

# CH Cygni: TiO molecule as a probe of temperature variations in the atmosphere of the cool component

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**Abstract.** We report our determination of  $T_{\text{vib}}$  from band systems of TiO in the visible spectra of the symbiotic star CH Cygni during its 1987-89 quiescent phase as well as  $\beta$  And and 30 Her, which are taken as comparison stars. The problems usually met by attempting to perform quantitative analysis of the atmospheres of late M-type stars have been taken into account and discussed in detail. Assuming the LTE, Born-Oppenheimer approximation, constant electronic transition moment for an electronic band and neglecting the vibration-rotation interaction but thanks to the sensitivity of the method used, the vibrational temperature of the outer atmospheric layers of the cool component of CH Cygni has been determined to be changing from about 2000K to 2200K during the observed two year period. The errors of the applied method are small enough to allow the interpretation of this temperature variation as a result of intrinsic variability of the cool component. The possible influence of the symbiotic mechanism has been excluded. The results obtained for CH Cygni fit well with the temperatures of the two comparison stars determined from the spectra on one hand and taken from the literature on the other.

**Key words:** stars: atmospheres – stars: binaries: symbiotic – stars: fundamental parameters – stars: individual: CH Cyg – stars: late-type

## 1. Introduction

The symbiotic star CH Cygni has been thoroughly investigated in its active phases by Mikolajewski et al. (1992) and Munari et al. (1996). There are not so many studies of the periods of inactivity (Jurdana and Kotnik-Karuza 1994, Bode et al. 1991, Kotnik-Karuza and Jurdana-Šepić 1997, Kotnik-Karuza and Jurdana-Šepić 1998), especially those trying to reveal the development of the physical conditions in the atmosphere of the cool component. The latter is of particular interest since it may lead to important conclusions about the origins and nature of the symbiotic phenomenon.

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Effective temperature of the M type cool component of CH Cygni, which is lower than 4000K (Taranova 1990) implies the apparition of molecular bands with a lot of lines which add to numerous atomic lines in the optical spectrum.

Molecules can serve as primary probes and direct diagnostic tools of atmospheric structure of stellar outer layers and CS envelopes (Tsuji 1986). In particular diatomic molecules present attractive possibilities for the determination of an excitation temperature due to exceptional temperature sensitivity of the molecular band intensities (Phillips 1954, Milone and Barbuy 1994, Valenti et al. 1998).

In the work we are describing here, we have sought the vibrational temperature, implied by the relative populations of vibrational states on the assumption of a Boltzmann distribution.

We have studied the absorption features of the titanium monoxide molecule TiO which is generally the main opacity contributor in the spectra of M-type stars, reaching its maximum intensity at the M8 type (Christy 1929). The TiO band systems blanket the spectrum from the visible region well into the infrared. Several electronic band systems of TiO dominate the visible spectrum of M type stars to such an extent that it has become the primary criterion for establishing spectral types. TiO is also known to affect the stellar atmosphere structure considerably (Jorgensen 1994).

Because of their prominence in stellar spectra, the electronic transition band systems of TiO have been the object of extensive experimental studies and more recently, of a number of theoretical investigations (Plez 1992 and 1998). The resulting set of molecular parameters is accurate enough to make possible the identification of spectral features and their intensity measurement, even in such complicated partially resolved spectra as in our case.

## 2. Observations

The spectrograms used in our measurements were observed with a Coude spectrograph at the 152 cm telescope of the Haute Provence Observatory and digitized with the PDS microdensitometer of the Trieste Observatory as described in our previous work (Kotnik-Karuza et al. 1992). The spectrograph was operated at reciprocal linear dispersion of 10-20 Å/mm. CH Cygni

was observed during its inactive phase 1987-89 and the comparison stars  $\beta$  And 1982 and 1988 and 30 Her 1967 and 1978.

### 2.1. General description of the spectrum

The extreme complexity of these rich spectra in the optical region  $\lambda$  3800-6800 Å is to a great extent a result of a large number of overlapping molecular bands belonging to different isotopes with multiple branches and generally unresolved rotational structure with  $\lambda$ -doubling in some electronic states. The largest number of these features belong to the TiO molecule which is the dominating opacity source in the photospheres of a wide range of M-type stars.

We searched our spectra for bands of the four band systems  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\gamma'$  (Table 1) which are the most important in the visual region (Jorgensen 1994). The  $\alpha$  system was difficult for identification and intensity measurement because of blending with numerous atomic lines characteristic for the blue part of the optical spectrum. Analysis of the beta system proved impossible as its bands were overlapped by the strong sequence of the  $\gamma'$  system and possibly other weak systems (Linton 1974). The  $\gamma'$  band system bridges the gap between the  $\alpha$  and  $\gamma$  systems and is blended with both of them. It is the only system where the satellite bands are of any relevance for the opacity and we managed to identify some of them. Finally, the  $\gamma$  system has proved to be the most productive since it absorbs in the red spectral range where the effects of blending and overlapping are reduced compared with other regions.

