

*Letter to the Editor***Detection of warm SO<sub>2</sub> gas in oxygen-rich AGB stars\***I. Yamamura<sup>1</sup>, T. de Jong<sup>2,1</sup>, T. Onaka<sup>3</sup>, J. Cami<sup>4,1</sup>, and L.B.F.M. Waters<sup>1,4</sup><sup>1</sup> Astronomical Institute “Anton Pannekoek”, University of Amsterdam, Kruislaan 403, 1098 SJ, Amsterdam, The Netherlands<sup>2</sup> SRON-Utrecht, Sorbonnelaan 2, 3584 CA, Utrecht, The Netherlands<sup>3</sup> Department of Astronomy, School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, 113-0033 Tokyo, Japan<sup>4</sup> SRON-Groningen, P.O. Box 800, 9700 AV, Groningen, The Netherlands

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**Abstract.** We report the discovery of the  $\nu_3$  band of SO<sub>2</sub> at 7.3  $\mu\text{m}$  in the ISO/SWS spectra of oxygen-rich AGB stars. The band is clearly detected in three stars, UX Cyg, *o* Cet and T Cep, and marginally detected in at least four other stars. The band is seen in absorption in UX Cyg, while it is in emission in *o* Cet. Seven spectra of T Cep taken at different phases show that the feature changes from emission to absorption on a time scale of twice the pulsation period. Using an LTE model, we find that the excitation temperature of SO<sub>2</sub> is typically 600 K, and that in T Cep the molecule occupies a region with dimensions of several stellar radii. The total number of molecules contained in this region is of order  $10^{47}$ , which requires a local gas density of at least  $10^9 \text{ H}_2 \text{ cm}^{-3}$ , and possibly up to  $10^{11} \text{ H}_2 \text{ cm}^{-3}$  depending on the SO<sub>2</sub> abundance. The variation with phase of the T Cep spectra can be explained by photodissociation of SO<sub>2</sub> molecules by soft UV photons.

**Key words:** stars: AGB and post-AGB – stars: atmospheres – stars: circumstellar matter – stars: late-type – stars: mass-loss – infrared: stars

**1. Introduction**

Recent observations with the Infrared Space Observatory (ISO; Kessler et al. 1996) have greatly enhanced our knowledge of the atmospheres and circumstellar envelopes of late-type giant stars (see Justtanont et al. 1996, Barlow et al. 1996, Cernicharo et al. 1996). One of the most remarkable discoveries made with the ISO Short Wavelength Spectrometer (de Graauw et al. 1996) are the CO<sub>2</sub> emission bands detected in the 13–17  $\mu\text{m}$  wavelength region of oxygen-rich AGB stars (Cami et al. 1997, Justtanont et al. 1998, Ryde et al. 1998). These bands are commonly detected in Miras and semi-regular variables with relatively small

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mass-loss rates ( $\leq 10^{-7} M_{\odot} \text{ yr}^{-1}$ ), exhibiting the 13  $\mu\text{m}$  dust feature. Preliminary modeling indicates that the CO<sub>2</sub> bands are formed in a dense warm molecular gas layer, probably located at a few stellar radii in between the stellar photosphere and the circumstellar envelope. The existence of such a layer has been postulated by Tsuji et al. (1997) and could be generated by pulsation shocks just above the stellar photosphere (see Bowen 1988, Bessel et al. 1996).

In this letter, we report the detection of another dioxide molecule, SO<sub>2</sub>, in the ISO/SWS spectra of oxygen-rich AGB stars. SO<sub>2</sub> has been detected before in the circumstellar envelopes of some oxygen-rich stars by mm and sub-mm observations of its pure rotational transitions (Lucas et al. 1986, Guilleoteau et al. 1986, Omont et al. 1992). However, this is the first detection ever of ro-vibrational bands of SO<sub>2</sub> in the spectra of cool giants stars.

**2. Observational result**

The data were obtained using the SWS/AOT01 observing mode which provides full-grating spectra from 2.38 to 45.2  $\mu\text{m}$  with a resolution of 300–1000 (depending on scan speed and wavelength). The data were reduced with the SWS Interactive Analysis package developed by the SWS Instrument Dedicated Team using the most recent set of calibration parameters (as of April 1998).

