

Titanium sulphide in the spectra of stellar atmospheres

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Accepted 1992 July 10. Received 1992 May 27

SUMMARY

Molecular spectra observed between 1.05 and 1.35 μm in S-type Mira variables, previously ascribed to ZrS, have been shown by laboratory studies to belong to two overlapping electronic transitions of the TiS molecule.

Key words: line: identification – stars: atmospheres – stars: variables: other.

1 INTRODUCTION

Lambert & Clegg (1980) suggested that sulphides of heavy metals, in particular zirconium sulphide (ZrS), were possible candidates for the carriers of the so-called Keenan–Wing bands (Keenan 1950; Wing 1972) found in the near-infrared region of the spectra of type S stars. This proposal was later found to be quite correct. Preliminary reports from Winkel (1987) and extended studies, including rotational analyses, in our laboratory (Jonsson, Lindgren & Taklif 1991; Jonsson, in preparation) showed that those bands not due to ZrO or FeH belong to ZrS.

In 1989, Hinkle, Lambert & Wing observed the infrared spectra of three type M or S Mira variables near minimum light. The observed region (1.05–1.35 μm) displayed two strong triplet-headed bands in the spectrum of the S star R And. Assuming these triplet bands to be the (0, 0) and (1, 0) bands of the predicted but unknown transitions $b'^3\Pi\text{--}a^3\Delta$ in ZrS (corresponding to a band system at 9299 Å in ZrO), Hinkle *et al.* (1989) assigned a seventh single-headed feature to the (0, 1) band, and gave a $\Delta G_{1/2}$ value of 553 cm^{-1} for the lowest triplet state of ZrS.

Jonsson *et al.* (1991) obtained $\Delta G_{1/2} = 524.3 \text{ cm}^{-1}$ in their laboratory work, which is significantly different from the value of 553 cm^{-1} obtained by Hinkle *et al.* Attempts by Jonsson *et al.* to observe these triplets in the laboratory resulted in weak but significant recordings of the triplet heads but no evidence of the proposed (0, 1) band.

In the course of our programme of laboratory studies of molecular spectra of astrophysical interest, we have now recorded infrared spectra of titanium sulphide (TiS). We can identify all the bands in the spectrum of R And observed by Hinkle *et al.* as due to two overlapping electronic transitions in the TiS molecule.

2 EXPERIMENTAL

A $^3\Delta\text{--}^3\Delta$ transition in the TiS spectrum was observed and rotationally analysed by Clements & Barrow (1969). Following their recipe for generating the molecule, a stoichiometric

mixture of ZnS and Ti powder was heated to 2000 K in a King-type furnace and the spectrum was observed in thermal emission. The spectrum was recorded with a Bomem FTS spectrophotometer DA3.002 using a resolution of 0.05 cm^{-1} . As well as the band system observed by Clements & Barrow, the infrared region revealed two new systems. The wavelengths and wavenumbers of all observed bandheads are given in Table 1.

A rotational analysis of these new bands indicates that they are transitions from two upper states, $A^3\Phi$ and $E^3\Pi$, to the common ground state $X^3\Delta$. [In labelling the electronic states we have followed the convention given by Huber &

Table 1. Observed bandheads in laboratory spectra of the TiS molecule and in R And.

Transition	Head Wavelength in air/Å	Wavenumber in vacuum/ cm^{-1}	R And/ cm^{-1} *
$C^3\Delta\text{--}X^3\Delta$ (1,0) R_2	8283.531	12068.829	
	R_1 8284.117	12067.976	
	R_3 8286.962	12063.832	
$C^3\Delta\text{--}X^3\Delta$ (0,0) R_2	8625.979	11589.703	
	R_1 8627.292	11587.940	(8628 Å)
	R_3 8629.498	11548.977	
$C^3\Delta\text{--}X^3\Delta$ (0,1) R_2	9062.392	11031.586	
	R_1 9063.912	11029.736	
	R_3 9066.230	11026.916	
$A^3\Phi\text{--}X^3\Delta$ (1,0) R_3	11718.899	8530.890	8530
	R_2 11819.4	8458.4	8459
	R_1 11933.8	8377.3	8379
$A^3\Phi\text{--}X^3\Delta$ (0,0) R_3	12451.215	8029.148	8030
	R_2 12565.013	7956.430	7957
	R_1 12694.081	7875.533	7877
$A^3\Phi\text{--}X^3\Delta$ (0,1) R_3	13381.157	7471.152	
$E^3\Pi\text{--}X^3\Delta$ (0,0) R_{1e}	13366.126	7479.554	7477
	R_{1f} 13372.135	7476.193	
	R_2 13446.28	7457.15	
	R_3 13434.28	7441.61	