### 2.2. Identification

By looking for sequencies and regarding the Doppler shift of the band heads, which should be approximately photospheric (Kotnik-Karuza et al. 1992), we have identified a large number of red degraded bands in our spectra. We looked for the band heads in Jorgensen's line data (1994) by searching for inflection points in wavenumber as a function of lower rotational quantum number  $J''$ . The isotopic bands were difficult to find because their intensities were too small. Anyway, we take them as one of the factors which hindered accuracy of our measurements. All the identified band heads of CH Cyg,  $\beta$  And and 30 Her are given in the electronic version of this paper (Table 5).

## 3. Methods

In order to determine the excitation temperature of the upper photospheric layers where the TiO molecules are formed, we used one of the three classical methods (Phillips 1951) which proved to be the most convenient for our spectra where the rotational fine structure of the molecular bands is almost completely unresolved. The method generally requires the measurement of the relative integrated intensities of individual bands within a given system and yields the vibrational temperature as a result.

In the case of thermodynamic equilibrium and Boltzmann population of the vibrational states the ratio of intensities of two

**Table 1.** Electronic transitions corresponding to the band systems of TiO in the visual

Band system	transition
$\alpha$	$C^3\Delta - X^3\Delta$
$\beta$	$c^1\Phi - a^1\Delta$
$\gamma$	$A^3\Phi - X^3\Delta$
$\gamma'$	$B^3\Pi - X^3\Delta$

bands is given by the equation (Phillips 1954)

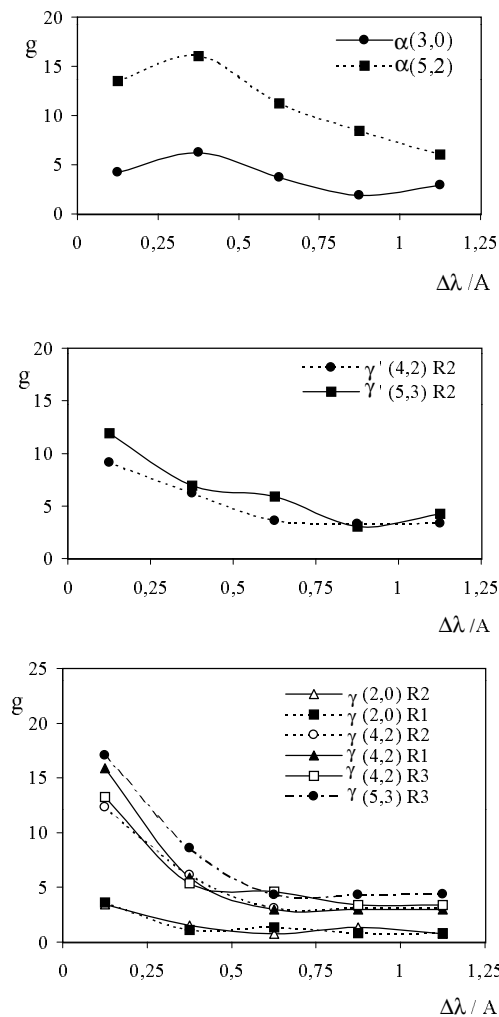
$$\frac{I_1(v', v'')}{I_2(v', v'')} = \frac{\nu_1(v', v'') q_1(v', v'')}{\nu_2(v', v'') q_2(v', v'')} \exp\left(-\frac{E_1(v'') - E_2(v'')}{kT}\right) \quad (1)$$

Subscripts 1 and 2 refer to any two bands of a system (with a different  $v''$ ).  $v'$  and  $v''$  refer to the vibrational levels of the higher and the lower electronic state respectively.  $\nu_1$  and  $\nu_2$  are the frequencies of their respective band origins;  $E_1(v'') - E_2(v'')$  is the difference in vibrational energy of the respective initial states;  $q_1$  and  $q_2$  are the Franck Condon factors (FCF). The FCF's have been taken from Bell et al. (1979).

The equation has been derived under assumption of the Born Oppenheimer approximation and when merging of the rotational structure is implied. The electronic transition moment for radiative transitions is assumed to be constant for an electronic band. This is justified for transitions from or to low vibrational levels as in our case. The FCF's vary over many orders of magnitude across the bands of a molecular spectrum (Nicholls 1965). They thus exert a controlling influence upon the intensity distribution in the system and are generally affected by the vibration-rotation interaction. The latter has been neglected in this work.

Regarding the validity of the LTE approximation, one has to be aware that it cannot be maintained at low temperatures and densities which are present high in the photosphere of the cool component (Valenti et al. 1998). Besides, the line formation mechanism for electronic transition bands from the ground state which refers to the  $\alpha$ ,  $\gamma'$  and  $\gamma$  band systems of TiO in the visible, could be scattering rather than absorption (Hinkle and Lambert 1975). This brings the validity of LTE in question (Brett 1990). Also, the adequacy of hydrostatic equilibrium and homogeneity assumption for the surface layers may be questioned because of the presence of strong winds around our late-type cool giant on one hand and convection as well as other large scale motions (waves and shocks) on the other (Plez 1992). Considering the error in vibrational temperature determined by this method, there are also saturation effects to be taken account of. It is well known that the TiO bands begin to saturate at temperatures lower than 3000K (Alvarez and Mennessier 1997), i.e. in the temperature interval in which we expect to obtain our results.

