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LETTER

Letter to the Editor

Warm molecular envelope of M giants and Miras: a new molecule forming region unmasked by the ISO SWS*

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Abstract. Our observations with the ISO SWS revealed that H_2O band at 2.7 μm appears as absorption already in an M2 giant β Peg and strengthens towards later M giants. Further, CO_2 4.2 μm band appears as absorption in an M7 giant SW Vir and especially strong in a Mira variable S Vir. The excitation temperatures of these molecular bands estimated from their band shapes turn out to be 750 – 1,250 K in M giants as well as in a Mira variable. Absorption features of CO and SiO at 4 μm region appear to be weaker in cooler M giants and almost disappear in S Vir (Mira), suggesting filling in by the emission of CO and SiO themselves. The absorption and/or emission may be produced in a rather warm molecule forming region above the photosphere. This molecular envelope should be related to the quasi-static molecular zone previously suggested from the high resolution FTS spectra of CO in the near IR.

Key words: Infrared: stars - molecular processes - stars: atmospheres - stars: circumstellar matter - stars: late-type

1. Introduction

Luminous cool stars represent the late stages of evolution of most stars with mass larger than about 1 $M_\odot$. They generally show the results of stellar nucleosynthesis in their surface chemical compositions and evidences of large mass-loss in a variety of observations. In view of a large number of these cool stars, they should be the most important element in recycling and hence in evolution of matter in the Universe. Despite such importance, our understanding on these cool objects is still rather poor. For example, we know that the outer atmosphere of these stars consists of hot chromosphere, dust shell, and expanding circumstellar envelope, but we are still far from a unified understanding of these different constituents and how mass-loss outflow is related to such a complex.

To resolve such problems, spectroscopy in the thermal infrared should be the most useful, since it will effectively probe the inner part of the outer atmospheres ($T \approx 300 - 5,000$ K) where major physical and chemical processes take place. For this purpose, we have planned systematic observations of cool luminous stars covering a wide range of physical and chemical properties by the use of the Short Wavelength Spectrometer – SWS (de Graauw et al. 1996) aboard the Infrared Space Observatory – ISO (Kessler et al. 1996). Here, we report our initial results on M giants and Miras, which are numerous and common in our Galaxy and possibly in most early-type galaxies.

2. Observation, data reduction, and analysis

Our ISO observations of 30g Her (M6III), SW Vir (M7III) and RT Vir (M7III) have been done by the use of the SWS normal grating mode (AOT S06) with resolution of about 1,600 while those of β Peg (M2III) and S Vir (Mira-type) by the rapid scan mode (AOT S01; speed 1) with resolution of about 200 (de Graauw et al. 1996). Data reduction has been done by the SWS Interactive Analysis software by one of us (IY) at Groningen.

We compare the observed spectra with the predicted ones based on our model photospheres, some backgrounds of which have been given elsewhere (Tsuji et al. 1997). For this purpose, we also prepared a database of infrared spectral lines including CO, OH, SiO, and CN. We also included H_2O opacity as a pseudo-continuum based on the high temperature laboratory data (Ludwig 1971). Also we employed basic stellar parameters as realistic as possible: for example, carbon (Tsuji 1991), nitrogen (Aoki & Tsuji 1997), and silicon (Tsuji et al. 1994) abundances are based on detailed quantitative analyses of FTS spectra of our program stars themselves.

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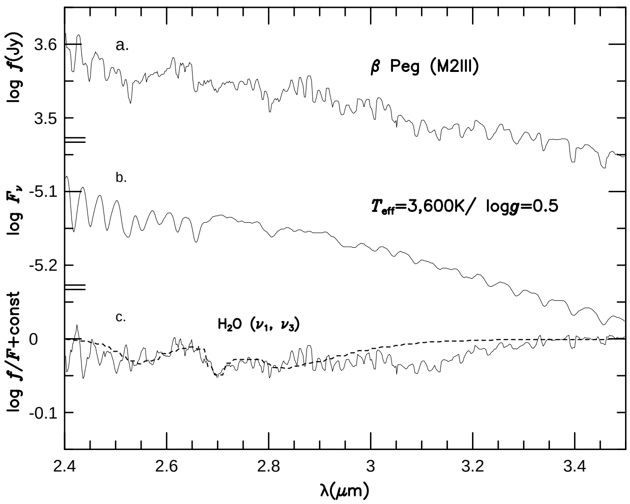

Fig. 1. a: Spectrum (log f_ν[Jy]) of β Peg by the ISO SWS. **b:** Predicted spectrum (log F_ν[erg/sec/cm^2/Hz]) based on our model photosphere of $T_{\rm eff}$ = 3,600 K, log g = 0.5 & $v_{\rm micro}$ = 3.0 km s^{-1}. **c:** The logarithmic difference between the observed and predicted spectra log f_ν(obs)$-$logF_ν(pred) (solid line) and the predicted H_2O absorption based on a model envelope of $T_{\rm ex}$ = 1,250 K, $N(H_2O)$ = 7 × 10^{18} cm^{-2} & $R_{\rm ME}$ = 2 R_* (dashed line).

