Search for TiO-band variability in the spectrum of the T Tauri star V410 Tau

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In 1991–1992, we observed the spectrum of the star V410 Tau in the vicinity of the TiO bands near 7100 Å with low spectral resolution and high signal-to-noise ratio. The star’s brightness is correlated with the strength of the TiO bands, confirming the suspected existence of cool spots on the star’s surface. We model this relationship using synthetic spectra of the photosphere and spots.

**Introduction.** T Tauri stars are well known as irregular variables, but against the background of irregular light variations one can also observe a periodic component. More than 20 T Tau stars are presently known whose brightness varies periodically. Their periods range from 2 to 15 days, and the amplitude of variability may reach several tenths of a magnitude (Shevchenko et al., 1991). For those instances in which the period derives from the axial rotation of the star, and the shape and phase of the light curve are sufficiently stable, periodic variability can be interpreted in terms of rotational modulation of the brightness by temperature irregularities (cool spots or hot spots) on the surface of the star, by analogy with what is observed in BY Dra and RS CVn stars. There is a large literature dealing with spotted T Tau stars [see, e.g., Bouvier and Bertout, 1989].

The best-studied of these stars is V410 Tau, which is dominated by a periodic, almost sinusoidal variability whose amplitude ΔV ranges up to 0.043, and whose period can remain stable at 14.871 for several years at a time (Herbst, 1989). V410 Tau has a weak T Tau type emission spectrum, with a strong lithium absorption line and the photospheric spectrum of a K3−K4 star (Herbig, 1977).

Although the light curve of V410 Tau can be satisfactorily fit by a model with one or two cool spots on the star’s surface (for an appropriate choice of a few free parameters), that model requires spectroscopic confirmation. The most informative method for mapping the surface of a star using absorption lines (Doppler imaging) requires high spectral resolution, which has yet to be achieved for any T Tau star. A similar approach relies upon low-dispersion spectroscopy of the TiO bands. These bands are either completely lacking or very weak in the spectra of K3 III stars, but if the temperature of the photosphere is only 500 K lower (moving from type K3 III to M0 III), they become much stronger. Observations of TiO bands have provided firm confirmation of the existence of cool spots on the surface of two RS CVn stars, HR 1099 (Ramsey and Nations, 1980) and II Peg (Vogt, 1981). Narrow-band filter photometry of V410 Tau at 7124 Å has revealed a correlation between the star’s brightness and color index, which is related to the depth of the TiO bands (Herbst and Levreault, 1990).

In the present paper, we analyze high-accuracy spectroscopic observations of V410 Tau with the aim of detecting a correlation between the star’s brightness and the strength of the TiO bands, perhaps obtaining numerical estimates that can impose tighter constraints on a spot model for the star.

**Observations.** The TiO bands near 7100 Å are the most suitable target for the present study, since in that region of the spectrum there are few atomic lines or blended bands of TiO, there are no strong terrestrial atmospheric lines, and the CCD array with which we observed was most sensitive there. These bands belong to the molecule’s γ system, which exhibits considerable multiplet splitting. The components of the A3Π−X3Δ electronic transition can be split by up to ~30 Å. Even at low spectral resolution, the individual R-branch subband heads are visible at 7054, 7087, and 7125 Å. The bands become prominent at temperatures $T_{\text{eff}} < 4350$ K.

We observed with a diffraction spectrograph mounted at the Nasmyth focus of the 2.6-m Shain telescope. The detection system was a domestically produced CCD camera (Berezin et al., 1991). With a dispersion of 100 Å/mm (2.2 Å/pixel) and a 1° input slit width, the spectral resolution was 7.5 Å. When the seeing was good, a 20-min exposure produced a spectrum of V410 Tau with signal-to-noise ratio 200 in one pixel, or more than 300 per spectral resolution element. Spectra of several K and M giants obtained with the same equipment are shown in Fig. 1.