It should be born in mind that a different degree of saturation of the two bands which form the pair in the intensity ratio leads to a higher value of estimated vibrational temperature than the real



**Fig. 1.** Verification of the band structure close to the band heads of the  $\alpha$ ,  $\gamma'$  and  $\gamma$  band systems which have been selected for the relative intensity measurements

one. Otherwise, if the saturation of the two bands is comparable, its effect is compensated and may be neglected.

### 3.1. Intensity measurement

One of the greatest problems in the measurement of band intensities is the lack of knowledge regarding the location and structure of the underlying continuum. Namely, an unresolved pseudo-continuum has been formed as a result of overlapping of molecular bands across the whole optical spectrum as well as atomic lines prevalently toward its blue part.

For the background intensity we took the “local” continuum which was reached immediately to the violet of the head. This simplifying assumption as to the intensity of the continuum undoubtedly introduced systematic errors into the determination of the intensity of an individual band. However, carrying out the same procedure for the two heads of a pair the effects of these errors would have a minor effect on the final intensity ratio. In our case of close bands the estimated uncertainty in the local

continuum level reduced to maximum 10% in the red, and 20% in the blue part of the optical spectrum.

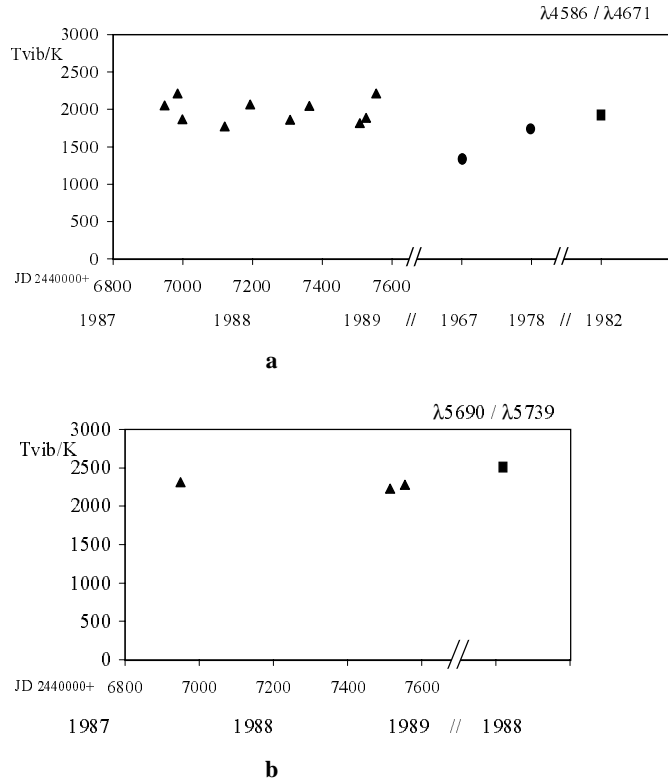
The total absorption of bands has been impossible to measure since the structure due to the upper rotational levels is almost always overlapped by the heads of other bands, and the position of even the “local” continuum can be estimated only near the band heads. Besides, some of the heads themselves are not well defined. We took the greatest absorption depth near the band head, which appears usually as the “break” in the continuum, as the measure for the total absorption in the band. This has been justified only for bands with the same structure and thus we had to verify it and to restrict our choice of candidates for intensity measurement to these bands. Considering the fact that the strong absorption at the head is produced by a blending of overlapped rotational lines which are closely spaced relative to their individual widths it was sufficient to test the structure in a rather narrow wavelength interval at the head as shown in Fig. 1. The total interval  $\Delta\lambda$  equal to  $1.25\text{\AA}$  has been divided in  $0.25\text{\AA}$  wide segments. The mean of the strengths  $g$  ( $g = q_{v',v''} S_{J',J''}$ ) of the corresponding rotational lines falling within each interval is represented by a point in the graphs of the Fig. 1.

There are other additional criteria which we have followed during the selection of band heads suitable for intensity measurement. Lower members of the sequences have been preferred since the ‘tails’ of the closer, higher ones are blended with the following bands of the sequence leading to a severe truncation of the continuum. Furthermore, the two heads forming the pair in each intensity ratio are chosen to be close enough in order to reduce the error in continuum estimation. On the other hand, the two heads should be well resolved. This condition determines the minimal separation limit.

Blending with atomic lines and molecular features must be also taken into consideration. In order to avoid, or at least to reduce the errors caused by saturation, we restricted ourselves to weaker bands in the spectra. This is consistent with the requirement for not too high FCF’s. Their values for the constituents of a band pair should be comparable in magnitude to provide a similar saturation in each band, but not too small to ensure a measurable intensity.