3. Results

3.1. H_2O at 2.7 μm

In Fig. 1, we compare the spectrum of β Peg by the SWS (top) with the predicted one based on our photospheric model and reduced to the same resolution as observed (middle). Although we have already confirmed that our model flux agrees with the calibrated KAO data (Cohen et al. 1995) within 5% between 1 and 30 μm except for the region of strong molecular absorption (Tsuji et al. 1997), the region between 2.4 and 3.5 μm was one of such regions of poor agreement. In Fig. 1c, we show the logarithmic difference between the observed and predicted spectra, and we notice an excess absorption peaked at 2.5 and 2.7 μm. We identify these features as due to H_2O ν_1 and ν_3 fundamentals, possibly originating from an envelope above the photosphere. In Fig. 1c, we compared the observed excess absorption with H_2O spectrum predicted by a simple model envelope of excitation temperature $T_{\rm ex}$ = 1,250 K, column density $N(H_2O) \approx 7 \times 10^{18}$ cm^{-2}, and effective radius $R_{\rm ME}$ = 2 R_* (R_* is the stellar radius) with the use of the experimental absorption coefficient of H_2O (Ludwig 1971). A broad depression centered at 3.1 μm cannot be explained by H_2O in gas phase.

We apply the same analysis to 30g Her and SW Vir which, however, were observed with the higher resolution. The results shown in Figs. 2 and 3 reveal that the observed (top) and predicted (middle) spectra are rather distinct. Nevertheless, the logarithmic difference (bottom) reveals the same pattern as in β Peg and we conclude that the observed spectra are largely disturbed by the absorption due to the H_2O envelope. Our simple envelope models suggest $T_{\rm ex}$ = 1,250 K for the both while $N(H_2O)$ $\approx 2 \times 10^{19}$ cm^{-2} (30g Her) and $\approx 3 \times 10^{19}$ cm^{-2} (SW Vir). In SW Vir, H_2O absorption appears already in the photospheric

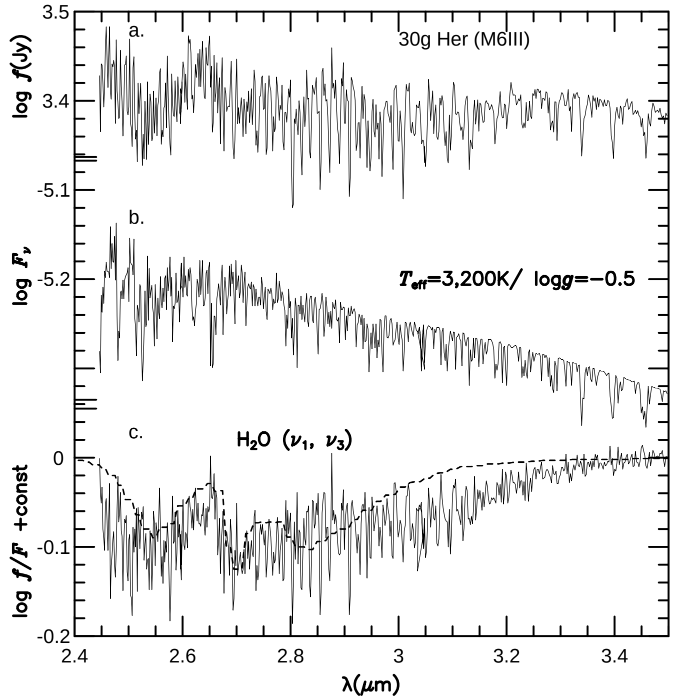

Fig. 2. a: Spectrum of 30g Her by the ISO SWS. **b:** Predicted spectrum based on our model photosphere of $T_{\rm eff}$ = 3,200 K, log g = -0.5 & $v_{\rm micro}$ = 3 km s^{-1}. **c:** The logarithmic difference (solid line) fitted with an absorption profile due to H_2O envelope of $T_{\rm ex}$ = 1,250 K, $N(H_2O)$ $\approx 2 \times 10^{19}$ cm^{-2} & $R_{\rm ME}$ = 2 R_* (dashed line).