Using the observed spectra of K and M stars, it can easily be shown that if on the surface of a K3 III star there is a cool spot whose temperature is some 1000 K lower than the su-

![FIG. 1. Spectra of V410 Tau and K−M standard stars. All spectra have been normalized to the continuum. The vertical scale and identification of the principal features refer to δ Vir; other spectra have been shifted vertically upward. The terrestrial atmospheric absorption spectrum is shown below.](image-url)
TABLE I

<table>
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<th>(r), %</th>
<th>(\sigma_r), %</th>
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<td>5/6 IV.1992</td>
<td>8718.229</td>
<td>10.86</td>
<td>5.5</td>
</tr>
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</table>

The measurement accuracy of the band intensity in the stellar spectrum should therefore be no worse than ±0.5%.

To reach that level of accuracy, the spectral observations must be differential measurements (i.e., standard star − variable − standard star). With the standard star being located as close as possible to the variable in order to make sure that terrestrial atmospheric lines (\(\text{H}_2\text{O}\) and \(\text{O}_3\)) are the same in both stellar spectra. The standard star must be of approximately the same spectral type as the variable. Simple division of the spectrum of the variable by the mean spectrum of the standard can then eliminate atmospheric lines. Only those features that distinguish the variable from the standard will then remain in the quotient spectrum − specifically, the TiO bands, if the temperature of the variable differed from that of the standard at the time of observation.

The standard star in our observations was \(\phi\) Tau (K3 III), an immediate neighbor. In Fig. 2, we have plotted two spectra of V410 Tau divided by the spectrum of \(\phi\) Tau, and normalized to the intensity at 7050 Å. The observations were differential measurements as described above. The spectra were obtained approximately one hour apart, and with a 20-min exposure of V410 Tau. In dividing one spectrum by the other, we can identify large-scale inhomogeneities due to variations in the earth’s atmosphere between exposures on the standard and the variable; we can also assess how the measurement accuracy is affected by quantum noise. In the vicinity of the TiO bands, where atmospheric lines exert a negligible influence,

![FIG. 2. Spectra of V410 Tau obtained approximately one hour apart. Relative intensity measurement accuracy is ±0.5% in one pixel.](image)

the measurement accuracy is ±0.5% of the continuum level for operations on one pixel, which is consistent with the statistical accuracy at that signal level. Since we employed about 10 pixels in determining the size of the intensity jump \(r\) in the TiO bands, we can count on reaching a measurement accuracy \(\sigma_r = ±0.2\%\) (the rms measurement error in the intensity jump at the 7054 Å band head). Detecting cool spots on the surface of this star is thus entirely feasible. Unfortunately, the 1991–1992 Crimean winter observing season was unusually poor, and we managed to obtain spectra on only nine nights; three of those nights were reasonably good, and we achieved ±0.2% accuracy. The accuracy on the other nights was ±0.4–0.6% (see Table I).

The magnitudes listed in Table I for the epochs of the spectroscopic observations were obtained from the light curve of V410 Tau for August–November 1991. Photometric data covering that period were kindly furnished by V. S. Shevchenko. Several of the magnitude estimates were obtained at the Crimean Astrophysical Observatory by D. N. Shakhovskii and M. N. Lovkaya in January–March 1992, and those are also in good agreement with Shevchenko’s light curve. This suggests that the light curve of V410 Tau was stable in 1991–1992. The period is \(14^d 872\), the brightness amplitude is \(\Delta V = 0^m 44\), and the amplitude of color-index variations is \(\Delta(B - V) = 0^m 06\). Although our spectroscopic observations were not made at exactly the same time as the photometric observations, the stability and smoothness of the light curve of V410 Tau during the 1991–1992 season enable us to calculate the phase and derive \(V\) to an accuracy of ±0.02. The spectroscopic observations span brightness values from maximum light to \(0^m 25\) lower.