The factor which generally hinders the accuracy of band intensity measurements in the spectra like ours is the presence of the four other less abundant titanium isotopes which together account for nearly 30% of the TiO molecules (Jorgensen 1994). They are all expected to have only about 10% of the intensity of the main isotope  $\text{Ti}^{48}\text{O}^{16}$  (Linton 1974). Hence, it is difficult to identify them in the spectra. We did not look for them, though we are aware of their contribution to the complex spectral structure.

The complexity of our spectra is also influenced by the splitting of the branches due to interactions in the molecule. The electronic states contributing to the  $\alpha$  and  $\gamma$  band systems are in Hund’s case (a) coupling, so that intermultiplicity transitions are extremely weak. We have left them out from our considerations since their contributions were found to be less than 6% for the  $\gamma$  and less than 0.2% for the  $\alpha$  system (Collins and Fäy 1974). On the other hand, the upper state of the  $\gamma'$  system uncouples fairly rapidly to case (b) with increasing rotation.



**Fig. 2a and b.**  $T_{vib}$  determined at different times in the spectra of CH Cyg (triangles), 30 Her (circles) and  $\beta$  And (squares) for the given intensity ratios of the band heads **a** :  $\alpha$  band system; **b** :  $\gamma'$  band system; **c** :  $\gamma$  band system

Consequently, the satellite branches of this system become allowed (Merer 1989) and relevant for the TiO opacity. Further, a breaking-off of branches in bands of the  $\alpha$  system has been ascribed to a series of perturbations experienced by excited vibrational states in the upper electronic state, with  $v'$  ranging from 4 to 7 (Phillips 1972). This fact should be taken into account when identifying the bands.

Since the resolution in our spectra is not high enough to resolve completely the individual rotational lines, instead of measuring the integrated band intensities we used the possibility to measure the peak absorption intensities at the band heads. Measurements of integrated band intensities has been also prevented by rather large overlapping of molecular spectral features even in the red spectral region with scarce atomic lines. The method is justified for the bands with the same structure, i.e. where the lines which contribute to its peak intensity lie within the same range of rotational quantum number  $J$  and, furthermore, the relative positions of these lines are the same for each band (Fig. 1). A high degree of accuracy could be reached if these conditions are fulfilled exactly and also if the individual bands are unblended, so that the true location of the background continuum at each band is known (Phillips 1954). In our spectra the condition concerning the structure of the measured bands has been fulfilled. The main contribution to the error in the vibrational temperature derived from this measurements is due to blending.

**Table 2.** Data for the  $TiO$  band heads used for the determinations of the vibrational temperature

$\lambda / \text{\AA}$	transition	$q_{v'v''}$	$J''_{head}$	$N_{[1\text{\AA}]}$
4584,288	$\alpha(3, 0)R_2$	0,05490	8	30
4670,280	$\alpha(5, 2)R_1$	0,16850	8	30
5689,624	$\gamma'(4, 2)R_2$	0,15180	14	35
5738,959	$\gamma'(5, 3)R_2$	0,19730	13	36
6321,188	$\gamma(2, 0)R_2$	0,03975	14	17
6351,267	$\gamma(2, 0)R_1$	0,03975	15	18
6420,594	$\gamma(4, 2)R_3$	0,15480	13	16
6447,880	$\gamma(4, 2)R_2$	0,15480	14	16
6478,987	$\gamma(4, 2)R_1$	0,15480	15	17
6484,644	$\gamma(5, 3)R_3$	0,20050	13	16

Besides, in the vibrational analysis one always has to allow for some discrepancies originating from the use of the heads instead of the band origins.

The great value of this method lies in its numerical sensitivity: the ratio of relative intensities of two bands which satisfies the basic expression for the vibrational temperature determination and which yields a temperature of the correct order of magnitude lies within a narrow interval of values. If the intensity ratio taken from the spectrum falls outside this interval, it is a sign that at least one member of the pair should be discarded either because of a wrong identification or as a result of a too large error in the measured intensity. This selfcontrolling effect leads to the ultimate reduction of the set of band heads chosen for the determination of the vibrational temperature (Table 2).

The measured absorption depths of the band heads of CH Cyg, 30 Her and  $\beta$  And are introduced in Table 3.

#### 4. Results

The numerical results are displayed in Tables 4a and b. Their graphical representation is given in Fig. 2a-c.

In the LTE approximation the values for the  $T_{vib}$  of CH Cyg for different band head intensity ratios in the same spectrum shown in the vertical columns of Tables 4a and 4b should be equal. Nevertheless, we do not give the mean value for  $T_{vib}$  across the entire optical spectrum at each time since the band heads belong to different band systems and spectral ranges where the intensity measurements could not be carried out with equal confidence. Hence, we give separately the vibrational temperatures obtained for different band systems. Particularly, for the  $\gamma$  system the mean value of the  $T_{vib}$  has been calculated for each spectrum by use of 11 intensity ratios. The mean quadratic error  $\sigma$  refers to the  $1\sigma$  dispersion related to the calculated average  $T_{vib}$ . In the  $\alpha$  and  $\gamma'$  systems only one intensity ratio could be taken for the determination of the vibrational temperature.

