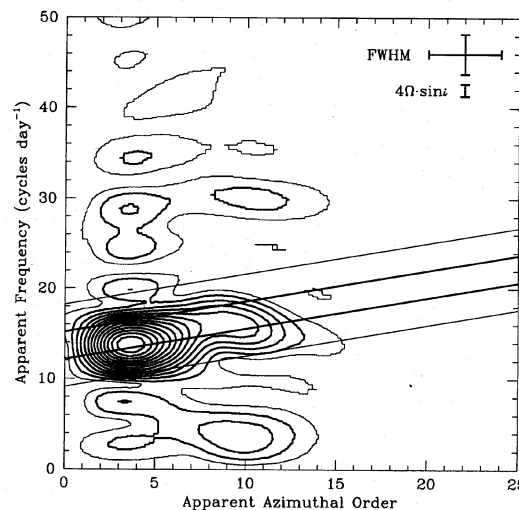


FIG. 5—The line-profile variations of θ^2 Tau were transformed in both time and space to produce this map of apparent frequency vs. apparent frequency of oscillation. The bar labeled 'FWHM' indicates the full width at half maximum resolution in both the temporal and spatial frequencies. The diagonal lines indicate the frequencies theoretically predicted to be unstable for (low-degree) prograde sectoral modes. Limiting values for models calculated with normal Helium abundance (thick lines) and for Helium-rich models (thin lines) are shown. The bar labeled ' $4\Omega \sin i$ ' gives an indication of the size of the rotational splitting. Contours have been drawn at intervals of intensity of 0.0003 relative to a continuum of unity.

to be 0.0006 relative to a continuum of unity. Above this level, there is a 99% chance that an observed peak could not be due to random (Gaussian) noise. Contours in Fig. 5 are plotted at intervals of 0.0003. Thin lines indicate amplitudes below the 99% confidence level and thick lines indicate amplitudes above this level.

Two obvious peaks can be identified in the Fourier spectrum. The largest peak occurs at apparent azimuthal order $\hat{m} = 3.6$ with frequency $\hat{\nu} = 13.8 \text{ cycles day}^{-1}$ corresponds to a low-degree mode. A smaller peak is also visible at $\hat{m} = 9.3$ with frequency $\hat{\nu} = 16.0 \text{ cycles day}^{-1}$ suggesting that high-degree variations are also present in this star. Most of the smaller peaks in Fig. 5 can be attributed to aliases of these two peaks resulting from the window function. Using Monte-Carlo simulations and approximating the variations as sinusoidal, errors in the measured quantities were estimated to be $\Delta \hat{m} = 0.2$ and $\Delta \hat{\nu} = 0.1$. However, note that if $v \sin i = 75 \text{ km s}^{-1}$ had been adopted for the star then the positions of the two largest peaks would be shifted in apparent azimuthal order to 4.3 and 11.1, respectively.

5. DISCUSSION

Using the apparent magnitude determined by Peterson et al. (1981) and the distance modulus to the Hyades cluster, the absolute magnitude of the primary star of θ^2 Tau was calculated to be $M_v = 0.47$. This corresponds to a luminosity of $L = 56L_{\odot}$. The effective temperature of the primary was estimated to be $T_{\text{eff}} = 8200 \pm 100 \text{ K}$. From these values a radius of $R = 3.7R_{\odot}$ was derived. Taking $v \sin i = 65 \text{ km s}^{-1}$, the amplitude of frequency splitting owing to first-order effects of rotation can be calculated. In Fig. 5, the frequency

separation between two modes with $\Delta m = 4$ is indicated by the bar labeled " $4\Omega \sin i$." For this calculation, the inclination is assumed to be $i = 90$. Obviously, the time series is too short to resolve frequency splittings of this magnitude.

Dziembowski (1990) has calculated the boundaries of unstable frequencies for oscillating stars with luminosities up to $L = 40L_{\odot}$. The range of frequencies spanned by unstable radial modes of oscillation were calculated for θ^2 Tau by adopting the values from Dziembowski's most luminous model (with mass $M = 2M_{\odot}$) and scaling these frequencies using the period-luminosity-color relation for δ Scuti stars (Breger 1979). The diagonal lines depicted in Fig. 5 show the theoretical limits extrapolated for prograde sectoral modes and adjusted for the effects of rotation. The thick line shows the region of instability for models which have normal Helium abundance. The thin lines illustrate the region of instability for models which are overabundant in Helium. Very good agreement is found between Dziembowski's model and the frequencies derived from photometric (and from the radial-velocity) variations.

As good as the CFHT observations are, they lack the frequency resolution necessary to identify all the low-degree modes known to be present in θ^2 Tau. The amplitude of the radial-velocity variations at $13.7 \text{ cycles day}^{-1}$ is large; it is therefore unlikely that the variations at this frequency could arise from a mode with $\ell > 2$. However, the large variations detected in the line profiles with apparent azimuthal order $m = 3.6$ at nearly the same frequency suggests that the mode responsible for the variations must be close to $\ell = 3$. Therefore, the most probable explanation for the low-degree variations detected in these observations is as an $\ell = 2$ (possibly sectoral) mode. However, because the resolution is so poor, it is not possible to say for sure whether the variations detected in radial velocity have the same origin as those seen in the line profiles. In order to fully resolve the spectrum of modes, observations lasting several days are required.

The natural explanation for the high-degree variation in θ^2 Tau is as a prograde, sectoral, pressure mode (say $\ell = 8$ or 9) trapped in the envelope of the star. If this is the case then Fig. 5 suggests that the mode has a frequency in the corotating frame which is not very different from the frequencies resulting from the low-degree variations. Similar correlations between the frequencies of high- and low-degree modes have been recognized in observations of τ Peg (Kennelly et al. 1992) and ν UMa (Korzennik et al. 1995). Why such a connection should exist between the oscillation frequencies is still unknown. The low-degree modes of θ^2 Tau have been shown to be consistent with p -modes of radial

order $n = 2$ or 3 (Breger et al. 1987). Thus, if the high-degree variations do in fact result from a pressure mode then the radial order of this mode must be less than $n = 2$ or 3. Theoretical calculations are needed in order to verify this possibility.

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