In the guaranteed time program AGBSTARS (P.I. T. de Jong) we observed a sample of 35 AGB stars with a wide range of mass-loss rates and chemical compositions (Justtanont et al. 1996, Yamamura et al. 1998). Only recently we found a remarkably strong absorption band of SO<sub>2</sub> at 7.3  $\mu\text{m}$  in the spectrum of one of the O-rich Mira variables, UX Cyg (M5, period 560 d). A successive careful search for this band in the other stars resulted in a definite detection in *o* Cet (M7IIIe, period 325 d) and at least four additional marginal detections (R Cen, RX Boo, Z Cas,  $\pi^1$  Gru) out of 10 O-rich Mira/semi-regular variables and 4 S-type stars. The spectra of UX Cyg and *o* Cet between 6.5 and 8.5  $\mu\text{m}$  are shown in Fig. 1. The band is seen as a deep absorption in UX Cyg, while it is in emission in *o* Cet.

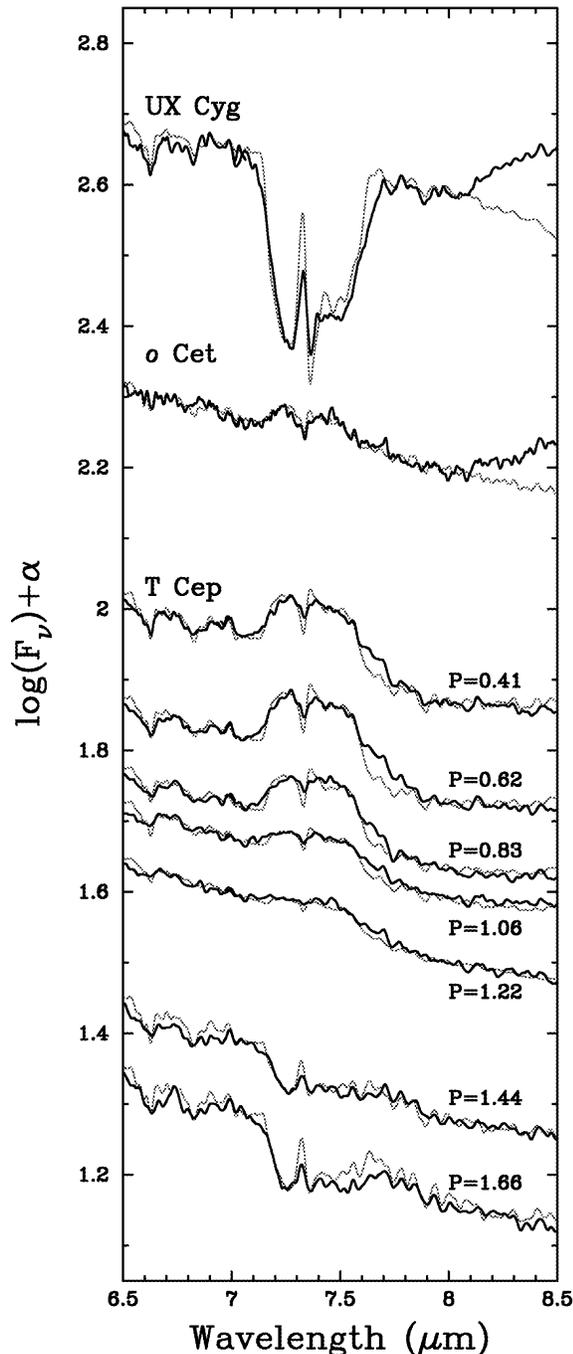
The 7.3  $\mu\text{m}$  SO<sub>2</sub> band is also detected in the Mira variable T Cep (M7IIIe, period 393 d). This star has been monitored over 16 months with the ISO/SWS in the open time program TIM-VAR (P.I. T. Onaka) using the AOT01 observing mode (Onaka et al. 1997). Seven observations were carried out with a phase interval of about 0.2 (Table 1). In T Cep, the SO<sub>2</sub> band is seen in emission at the first minimum, then decreases in intensity around maximum and turns to absorption at the next minimum.

