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LETTER

Letter to the Editor

Detection of fine-structure line emission from carbon-rich and oxygen-rich AGB stars by the ISO SWS*

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Abstract. We detected five forbidden lines of iron, silicon and sulfur in red giants by the ISO SWS. [Fe I] 24 μm emission was detected in two carbon stars, TX Psc and WZ Cas, and [S I] 25.2 μm emission was also detected in TX Psc, while none of these emission lines were detected in an oxygen-rich giant, 30g Her. On the other hand, the [Fe II] 26 μm, [Si II] 34.8 μm and [Fe II] 35.3 μm emission lines were detected in the spectrum of 30g Her, while only [Fe II] 26 μm was detected in TX Psc. Namely the emission lines of neutral metals were detected in carbon stars while the lines of ions were detected in an oxygen-rich giant.

This result suggests that the ionization states of metals in the outer atmosphere as well as the ultraviolet radiation field of carbon stars are different from those of M giants. We estimate that the mass of the line forming region is several $\times 10^{-6} M_\odot$ and the temperature is several hundred Kelvin or higher. This implies that there is a rather dense and warm region close to the star in addition to the well known expanding envelope.

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

1. Introduction

The outer atmosphere of cool evolved stars is considered to play an important role in the acceleration of the mass-loss outflow as well as in the nucleation of dust grains. However, our understanding on this region has not yet been sufficient. For the study of the outer atmosphere, forbidden lines of metals in the infrared region are good probes. For example, the [O I] 63 μm and [Si II] 35 μm fine-structure lines were detected in α Ori by Haas & Glassgold (1993) using Kuiper Airborne Observatory. They concluded that these emission lines arise in dense and warm gas in the inner part of the expanding envelope.

We have observed six red giants by the Short Wavelength Spectrometer – SWS (de Graauw et al. 1996) aboard the Infrared Space Observatory – ISO (Kessler et al. 1996), and detected five fine-structure emission lines of iron, silicon and sulfur in two carbon stars and an M giant.

Table 1. Summary of observations

star	sp. type	obs. date	$\dot{M}^{(1)}$	$v_e^{(1)}$	$D^{(2)}$
30g Her	M6III	23 Aug 1996	1.1	8.0	110
SW Vir	M7-8III	20 Jul 1996	4.0	7.0	140
TX Psc	C7,2	26 Nov 1996	0.91	10.5	230
WZ Cas	C9,2JLi	22 Jul 1996	0.26	5.1	780:
T Lyr	C6,5J	12 Nov 1996	0.71	12.4	630:
V CrB	C6,2e	29 Jul 1996	2.4	7.1	–

(1) The mass loss rate ($10^{-7} M_\odot \mathrm{yr}^{-1}$) and the expansion velocity (km s^{-1}) measured by Kahane & Jura (1994) for M giants and by Olofsson et al. (1993) for carbon stars.
(2) The distance based on the Hipparcos catalogue.

2. Observations and results

The objects we observed are given in Table 1. Both carbon-rich and oxygen-rich stars are included in our sample. All the observations were done by the use of the SWS normal grating mode (AOT06) with the resolution of $1000 \sim 1200$ in the wavelength regions studied in the present work. The data reductions were done by the SWS Interactive Analysis software. The spectra around 25 μm are shown in Fig. 1, where some neutral and ionized atomic lines were observed. Since these emission lines were detected in the spectra both by the up and down grating scans, these are very unlikely spurious features.

We detected forbidden lines of iron, silicon and sulfur in three stars (30g Her, TX Psc and WZ Cas) as summarized in Table 2. These lines were detected in red giants for the first