**Results.** The TiO band heads are quite evident in the “differential” spectra of V410 Tau and \(\phi\) Tau (Fig. 2), since the effective temperature of the former is somewhat lower than that of the latter. Table I lists the dates of all observations, the measured size \(r\) of the intensity jump at the 7054 Å band head, and the rms error \(\sigma_r\). In Fig. 3 we have plotted \(V\) against the intensity jumps. We are confident that the star’s brightness is...
correlated with the strength of the TiO molecular bands, which qualitatively confirms the existence of a previously hypothesized cool spot on the surface of V410 Tau. The analysis can be made quantitative by comparing photometric and spectroscopic models of the spot. Taking the approach described by Dorren (1987), and having determined an effective temperature 4250 K for V410 Tau at maximum light based upon the strength of the TiO bands, we have found that the 1991–1992 light curves and color of V410 Tau can be fit by a model spot at 3600 K that covers 50% of the star’s visible disk. The star’s limb darkening coefficient has been taken to be 0.89 (Herbst, 1989). Although the approach taken by Dorren (1987) enables one to find a spot radius and location on the stellar disk, it would be unwarranted to read any physical meaning into it, as it only amounts to substituting one or two circular spots for a complex topography of temperature irregularities.

**Synthetic spectra.** With a spot model derived from the photometric data, we can model the V-dependence of r shown in Fig. 3 using synthetic spectra of the spot and the unperturbed photosphere. To calculate the synthetic spectrum of the (0, 0) R system of TiO, we used the model of Bell et al. (1976) in the 4000 to 5000 K temperature range, and the model of Johnson et al. (1980) from temperatures 2500 to 4000 K. On the 4000–5000 K grid, we interpolated two models: the first, with Teff = 4360 K and log g = 2.2, to fit the observed spectrum of φ Tau, and the second, with Teff = 4250 K and log g = 2.0, to fit the observed spectrum of V410 Tau at maximum light.

We calculated synthetic spectra for log g = 2.0 and temperatures 4000, 3600, 3200, and 2500 K, and temperatures 4000, 3600, 3200, and 2500 K. Phillips (1973) has measured and listed the rotational lines of the TiO molecule in the 7000–7200 Å range. Lower-level excitation potentials and oscillator strengths for all lines were taken from the dissertation by Khyanni (1985). We assumed a value of 0.36 for the (0, 0) electron oscillator strengths. Since the observed spectrum of V410 Tau was divided by the spectrum of φ Tau and normalized to the intensity at 7050 Å, we treated the synthetic spectra of those stars in the same way, and reduced the results to the observational spectral resolution.

In Fig. 4, we compare the calculated and observed V410 Tau/φ Tau ratio. The integrated spectrum of the star plus spot was calculated at different rotation phases according to

\[ F_{\text{total}} = (1 - A) \cdot F_{\text{phot}} + A \cdot F_{\text{spot}}, \]

where A is the relative area of the spot at a given phase, as calculated by integrating across the disk of the star with limb darkening taken into account. Next, we used the integrated synthetic spectrum at each phase to determine the size of the intensity jump r, and we used the light curve computed with the same spot model to calculate the V magnitude. The theoretical behavior obtained in this way for various spot temperatures is shown by the dashed curves in Fig. 3. The fit to the observations is clearly good overall, but as the star becomes fainter, the observed value of r differs from the value calculated for a spot temperature of 3600 K, i.e., the TiO bands are modulated less strongly than implied by the photometric model of the spot.

**Discussion and conclusions.** Our principal result is that the spectroscopic observations yielded reliable confirmation that a cool spot exists on the surface of V410 Tau. The discrepancy between the observed and calculated modulation of the TiO bands can be eliminated if we accept a temperature difference between the photosphere and the spot of about 1500 K, although this with be inconsistent with the 1991–1992 amplitude of color-index variations, \( \Delta(B - V) = 0.06 \). One possible reason for this problem is that our model atmospheres for cool stars are not entirely consistent with the actual atmosphere above the spot, in the sense that that region of the atmosphere, where the molecular TiO lines are produced, is somewhat hotter than predicted by the model. This is a preliminary conclusion, as we have no spectra of V410 Tau at minimum light. We hope to obtain more complete data from forthcoming observations in 1992–1993.

We thank V. S. Shevchenko for providing photometric results on V410 Tau prior to publication, and D. N. Shakhovskii and M. N. Lovkaya for estimating the brightness of V410 Tau at the time of our observations.


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