SO<sub>2</sub> has several ro-vibrational bands in the wavelength region covered by the SWS. The  $\nu_3 + \nu_1$  band at 4.0  $\mu\text{m}$  is also detected in UX Cyg, but all bands other than the  $\nu_3$  one are contaminated by other spectral features such as the SiO first overtone band at 4.1  $\mu\text{m}$  and the 10 and 18  $\mu\text{m}$  silicate dust features, and are not suitable for detailed analysis.

### 3. Spectral modeling

A simple plane-parallel LTE model has been developed to derive physical parameters for the SO<sub>2</sub> layer. The geometry adopted is illustrated in Fig 2. The star is assumed to radiate like a blackbody. Molecular layers with uniform excitation temperatures and densities are placed in front of the star and radiative transfer is calculated through these layers one by one. The layer can be extended beyond the star in order to reproduce the emission feature. The molecular layer is thus characterized by a set of four parameters: the excitation temperature ( $T$ ), the column density ( $N$ ), the turbulent velocity ( $v_{\text{turb}}$ ) and the radius of the layer ( $R$ ). In the present calculation a constant turbulent velocity,  $v_{\text{turb}} = 3 \text{ km s}^{-1}$ , is assumed for all molecular layers. The resulting spectrum is not much affected by  $v_{\text{turb}}$  as long as it is within a factor two from the value adopted. The infrared line data for SO<sub>2</sub> are taken from the HITRAN database (Rothman et al. 1996). The list contains 3818 lines in the  $\nu_3$  band of <sup>32</sup>S<sup>16</sup>O<sub>2</sub> with energies of the lower levels up to about 1745  $\text{cm}^{-1}$ . We have also included the molecules H<sub>2</sub>O and SiO in the modeling because they affect the shape of the baseline spectrum. Since these molecules are assumed to be in or just above the photosphere we adopt  $R_{\text{H}_2\text{O}} = R_{\text{SiO}} = R_*$ .

In the modeling we first adjust the blackbody temperature of the star and the H<sub>2</sub>O and SiO parameters to reproduce the background spectrum. A relatively high temperature of 3000 K is necessary to reproduce the T Cep spectra. Somewhat lower temperatures of 1500 K and 2000 K are used for UX Cyg and *o* Cet, respectively. The three independent parameters for the SO<sub>2</sub> layer ( $T_{\text{SO}_2}$ ,  $N_{\text{SO}_2}$ ,  $R_{\text{SO}_2}$ ) can be determined separately.  $R_{\text{SO}_2}$  determines whether the feature is seen in emission or absorption. A higher excitation temperature broadens the band shape. The column density affects the strength of the feature as well as the shape of the band. This is because part of the SO<sub>2</sub> lines are optically thick and saturated. Larger column densities increase the number of saturated lines while the relative contributions of the saturated and the unsaturated lines in the band affect the global shape of the feature. Model spectra are calculated with various sets of parameters exploring a reasonable fraction of parameter space and the results are evaluated by a  $\chi^2$  test of the residual as well as by eye-fitting. The best fit



**Fig. 1.** ISO/SWS spectra (*thick solid line*) and the best fit models (*thin dotted line*) of the SO<sub>2</sub>  $\nu_3$  band in three oxygen-rich Miras. The spectral resolution is about 500 for *o* Cet and 300 for the other stars. The phase of the observations is indicated for T Cep. The discrepancy between the models and the observations in the wings of the band is due to lack of line data at high energy levels.

model spectra are shown in Fig. 1 by dotted lines overlaying the observations. The estimated error of the parameters are  $\pm 100$  K for  $T_{\text{SO}_2}$ , a factor of two for  $N_{\text{SO}_2}$ , and about 5% in  $R_{\text{SO}_2}$ .

We find that an excitation temperature of 600 K gives the best results for all spectra fitted. The column density can be

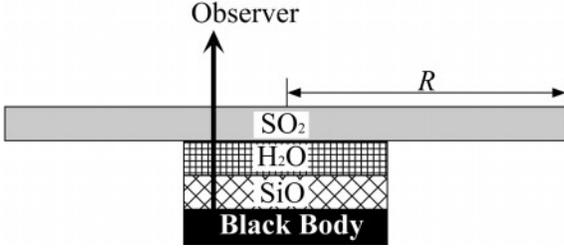


Fig. 2. Geometry adopted in the model calculation.

translated into the total number of SO<sub>2</sub> molecules by  $\mathcal{N}_{\text{SO}_2} = N_{\text{SO}_2} \pi (R_{\text{SO}_2})^2$ , and the average density of SO<sub>2</sub> molecules in the shell between the stellar surface and  $R_{\text{SO}_2}$  equals  $n_{\text{SO}_2} = \mathcal{N}_{\text{SO}_2} / (4/3\pi \{(R_{\text{SO}_2})^3 - (R_*)^3\})$ .