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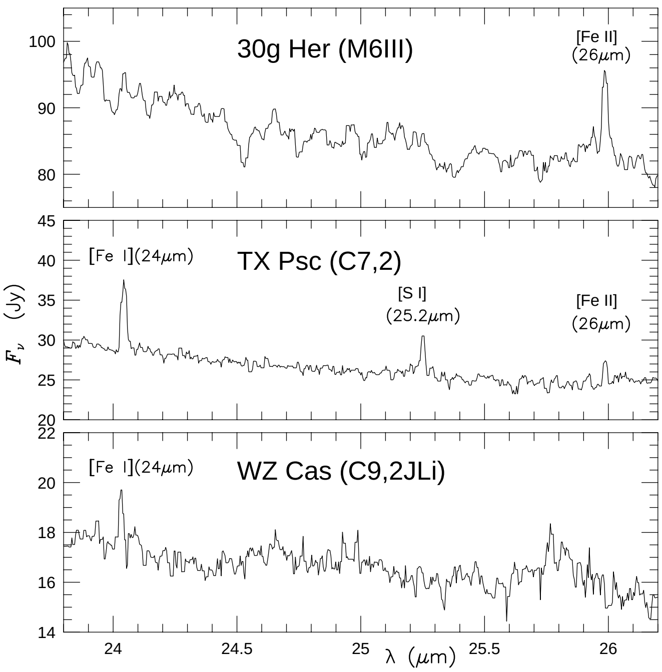

Fig. 1. Examples of the observed spectra around 25 μm

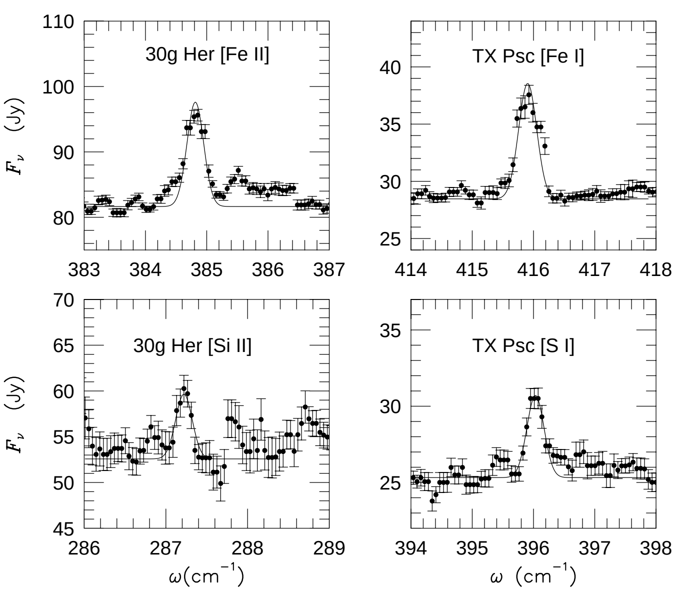

Fig. 2. Examples of the lines detected in 30g Her and in TX Psc. The dot is the median of the signals in each grid defined by the resolution, and the error bar indicates $\pm 1\sigma$. The solid line indicates the best least-square fit assuming a flat continuum and a superposed Gaussian line profile

time, while the [Si II] 34.8 μm line has been detected in an M supergiant α Ori so far (Haas and Glassgold 1993). In the spectra of the other three stars (SW Vir, T Lyr and V CrB), no emission line was detected.

The lines detected are shown in Fig. 2, where the dot is the median of the signals of each grid defined by a resolution element, and the error bar indicates $\pm 1\sigma$ (the standard deviation). The solid line indicates the best least-square fit on the assumption of a flat continuum and a Gaussian line profile. In the fitting, the line width is fixed at the instrumental resolution ($R = 1200$), because of the low signal-to-noise ratios in some lines. Therefore the free parameters in the fitting are the continuum level, the line strength and the central wavelength of the line.

We estimate the temperature of the line emitting region to be as high as several hundred Kelvin, because the upper excitation potentials (E_u's) of the lines detected are between 287 and 667 cm^{-1}. On the other hand, [Fe II] 17.9 μm ($E_u = 2430$ cm^{-1}) was not detected in any spectrum and the temperature would not be so high as 3000K. The temperature of about 1000-2000K is derived from the flux ratio of the two [Fe II] lines in 30g Her, though the line flux of [FeII] 35 μm is rather uncertain. For carbon stars we can not estimate the temperature by flux ratios of emission lines, because of the low signal-to-noise ratio in the wavelength region longer than 27 μm. Summarizing the above discussion, the temperatures of the line emitting regions of the three stars are estimated from several hundred to 2000 Kelvin.