*From Hinkle, Lambert & Wing (1989).

Herzberg (1979) for TiO.] The (0,0) and (1,1) bands of the E-X transition lie close to the (0,1) band of the A-X transition. As the upper states of these two transitions do not interact, perturbations do not complicate the spectrum and the rotational analysis was rather straightforward. The observed systems correspond to the γ and ϵ bands of TiO.

The complete details of the rotational analysis will be published in a forthcoming paper (Jonsson & Launila 1992). It is worthy of note that the $E^3\Pi-X^3\Delta$ transition which is found to be very weak in TiO is as intense as the $A^3\Phi-X^3\Delta$ transition in TiS.

3 COMPARISON BETWEEN STELLAR OBSERVATIONS AND THE LABORATORY SPECTRUM OF TiS

As mentioned in the Introduction, Hinkle *et al.* observed two strong triplet-headed bands, clearly due to molecules in the spectrum of the S-type star R And in the infrared atmospheric window between 1.05 and 1.35 μm . These bandheads were also observed in the mild S-type star χ Cyg but not in the M star R Cas. These bandheads, which were degraded to longer wavelengths, were found at 7877, 7957, 8030 cm^{-1} and 8379, 8459, 8530 cm^{-1} . Close to the edge of the atmospheric window a seventh strong band was observed at 7477 cm^{-1} . These stellar spectra were observed at a resolution of 1.85 cm^{-1} using the FTS at Kitt Peak. TiO bands of the ϕ system ($b^1\Pi-d^1\Sigma^+$) were identified in the spectra of χ Cyg and R Cas, but not in R And.

Hinkle *et al.* also reported low-resolution studies of the same wavelength region for a number of S stars. With a resolution of about 20 cm^{-1} the bands at 7877, 7957 and 8030 cm^{-1} were clearly present in R And but not in the three other S stars (χ Cyg, R Cyg and T Cam). These three stars were observed at warmer phases than R And.

Reticon spectra at a resolution of 0.8 cm^{-1} were also reported. Spectral regions from 10 140 to 8300 Å were recorded for R And, but at a time between minimum and maximum light. The Keenan-Wing bands (due to ZrS) were not prominent in these spectra but the 8610-Å band ($b^3\Phi_3-a^3\Delta_2$) was present as was another band at 8628 Å. All TiO systems (γ , δ and ϵ) in this region were observed.

In Fig. 1(a) the stellar spectrum of R And recorded by Hinkle *et al.* is displayed. All seven bands are clearly visible. To facilitate a comparison between the laboratory (emission) spectrum of TiS (Fig. 1c) and the absorptions observed in the star it is useful to degrade the laboratory spectrum to match the resolution of the stellar spectrum. This has been done by convolving the spectrum with an instrument profile corresponding to a half-width of 2 Å. The resulting emission profile is displayed in Fig. 1(b).

A visible comparison immediately reveals good agreement between the appearances of the two spectra.