The numbers derived are listed in Table 1. We have assumed the same stellar radius  $R_* = 3.0 \times 10^{13}$  cm for all stars.

#### 4. Discussion

The results of our simple model analysis suggest that the SO<sub>2</sub> molecules are located in a region just above the stellar atmosphere within a few stellar radii from the surface of the star, where the temperature is typically 600 K. A crude estimate of the gas density in this region can be made based on the derived value of the SO<sub>2</sub> density,  $n_{\text{SO}_2}$ . Although the abundance of the SO<sub>2</sub> molecule is not known, the high number density found from the model fitting suggests that a large fraction of the sulfur atoms is in the form of SO<sub>2</sub>. Assuming that all sulfur is in SO<sub>2</sub> and that the sulfur abundance is little affected by dredge-up processes in low- and intermediate-mass stars, we may adopt the cosmic abundance, S/H =  $1.5 \times 10^{-5}$ , as an upper limit for the SO<sub>2</sub> abundance. We then find lower limits to the hydrogen gas density of  $n_{\text{H}_2} = 4.4 \times 10^9 \text{ cm}^{-3}$  (UX Cyg),  $1.0 \times 10^8 \text{ cm}^{-3}$  (*o* Cet), and  $8.5 \times 10^8 \text{ cm}^{-3}$  (T Cep, average), respectively. In a more realistic model calculation Beck et al. (1992) find a SO<sub>2</sub> peak abundance of a few times  $10^{-6}$  which would raise the gas densities by about one order of magnitude. Also, if the SO<sub>2</sub> molecules are concentrated in a thin shell at  $R_{\text{SO}_2}$  or in clumps, rather than uniformly distributed above the photosphere, this would further increase the estimated gas density. We therefore conclude that the local gas density in the SO<sub>2</sub> layer is very likely in the range  $10^{11} - 10^{12} \text{ cm}^{-3}$ .

We note that the detailed model analysis of five CO<sub>2</sub> emission bands in the high-resolution (AOT06) ISO/SWS spectrum of the O-rich AGB star EP Aqr by Cami et al. (1997) indicate the existence of an extended molecular layer with temperatures and densities similar to those derived here for the SO<sub>2</sub> layer. Recently, Reid and Menten (1997) reported the detection of radio continuum emission from Mira. They explained this as due to a “radio photosphere” at 5–6 stellar radii with a Hydrogen gas density of about  $10^{12} \text{ cm}^{-3}$ , in quite good agreement with the picture that results from our analysis.

In Fig. 3 we plot values of  $\mathcal{N}_{\text{SO}_2}$  and of  $R_{\text{SO}_2}$  for T Cep as a function of the optical phase. The plot shows that the total number of SO<sub>2</sub> molecules around T Cep decreases to about 20% of

Table 1. Optical phases and best fit model parameters

Name	Obs.Date D/M/Y	Phase <sup>1</sup>	$R_{\text{SO}_2}$ $\times R_*$	$\mathcal{N}_{\text{SO}_2}$ $\times 10^{47}$	$n_{\text{SO}_2}$ $\times 10^4 \text{ cm}^{-3}$
UX Cyg	08/11/96	0.53	1.82	0.75	13.2
<i>o</i> Cet	09/02/97	0.99	4.58	0.30	0.28
T Cep 1	05/08/96	0.38	5.74	4.67	2.19
T Cep 2	27/10/96	0.58	5.87	6.83	2.99
T Cep 3	15/01/97	0.79	5.74	7.46	3.50
T Cep 4	13/04/97	1.02	5.47	6.76	3.68
T Cep 5	13/06/97	1.17	5.40	3.30	1.86
T Cep 6	07/09/97	1.39	4.44	1.67	1.71
T Cep 7	01/12/97	1.61	4.01	1.37	1.90

<sup>1</sup> Phases are determined based on AAVSO data.