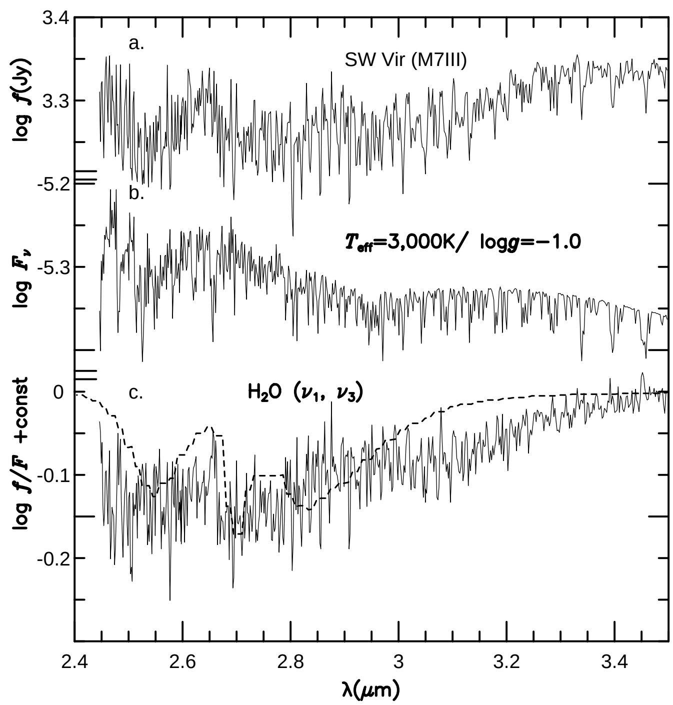

Fig. 3. The same as Fig. 2 but for SW Vir. Note, however, that we now apply a model photosphere of $T_{\rm eff}$ = 3,000 K, log g = -1.0 & $v_{\rm micro}$ = 3 km s^{-1}(**b**) and assume $N(H_2O) \approx 3 \times 10^{19}$ cm^{-2} (**c**).

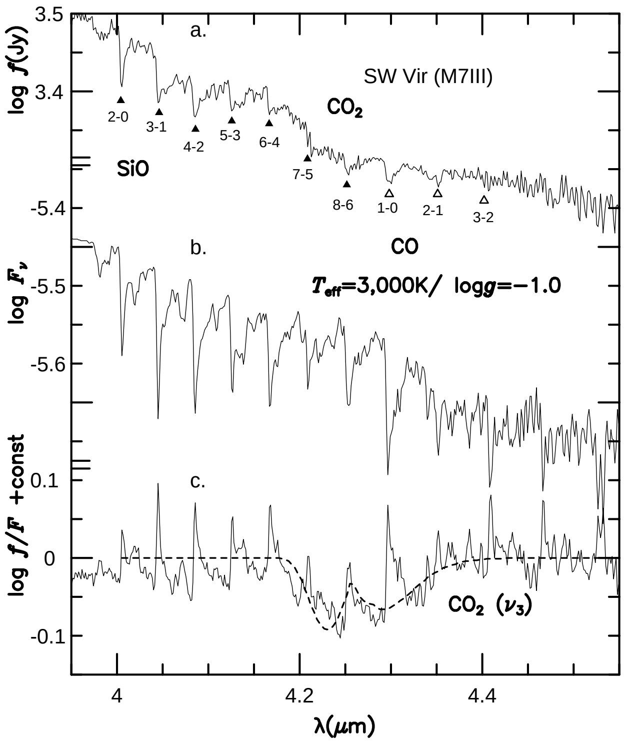

Fig. 4. a: Spectrum of SW Vir by the ISO SWS. **b:** Photospheric spectrum predicted by the same model as in Fig. 3. **c:** The logarithmic difference $\log f_\nu(\mathrm{obs}) - \log F_\nu(\mathrm{pred})$ (solid line) and absorption profile of CO_2 based on a model envelope with $T_{\rm ex}$ = 750 K, $N(CO_2)$ $\approx 1.2 \times 10^{17}$ cm^{-2} & $R_{\rm ME} = 2\,R_*$ (dashed line).