The R_1 heads of the (0,0) band of the E-X transition and the R_2 head of the (0,1) band of the A-X transition constitute what is observed as one head in a low-resolution recording of the 7500- cm^{-1} region. To be precise, it is the E-X heads which form the observed head at low resolution. This overlap also accounts for the strength of the absorption at

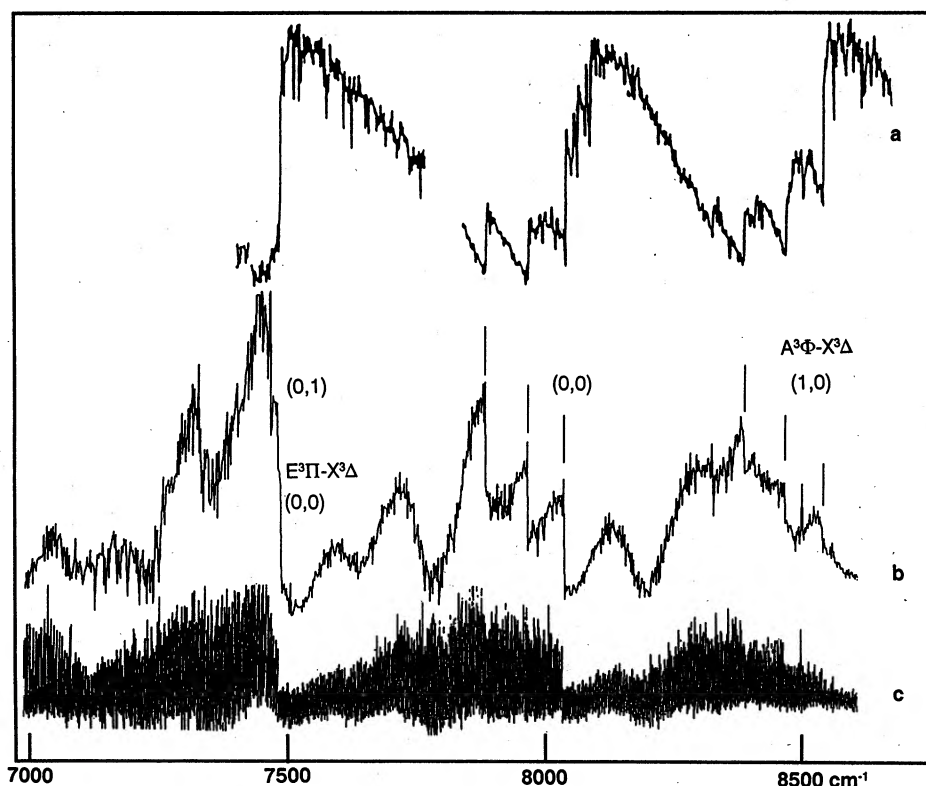


Figure 1. (a) The spectrum of the S star R And (from Hinkle *et al.* 1989) near minimum light in the spectral region 1.15–1.35 μm . (c) The laboratory emission spectrum of the TiS molecule recorded with an FTS spectrometer at a resolution of 0.05 cm^{-1} . (b) The same spectrum as in (c) degraded to match the 1.85- cm^{-1} resolution of the stellar spectrum.

this wavelength – which is clearly too strong to be due to a (0, 1) band alone.

The measured interval of 553 cm^{-1} (Hinkle *et al.* 1989) is thus the separation between the (0, 0) bands of the two electronic transitions involved. Even a discrepancy of 5 cm^{-1} between the $\Delta G_{1/2}$ value of Hinkle *et al.* and that of Clemens & Barrow is too high according to the accuracy – probably the reason why TiS was never considered.

As the TiS molecule is now identified in the spectrum of R And, Clements & Barrow's $^3\Delta-^3\Delta$ should be searched for. They report three bandheads [(0, 0) bands] at 8626.0, 8627.3 and 8629.5 Å. These bands might very well account for the feature around 8628 Å which Hinkle *et al.* observed in the Reticon spectra of R And. This feature was also mentioned by Lambert & Clegg (1980).

Compared to R Cyg, it is obvious that R And is not a pure type S star. TiS and YS (Lambert & Clegg 1980) are both present in R And but not in R Cyg, while the Keenan–Wing bands are not prominent in R And but are characteristically strong in R Cyg.

4 CONCLUSIONS

Our laboratory studies of the spectrum of TiS have identified two new transitions in the infrared region: $E^3\Pi-X^3\Delta$ and

$A^3\Phi-X^3\Delta$. These two transitions account for the infrared absorptions between 1.15 and $1.35\text{ }\mu\text{m}$ observed by Hinkle *et al.* (1989) in R And and χ Cyg. These two stars cannot be regarded as pure type S stars.

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