The greatest credibility has been assigned the  $\gamma$  system not only because of the great number of intensity ratios compared to the other two systems. It dominates the red spectral region with almost no atomic absorption to quench the continuum and hence to give an impression of a higher vibrational temperature. Furthermore, the members of a triplet ( $R_1, R_2, R_3$ ) have the

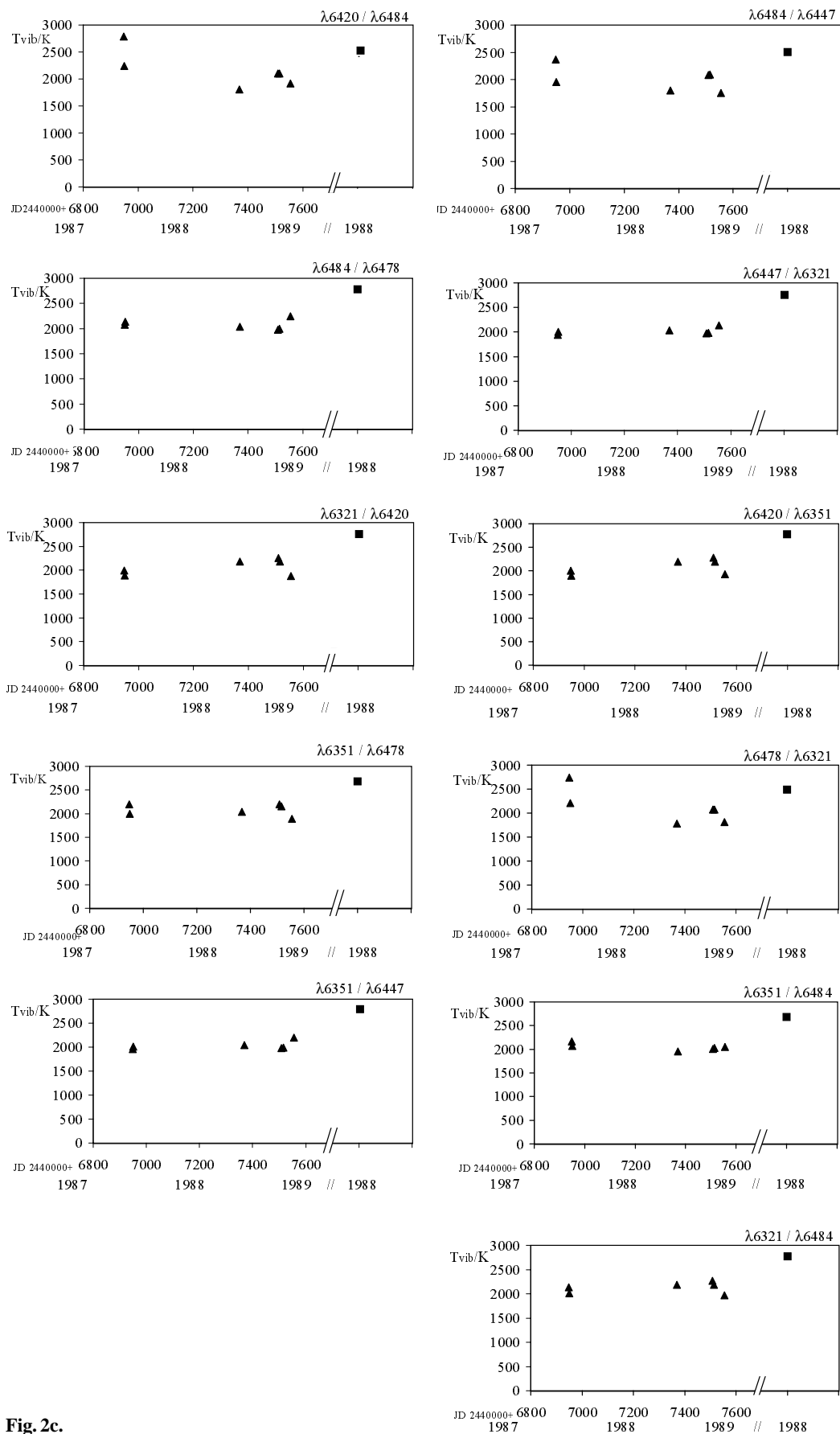


Fig. 2c.