3. Discussion

3.1. Ionization state in the outer atmosphere

The contrast of the emission lines observed in carbon stars and in an M giant is remarkable; the emission lines of neutral metals (Fe I and/or S I) were detected in two carbon stars (TX Psc and WZ Cas) while emission lines of ionized metals (Fe II and Si II) were detected in an M giant (30g Her).

The ionization of metals by the chromospheric ultrviolet (UV) radiation is expected in the inner part of the circumstellar envelope, while the interstellar UV radiation ionizes metals in the outer part. Since the line emitting region should be as warm as several hundred Kelvin, this region would not be the outer part of the circumstellar envelope, but the inner part where the photoionization by the chromospheric UV radiation is effective. Unfortunately, the spectra in the far UV region of our sample stars are not available. However, our infrared observations imply that the activity of the chromosphere where the UV photons with high energy (e.g., $\lambda < 1575$ Å corresponding to the ionization potential of iron) are emitted is not so strong in TX Psc as in 30g Her, or there is some attenuation of the UV radiation in TX Psc. Though our sample is small, we suggest that the ionization states in the outer atmosphere of carbon stars are quite different from those of oxygen-rich stars.

The neutral metals (Mn and Fe) in the circumstellar envelopes of TX Psc and 30g Her were observed as the overlying absorption on the Mg II h and k emission lines around 2800Å (e.g., Eriksson et al. 1986, Luttermoser et al. 1994). The column densities of Mn I and Fe I estimated are larger in TX Psc than in 30g Her, though the values are quite uncertain due to the saturation of the overlying absorption. Further, the recent UV observation of Fe II emission lines by Carpenter et al. (1997) showed that the ionization fraction of iron (Fe II/Fe I) is significantly lower in the outer atmosphere of TX Psc than in that of M giants. Our result that the lines of neutral metals were detected

Table 2. The emission lines detected in the observed spectra

λ	species	transition	$E_{\rm u}$	$E_{\rm l}$	$A_{\rm ul}$	line flux (10^{-16}Wm^{-2})		
(μm)			(cm^{-1})	(cm^{-1})	(10^{-3}s^{-1})	30g Her	TX Psc	WZ Cas
24.042	[Fe I]	$^5D_4$-$^5D_3$	415.9	0.0	2.50	–	11.2	3.07
25.249	[S I]	$^3P_2$-$^3P_1$	396.8	0.0	1.39	–	5.70	–
25.988	[Fe II]	$^6D_{9/2}$-$^6D_{7/2}$	384.8	0.0	2.13	16.3	3.22	–
34.814	[Si II]	$^2P_{1/2}$-$^2P_{3/2}$	287.0	0.0	0.217	5.41	–	–
35.349	[Fe II]	$^6D_{7/2}$-$^6D_{5/2}$	667.6	384.8	1.57	5.41	–	–

in TX Psc but not in 30g Her is consistent with the results of these UV observations.

Next we discuss the characteristics of ionization in the individual objects. In 30g Her no emission line of neutral metals was detected. This fact means that metals, at least iron and sulfur, are fully ionized in the outer atmosphere, or that the region where metals recombine is too cool to emit the lines, or that the metals are suddenly depleted by grains after the recombination.

In the spectrum of TX Psc, S I and Fe I were detected simultaneously. In cool and carbon-rich environment, generally, the major part of sulfur atoms is locked up into CS and/or SiS molecules if the chemical equilibrium is assumed. However, neutral sulfur atoms should exist in the outer atmosphere of TX Psc, because the [S I] 25 μm line clearly appears in TX Psc. The photodissociation of CS whose dissociation energy is 7.86 eV will not be so effective, because iron, whose ionization potential (7.87 eV) is nearly the same as the dissociation energy of CS, is not so ionized in TX Psc. The neutral sulfur atoms may be supplied by the photodissociation of SiS, which has lower dissociation energy of 6.36 eV.