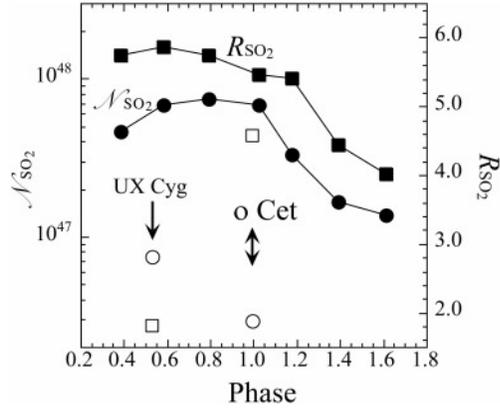


Fig. 3. Derived total number of SO<sub>2</sub> molecules (circles) and the size of the SO<sub>2</sub> layer (in units of the stellar radius, squares) plotted against variable phase. Filled symbols connected by lines are for T Cep, and open symbols are for UX Cyg and *o* Cet.

the maximum value in one year, and that simultaneously  $R_{\text{SO}_2}$  shrinks by about 30%. We note that the CO<sub>2</sub> emission features in T Cep increase in strength with time (see also Onaka et al. 1997). Modeling the CO<sub>2</sub> emission features using a model similar to that used for SO<sub>2</sub> indicates that the total number of CO<sub>2</sub> molecules is one order of magnitude smaller than the number of SO<sub>2</sub> molecules, and probably increases while SO<sub>2</sub> decreases. The process which destroys SO<sub>2</sub> apparently does not affect the CO<sub>2</sub> molecules. It is even conceivable that the oxygen atoms released from SO<sub>2</sub> are used to form additional CO<sub>2</sub> molecules.

One possible destruction process of SO<sub>2</sub> is photodissociation by UV photons. The photodissociation cross section of CO<sub>2</sub> rapidly decreases with increasing wavelength and drops off to about  $10^{-3}$  of the maximum value at 160 nm, while that of SO<sub>2</sub> is still  $10^{-1}$  of the maximum value at 180 nm (van Dishoeck, private communication; see also van Dishoeck and Dalgarno 1984 and Lee 1984). This difference could have a large effect in a low-temperature radiation field. We note that the SO<sub>2</sub> gas observed in our stars is optically thick in the UV so that all stellar photons are available for destruction of SO<sub>2</sub>.

To dissociate the number of SO<sub>2</sub> molecules observed to disappear in T Cep in one year we need a radiation field with a

luminosity of  $\sim 10^{-4} L_{\odot}$  in the 150–200 nm window. This luminosity happens to be exactly emitted by a star with the parameters that we have adopted for T Cep in our model calculations. In this radiation field SO<sub>2</sub> is about 800 times more easily dissociated than CO<sub>2</sub>. The temperature of the radiation field should not exceed 9500 K because then the CO<sub>2</sub> photodissociation rate reaches a value of about 0.1 of SO<sub>2</sub> so that the CO<sub>2</sub> molecules would be dissociated at the same rate as SO<sub>2</sub>. This is inconsistent with the observed increase in CO<sub>2</sub> unless the formation rate of CO<sub>2</sub> would be much higher than that of SO<sub>2</sub>.

Using a crude energy balance argument we estimate that the soft UV photons required for the destruction of SO<sub>2</sub> might also be generated as cooling line radiation in the gas behind pulsation shocks.

According to a similar estimate as given above for T Cep the SO<sub>2</sub> molecules in *o* Cet could also be destroyed by the UV radiation field of its B-type companion star (cf. Karovska et al. 1997).

The formation process of SO<sub>2</sub> is not clear. The major sulfur containing molecules under LTE condition are H<sub>2</sub>S, SiS, and HS (Tsuji 1973). Based on their non-equilibrium chemical calculations Beck et al. (1992) found SO<sub>2</sub> abundances up to a few times 10<sup>-6</sup>. It is also known that slow shocks with velocities below 15 km s<sup>-1</sup> can change the chemical composition in molecular clouds, and enhance the abundances of sulfur containing molecules (Mitchell 1984).

Our results suggest the existence of a close relation between the physical and chemical conditions in the extended atmosphere and the presence of shocks due to stellar pulsation. The warm gas detected in SO<sub>2</sub> and CO<sub>2</sub> molecules could be the site of dust formation.

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