**Table 3.** Measured  $TiO$  band heads in the spectra of CH Cyg during the period 1987-89, 30 Her and  $\beta$  And. Symbols: (-)not identified, (/)not in the wavelength range of the spectrogram

$\lambda_{\text{head}} / \text{\AA}$	transition	CH Cygni															30 Her		$\beta$ And		
		1.6. 87.	2.6. 87.	4.6. 88.	9.7. 88.	20.7 87.	21.11 87.	18.2. 88.	27.5. 88.	21.7. 88.	25.7. 88.	13.12 88.	15.12 88.	21.12 88.	29.12 88.	27.1. 89.	29.1. 89.	1967	1978	1982	1988
4584,288	$\alpha$ (3,0) $R_2$	0,87	/	/	0,81	0,81	0,67	0,93	0,82	0,97	/	0,85	/	/	0,88	0,92	/	0,52	0,78	0,85	/
4670,280	$\alpha$ (5,2) $R_1$	0,65	/	/	0,67	0,60	0,40	0,70	0,53	0,72	/	0,53	/	/	0,58	0,76	/	0,23	0,47	0,64	/
5689,624	$\gamma'$ (4,2) $R_2$	/	-	0,40	-	/	/	/	/	/	/	/	/	0,38	0,49	/	/	/	/	/	0,19
5738,959	$\gamma'$ (5,3) $R_2$	/	-	0,28	-	/	/	/	/	/	/	/	-	0,26	/	/	0,34	/	/	/	0,14
6321,188	$\gamma$ (2,0) $R_2$	/	0,25	0,24	-	/	/	/	/	/	0,31	/	0,29	0,35	/	/	0,31	/	/	/	0,11
6351,267	$\gamma$ (2,0) $R_1$	/	0,24	0,26	-	/	/	/	/	/	0,28	/	0,24	0,28	/	/	0,37	/	/	/	0,11
6420,594	$\gamma$ (4,2) $R_3$	/	0,22	0,22	-	/	/	/	/	/	0,29	/	0,26	0,29	/	/	0,31	/	/	/	0,15
6447,880	$\gamma$ (4,2) $R_2$	/	0,24	0,24	-	/	/	/	/	/	0,29	/	0,26	0,29	/	/	0,33	/	/	/	0,15
6478,987	$\gamma$ (4,2) $R_1$	/	0,22	0,22	-	/	/	/	/	/	0,29	/	0,26	0,29	/	/	0,32	/	/	/	0,15
6484,644	$\gamma$ (5,3) $R_3$	/	0,17	0,15	-	/	/	/	/	/	0,17	/	0,17	0,19	/	/	0,19	/	/	/	0,11

same band structure (Fig. 1), which means that the band heads should have approximately the same intensity. Hence, they can be used for better verification of the local continuum. On the other hand, the  $\alpha$  system covers the blue part of the spectrum where the continuum is heavily truncated by atomic lines. In addition, due to its high absorption coefficient (Jorgensen 1994) it is reasonable to assume that the band heads are saturated which would lead to higher vibrational temperatures than the real ones.

The perturbations in the upper electronic state of the  $\alpha$  system occurring in the region of the vibrational levels of the measured band, could also influence the errors of the vibrational temperature determined from this system. The  $\gamma'$  system falls in the green part of the optical spectrum where it overlaps with  $\alpha$ ,  $\beta$  and  $\gamma$  band systems of TiO. Apart from this reason the intensity measurements at the band heads have been less reliable than in the  $\gamma$  system because the different band structures of the triplet members ( $R_1$ ,  $R_2$ ,  $R_3$ ) do not make possible a reliable determination of the local continuum.

With regard to the given arguments, we accept the results obtained from the  $\gamma$  band system as the upper limit for the vibrational temperature at various times during the observed two year period. This conclusion is supported by comparison with  $\beta$  And and 30 Her taken as comparison stars. In Fig. 2 the obtained values for CH Cyg are represented by triangles, for 30 Her by circles, and for  $\beta$  And by squares. Our measurements confirm a higher vibrational temperature for the earlier type star  $\beta$  And (M0III) with exception of the  $\alpha$  system in the blue spectral region, the results of which are to be taken with minor confidence for the reasons mentioned above. For 30 Her (Sr M6III) which is approximately of the same spectral type as CH Cyg, we had only two blue spectra on our disposal. The vibrational temperature obtained from the spectrum taken in 1978 fits well with CH Cyg (Fig. 2a). The deviation of the value from the 1967 spectrum toward lower temperatures than expected could be explained either by less reliable results from the  $\alpha$  system and/or by the variability of this star. It is well known that the hydrostatic equilibrium is a questionable assumption and that there are departures from LTE which may cause structural changes in the atmosphere (Plez 1992).

The deviations from a steady value of  $T_{\text{vib}}$  across a prolonged period of time (horizontal rows in Tables 4a and 4b) could reflect either a variation of physical conditions caused by the symbiotic phenomenon, as for example heating of the red giant's atmosphere by the hot component, or they could be due to the intrinsic variability of the red giant. In favour of the latter assumption speak erratic vibrational temperature variations spread over an interval of 400K.

The maximal temperature change  $\Delta T_{\text{vib}} = T_{\text{max}} - T_{\text{min}}$  in the observed two year period for CH Cyg has been given in Tables 4a and b. This agrees with the intrinsic variability effective temperature variations of  $|400\text{K}|$  given by Taranova (1990) and is by an order of magnitude superior to the experimental error.