3.2. Location of the line forming region

In this section we estimate the mass and location of the line forming region of 30g Her and TX Psc.

If the line is optically thin, the line flux ($F_{\rm ul}$) is

$$F_{\rm ul} = \frac{N_{\rm u} A_{\rm ul} E_{\rm ul}}{4\pi D^2},$$

where $N_{\rm u}$ is the total number of atoms in the upper level, D is the distance to the star, and the other quantities are expressed in standard notation. $N_{\rm u}$ is derived from the line flux measured for 30g Her and TX Psc (Table 2) by the use of the distance given in Table 1. The derived $N_{\rm u}$ is given in Table 3.

The number of nuclei of the element ($N_{\rm elem}$) is estimated from $N_{\rm u}$ on the assumptions that the level populations are in thermal equilibrium, and all the atoms are in the ionization state of the detected line. Then the number of hydrogen atoms ($N_{\rm H}$) corresponding to $N_{\rm elem}$ is derived assuming the solar abundance. The $N_{\rm elem}$ and $N_{\rm H}$ are also given in Table 3. The $N_{\rm H}$'s derived from two or three lines agree well and they correspond to about $2\times10^{-6} M_\odot$ and $6\times10^{-6} M_\odot$ in 30g Her and in TX Psc, respectively. These values are probably the lower limits of the masses of the line forming regions, because we assume that the lines are optically thin and neglect the depletion of these metals by grains and/or molecules.

Table 3. Estimation of mass in line forming region

	$N_{\rm u}$ (10^{46})	$N_{\rm elem}$ (10^{46})	$N_{\rm H}$ (10^{51})	M ($10^{-6} M_\odot$)
30g Her				
[Fe II] 26μm	1.5	6.6	2.1	1.7
[Fe II] 35.3μm	0.89	8.0	2.5	2.1
[Si II] 34.8μm	6.3	12	3.4	2.8
TX Psc				
[Fe II] 26μm	1.3	5.7	6.7$^{(1)}$	5.6$^{(1)}$
[Fe I] 24μm	3.4	15		
[S I] 25μm	3.3	13.2	8.4	7.0

$^{(1)}$ The sum of the $N_{\rm H}$'s (the masses) derived from [Fe II] 26 μm and [Fe I] 24 μm.

To investigate where these emission lines arise, we examine two extreme cases; (a) expanding circumstellar envelope with a constant mass loss rate, and (b) dense and static zone in the upper photosphere.

(a) The extension of the line forming region can be estimated if these lines form in the spherically symmetric and expanding envelope with a constant mass loss rate ($\dot{M}$). On these assumptions, the number of hydrogen atoms ($N_{\rm H}$) from $r = R_*$ (stellar surface) to $r = R_{\rm max}$ is

$$N_{\rm H} = \int_{R_*}^{R_{\rm max}} n_{\rm H} 4\pi r^2 dr = \frac{\dot{M}}{m_{\rm H}} \int_{R_*}^{R_{\rm max}} \frac{1}{v_{\rm e}} dr,$$

where $n_{\rm H} = \dot{M}/(4\pi r^2 v_{\rm e} m_{\rm H})$ is the number density of hydrogen, and $v_{\rm e}$ is the expansion velocity. If the constant mass loss rate ($\dot{M} = 10^{-7} M_\odot {\rm yr}^{-1}$) and the constant expansion velocity ($v_{\rm e} = 10$ km s^{-1}) are assumed, $R_{\rm max}$ must be as large as 10^{15}cm ($\sim 40R_*$) for 30g Her and 2×10^{15}cm ($\sim 100R_*$) for TX Psc to explain the mass of the line forming region derived above. If we assume $T = 1000$K at $r = 10^{14}$cm (several $\times R_*$) from the central star, around where dust grains might form, and temperature declines with $r^{-0.5\sim-1}$, the temperature at $r = 40R_*$ or $r = 100R_*$ would be about $100 \sim 300$K or lower. This may not be high enough to excite the metals to the upper levels of the lines detected in our observations. The line fluxes observed in our sample stars will not be explained by this picture.