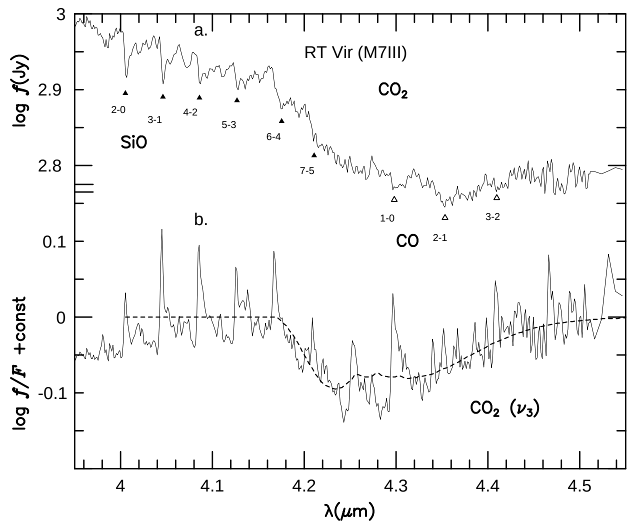

Fig. 5. a: Spectrum of RT Vir by the ISO SWS. **b:** The logarithmic differences $\log f_\nu(\mathrm{obs}) - \log F_\nu$(pred; by the same photospheric model as for SW Vir) (solid line) and absorption profile due to CO_2 model envelope of $T_{\rm ex}$ = 1,000 K, $N(CO_2) \approx 3 \times 10^{17}$ cm^{-2} & $R_{\rm ME} = 2\,R_*$ (dashed line).

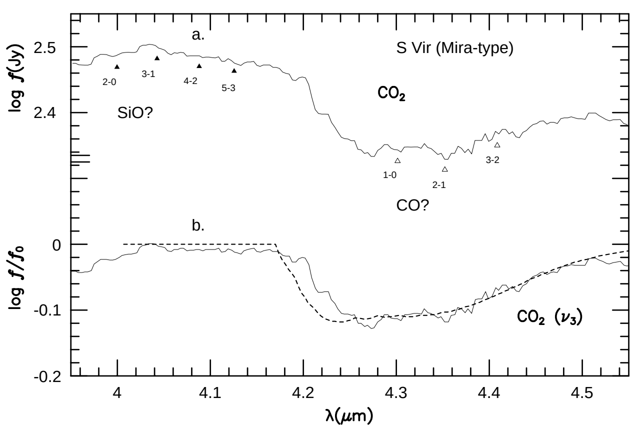

Fig. 6. a: Spectrum of S Vir by the ISO SWS. **b:** The normalized spectrum (solid line) and absorption profiles due to CO_2 model envelope of $T_{\rm ex}$ = 1,250 K, $N(CO_2) \approx 1.5 \times 10^{18}$ cm^{-2} & $R_{\rm ME} = 2\,R_*$ (dashed lines).

model spectrum as a depression near 3 μm(Fig. 3b). The band shape of this hot H_2O absorption is clearly different from that of the H_2O bands due to the molecular envelope characterized by the lower temperature.

3.2. CO and SiO at 4 μm region

The 3.95–4.55 μm spectrum of SW Vir in Fig. 4 reveals that the observed SiO (first overtone) and CO (fundamental) bands appear to be too weak (top) as compared with the prediction based on the photospheric model (middle), and the difference spectrum of these two shows excess emission (bottom). Such an excess emission is what can be expected from the quasi-static molecular formation zone proposed on the basis of an excess absorption in the first overtone bands of CO found on the high resolution FTS spectra of late M giants (Tsuji 1988). The excitation temperature of this CO zone was estimated to be $2,163 \pm 158$ K for SW Vir. This will easily produce emission at 4.3 μm instead of absorption at 2.3 μm if the molecular envelope is located at about 2 R_*. Also we already know that SiO lines in the 4 μm region show excess flux over photospheric line profiles on high resolution FTS spectrum of SW Vir (Tsuji et al. 1994). Also, CO and SiO bands near 4 μm almost disappear in a Mira variable S Vir (Fig. 6a). By the ISO SWS, the SiO fundamental bands near 8 μm appear to be very weak, both in SW Vir and S Vir, again indicating filling in by emission.

3.3. CO_2 at 4.2 μm

Further inspection of the difference spectrum of SW Vir in Fig. 4c reveals a broad excess absorption in 4.2–4.5 μm, which was not seen in 30g Her nor in β Peg (Tsuji et al. 1997). We identify this absorption as due to CO_2 ν_3 fundamental. This band has also been identified in NML Cyg (Justtanont et al. 1996), where it is not only much weaker but also much narrower than in Fig. 4. We have again used our simple model envelope to predict the excess absorption by using the CO_2 absorption coefficient based on the band model (Tsuji 1994), and the results are overlayed on the difference spectrum in Fig. 4c. We estimate $T_{\rm ex}$ to be 750 K and $N(CO_2) \approx 1.2 \times 10^{17}$ cm^{-2}.