Since the majority of TiO bands are formed in the outer surface layers of the red giant's atmosphere (Brett 1990), they would be the best indicator of a possible heating of the cool atmosphere by the hot component. Our results rule this effect out and support the evidence given by Huang et al.(1994). Taking all of the uncertainties and discrepancies mentioned above into account, as well as the intrinsic variability of the red giant, we take the mean vibrational temperature variations between 1980 and 2216K of the  $\gamma$  system during the observed two year period as our final result.

## 5. Discussion and conclusions

The results of the present paper compared with estimates for other M giants obtained from literature are shown in the  $T_{\text{exc}}$  vs.  $T_{\text{eff}}$  diagrams Figs. 3a-b. In Fig. 3a the calibration of the effective temperature scale for M giants has been taken from Tsuji 1978 and in Fig. 3b from Bell and Houdashelt 1997. The referred values of atomic excitation temperatures are marked with white symbols: diamonds (Kotnik-Karuza and Jurdana-Šepić 1998), circles (Yamashita 1965) and squares (Komarov et al. 1974, Komarov et al. 1977). Black symbols stand for the molecular data: vibrational temperatures of CH Cyg,  $\beta$  And and 30 Her from this work (diamonds), rotational temperatures of some other M giants from Tsuji 1991 (circles), Komarov et

**Table 4a and b.**  $T_{\text{vib}}$  of CH Cyg, 30 Her and  $\beta$  And determined at different times for the given intensity ratios of the band heads belonging to the: **a**  $\alpha$  band system; **b**  $\gamma'$  and  $\gamma$  band systems

**a)**

		$T_{\text{vib}}/\text{K}$										$\Delta T_{\text{vib}}$	$T_{\text{vib}}/\text{K}$		
Band system		CH Cyg											30 Her		$\beta$ And
	Date	1.6. 1987	9.7. 1987	20.7. 1987	21.11. 1987	18.2. 1988	27.5. 1988	21.7. 1988	13.12. 1988	29.12. 1988	27.1. 1989	-	1967	1976	1982
	JD 244000+	6947	6985	6998	7120	7193	7308	7363	7507	7526	7553	-	-	-	-
$\alpha$	$\lambda 4586$ $\lambda 4671$	2054	2215	1871	1769	2065	1861	2044	1818	1884	2213	446	1492	1779	2065

**b)**

		$T_{\text{vib}}/\text{K}$							$\Delta T_{\text{vib}}$	$T_{\text{vib}}/\text{K}$
Band system	Date	CH Cyg								$\beta$ And
		2.6. 1987	4.6. 1987	25.7. 1988	15.12. 1988	21.12. 1988	29.1. 1989	-	1988	
	JD 2440000+	6948	6950	7367	7509	7515	7555	-	-	
$\gamma'$	$\lambda 5690/\lambda 5739$	-	2316	-	-	2232	2283	84		
$\gamma$	$\lambda 6420/\lambda 6484$	2798	2237	1805	2098	2104	1914	993	2528	
$\gamma$	$\lambda 6484/\lambda 6447$	2364	1954	1795	2085	2091	1755	609	2509	
$\gamma$	$\lambda 6484/\lambda 6478$	2741	2205	1784	2070	2076	1814	957	2488	
$\gamma$	$\lambda 6447/\lambda 6321$	2075	2138	2037	1977	1992	2243	266	2782	
$\gamma$	$\lambda 6321/\lambda 6420$	1946	2002	2031	1971	1986	2132	186	2771	
$\gamma$	$\lambda 6420/\lambda 6351$	1995	1890	2181	2258	2181	1878	380	2758	
$\gamma$	$\lambda 6351/\lambda 6478$	2008	1901	2196	2274	2196	1939	373	2782	
$\gamma$	$\lambda 6478/\lambda 6321$	1958	2015	2044	1984	1986	2198	240	2795	
$\gamma$	$\lambda 6351/\lambda 6447$	2131	2011	2188	2266	2188	1964	302	2770	
$\gamma$	$\lambda 6351/\lambda 6484$	2202	1992	2040	2202	2155	1889	313	2678	
$\gamma$	$\lambda 6321/\lambda 6484$	2162	2074	1950	2011	2023	2054	212	2686	
	$\overline{T}_{\text{vib}}$	2216	2038	2004	2108	2088	1980	-	2686	
	$\sigma$	90	35	47	37	25	48	-	36	