(b) On the other hand, a dense and quasi-static molecular formation zone in the outer atmosphere has been found from the excess absorption of low excitation lines of the CO first overtone bands in M giants and carbon stars including 30g Her (Tsuji 1988) and TX Psc (Ohnaka 1997). According to their analyses, the molecular formation zone is characterized by the temperature of about 1000K, the high column density (N_c(CO)$\sim 10^{20}$cm^{-2}), and the proximity to the star. Further, the existence of a rather warm molecule forming region around red giants is revealed by the ISO observations of the absorption features of H_2O and CO_2 (Tsuji et al. 1997) and of the CO_2 emission (Justtanont et al. 1998).

If we assume that the emission lines detected by our observations form within $3R_*$ ($\sim 10^{14}$cm) from the central star, the density of the line forming region must be as high as 10^9cm^{-3} to explain the mass of the region derived above. This gives the hydrogen column density of about 10^{23}cm^{-2}, which is consistent with that derived by the CO excess absorption.

The real outer atmosphere of red giants would be the intermediate one between the above two extreme cases, i.e., it consists of the dense region close to the central star with the small (or zero) expansion velocity and the expanding envelope with $v_e \sim 10\,\mathrm{km\,s^{-1}}$. We cannot derive the velocity structure from the fine-structure lines due to the limited resolution of the SWS06. However, the high resolution UV observation of TX Psc by Carpenter et al. (1997) revealed that the fluorescent lines of Fe I and the absorption features of Fe I and Mn I overlying the Mg II emission lines show the outflow of about $5\,\mathrm{km\,s^{-1}}$ or no sign of an outflow. This result of the UV observation supports our proposition that the fine-structure lines form in the quasi-static region close to the star where the acceleration of the mass-loss outflow is not so effective.

4. Concluding remarks

We detected the five forbidden lines of Fe, Si and S in the three red giants by the ISO SWS. It is found that the ionization states of metals in the outer atmosphere are related to the chemical composition (carbon-rich or oxygen-rich). This will give an important restriction in the modeling of the chemical processes in the outer atmosphere. Further, no emission line was detected in the three sources (SW Vir, T Lyr and V CrB), which have lower effective temperature than the other three stars showing the emission lines. This fact is also important to understand the condition of the formation of these emission lines. It should be noted that we assume the homogeneous and spherically symmetric outer atmosphere in the above discussion. However, the deviation from these assumptions has been discussed for 30g Her and TX Psc (Plez & Lambert 1994, Jørgensen & Johnson 1991). The more comprehensive and detailed study is required to interpret consistently these metal emission lines as well as molecular and/or dust features.

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References

Carpenter K.G., Robinson R.D., Johnson H.R., Eriksson K., Gustafsson B., Pijpers F.P., Querci F., Querci M., 1997, ApJ 486, 457
de Graauw Th. et al., 1996, A&A 315, L49
Eriksson K., Gustafsson B., Johnson H.R., Querci F., Querci M., Baumert J.H., Carlsson M., Olofsson H., 1986, A&A 161, 305
Haas M.R., Glassgold A.E., 1993, ApJ 410, L111
Jørgensen U.G., Johnson H.R., 1991 A&A 244, 462
Justtanont K., Feuchtgruber H., de Jong T., Cami J., Waters L.B.F.M., Yamamura I., Onaka T., 1998, A&A 330, L17
Kahane C., Jura M., 1994 A&A 290, 183
Kessler M. F. et al., 1996, A&A 315, L27
Luttermoser D.G., Johnson H.R., Eaton J.A., 1994, ApJ 422, 351
Ohnaka K., 1997, Ph. D. Thesis, The University of Tokyo
Olofsson H., Eriksson K., Gustafsson B., Carlström U., 1993, ApJS 87, 267
Plez B., Lambert D.L., 1994, ApJ 425, L101
Tsuji T., 1988, A&A 197, 185
Tsuji T., Ohnaka K., Aoki W., Yamamura I., 1997, A&A 320, L1