We are convinced of this identification by the stronger absorption in RT Vir (Fig. 5a) and S Vir (Fig. 6a), which can directly be recognized on the observed spectra without subtracting the photospheric contribution. We applied the same analysis to RT Vir with the same photospheric model as for SW Vir and the resulting difference spectrum can be fitted with CO_2 spectrum predicted from a model envelope with T_{ex} = 1,000 K (Fig. 5b). For a lower resolution spectrum of S Vir, for which stellar parameters and photospheric model are also not well known, we simply normalized the observed spectrum by an estimated continuum and the result is fitted with CO_2 spectrum by our envelope model of T_{ex} = 1,250 K (Fig. 6b).

4. Discussion and concluding remarks

The ISO SWS provided clear infrared spectra free from the disturbance of the Earth's atmosphere for the first time. The spectra of several M giants appeared to be quite different from what we could expect from the present model atmospheres. Although the upper photosphere of cool stars is not well modeled yet, such discrepancies may be too large to be relaxed by improving the model of the photosphere. Instead, all these features can be consistently interpreted as due to excess absorption and/or emission originating in a region above the photosphere which, however, is clearly different from the cool expanding circumstellar envelope already known. Thus we conclude that a rather warm molecular envelope exists in the outer atmosphere of M giant stars as well as of Mira variables.

Possible presence of a molecule forming region which may still be not expanding and thus quasi-static has been suggested from a more subtle evidence on the first overtone bands of CO accessible from the ground, and the high resolution FTS revealed the kinematic property of the envelope to be clearly different from that of the photosphere (Tsuji 1988): for example, the quasi-static CO envelope of SW Vir is characterized by $T_{ex} \approx 2,000\,\mathrm{K}$, $N(\mathrm{CO}) \approx 10^{20}\,\mathrm{cm}^{-2}$, $v_{tur} > 9\,\mathrm{km\,s}^{-1}$, and a systematic motion of $-6.3\,\mathrm{km\,s}^{-1}$ relative to the photosphere. In the case of Mira variables, the presence of such an extra component well distinct from the photosphere has been shown more clearly by observing stationary CO lines against the photospheric CO lines shifted by stellar pulsation (Hinkle et al. 1982). Now, the presence of the warm molecular envelope has been consistently shown by the two independent observations – the ISO from the space and the FTS from the ground.

In the molecular envelope of SW Vir, for example, abundance (column density) ratio of CO : H_2O : CO_2 $\approx$ 1 : 0.3 : 0.001 may be not inconsistent with what can be expected for the thermochemical equilibrium, but different molecules are stratified at different temperatures (750 – 2,000 K) and non-equilibrium chemistry should probably play some roles. If we assume C/H of about 10^{-4}, hydrogen column density may be as high as $10^{24}\,\mathrm{cm}^{-2}$. If the thickness of the envelope is comparable to the stellar radius ($\approx 10^{13}$ cm), the number density may be about $10^{11}\,\mathrm{cm}^{-3}$. Also, the fact that absorption is observed at shorter wavelength (2.5 – 5 μm) and for lower temperature ($\lesssim 1,250$ K) while emission appears at higher temperature ($\approx 2,000$ K) suggests the location of the molecular envelope to be at about 2 R_*.

The presence of a rather warm molecular envelope close to the photosphere presents a new problem on stellar physics. For example, how such a molecule forming region can be developed and how it can coexist with the hot chromosphere which is also situated close to the photosphere? This problem may have a close connection with the recent discovery of a spatially resolved CO component in the solar chromosphere (Solanski et al. 1994). Such a bifurcated structure may be a more fundamental characteristic of cool stars in general from the Sun to red giants and beyond, and may radically innovate our understanding of the stellar outer atmosphere.

A reasonably dense and warm region above the photosphere provides a necessary environment for various physical and chemical processes to occur. Especially, the rich chemistry around cool evolved stars revealed by the recent ISO observations may first be understood by the chemical reactions in the warm molecular envelope, since chromosphere is too hot while expanding envelope is too rarefied for chemical reactions to be activated. Also, the warm molecular envelope will provide a site for dust formation, even without pulsation by which matter had to be levitated to the dust condensation point. Now, a more general mechanism of stellar mass-loss can be developed by taking the warm molecular envelope into account. Thus, a missing link for a unified understanding of the outer atmosphere of cool luminous stars may finally be found in the warm molecular envelope, and a new means of empirical approach for this purpose is now at our hand thanks to the new capabilities opened by the ISO.

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