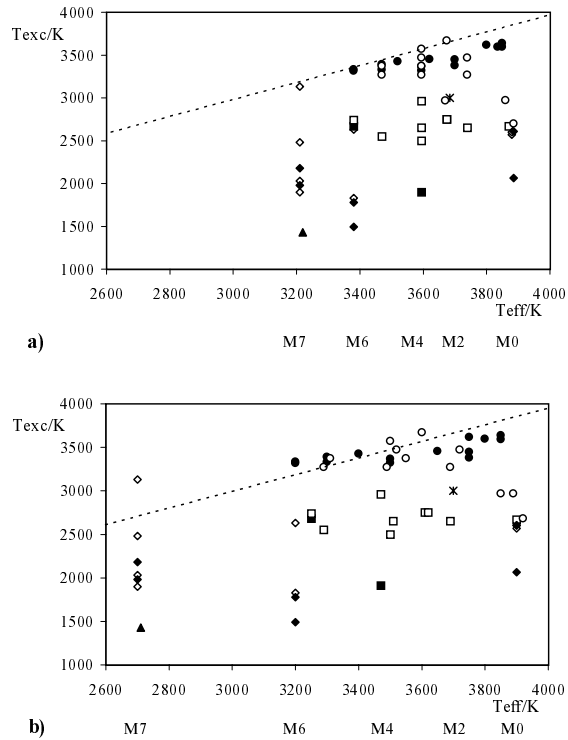
al. 1977 (squares), Phillips and Davis 1987 (asterisk), Keller et al. 1970 (triangle). The function  $T_{\text{exc}} = T_{\text{eff}}$  is represented by a straight line.

The  $T_{\text{eff}}$  of the stars has been deduced according to their spectral subtype. All molecular data refer to TiO except for the  $T_{\text{exc}}$  of Tsuji 1991 (black circles) which belong to CO. Regarding the reliability of the given values we can comment only our results (diamonds). The questionable one is that represented by the white diamond with the highest  $T_{\text{exc}}$ . It was obtained from the spectrum of CH Cyg taken at the end of its outburst, the remnants of which could influence the M giant's spectrum (Jurdana and Kotnik-Karuza 1994). Besides, signs of radiation from a source of an earlier spectral subtype than M6 are possibly present in isolated periods of the quiet phase (O'Connell 1973).

Figs. 3a-b show that the relationship between  $T_{\text{exc}}$  and  $T_{\text{eff}}$  for red giants is sensitive to the choice of the  $T_{\text{eff}}$  calibration scale. Contrary to the rough methods from the past that made use of the approximation  $T_{\text{eff}} \sim T_{\text{exc}}$  (Querci 1986), it is obvious from our diagrams that  $T_{\text{exc}} < T_{\text{eff}}$  since the plotted data

predominantly fall under the straight line  $T_{\text{exc}} = T_{\text{eff}}$ . This fact has been generally supported by other authors (Wright 1948, Hack and Struve 1969, Keller et al. 1970).

The different deviation of  $T_{\text{exc}}$  with respect to  $T_{\text{eff}}$  for various stars and for different atomic and molecular species indicates that the molecular bands and atomic absorption lines are formed at different depths in the atmosphere of cool giant stars. There is a considerable temperature gradient in the upper atmospheric layers manifested as a nonlinear dependence of the source function on optical depth (Yamashita 1965). In agreement with this, the lowest values of  $T_{\text{exc}}$  in our diagrams belong to the TiO molecule which is formed in the surface layers (Tsuji 1978). High molecular excitation temperatures which are close to  $T_{\text{eff}}$  refer to weak rotational CO lines and give evidence of the thermal structure of the layer where these lines are formed. In the case of  $T_{\text{eff}}$  calibration after Tsuji (Fig. 3b) the atmospheric structure in this layer may change at about M4 in such a way as to yield  $T_{\text{exc}} < T_{\text{eff}}$  in early M giants while  $T_{\text{exc}} > T_{\text{eff}}$  in late M giants (Tsuji 1991).



**Fig. 3.**  $T_{\text{exc}}$  determined from atomic lines (white symbols) and molecular bands (black symbols) from the spectra of M giants as a function of  $T_{\text{eff}}$ . References taken from: this work (black diamonds), Komarov et al. 1974 and Komarov et al. 1977 (white and black squares), Keller et al. 1970 (triangle), Tsuji 1991 (black circles), Phillips and Davis 1987 (asterisk), Yamashita 1965 (white circles), Kotnik-Karuzza and Jurdana-Šepić 1998 (white diamonds). The dashed straight line represents  $T_{\text{exc}} = T_{\text{eff}}$ . The effective temperature scale calibrations have been taken from **a**: Bell and Houdashelt 1997; **b**: Tsuji 1978

We have considered CH Cyg to be an M7 star though this choice should be taken with care. On one hand it is a highly variable star, and on the other the degree of accuracy of temperature determination for such extremely cool stars is relatively low. Some authors claim that CH Cyg could be of type M8 (Huang et al. 1994, Mikolajewski et al. 1992). This could be another possible explanation for the low  $T_{\text{vib}}$  in our results. This low values relative to  $T_{\text{eff}}$  are supported by the presence of rapid decrease of  $T_{\text{eff}}$  at Mira variables later than M7, in agreement with Tsuji (1978) who gives a  $T_{\text{eff}}$  of  $2300 \pm 300\text{K}$  for the M8 stars.

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