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Letter to the Editor

Discovery of CO_2 emission in AGB stars with the 13 μm dust feature*

K. Justtanont[1], **H. Feuchtgruber**[2], **T. de Jong**[1,3], **J. Cami**[1,3], **L.B.F.M. Waters**[3,1], **I. Yamamura**[4,1], **and T. Onaka**[4]

[1] SRON-Groningen, P.O.Box 800, 9700 AV Groningen, The Netherlands
[2] Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, D-85740 Garching, Germany
[3] Astronomical Institute 'Anton Pannekoek', University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
[4] Department of Astronomy, University of Tokyo, 2-11-16 Yayoi-cho, Bunkyo-ku, Tokyo 113, Japan

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Abstract. We have detected strong emission lines at 13.48, 13.87, 14.97, 15.40 and 16.28 μm in the ISO/SWS spectra of O-rich AGB stars. These lines are only found in the spectra of Miras and semi-regular variables when they also show the 13 μm dust emission feature. The lines appear just resolved in the high-resolution (AOT06, resolution $\sim$ 1500) SWS spectra that we recently obtained.

Here we report the identification of these emission lines as the Q-branches of ro-vibrational transitions in CO_2 molecules. This identification is corroborated by our SWS Fabry-Perot observation of the 13.87 μm line in W Hya where individual Q-branch components of the $10^00\,\Sigma_g^+ - 01^10\,\Pi_u$ transition of CO_2 have been detected. The 15.40 μm line is probably due to $^{13}CO_2$.

We speculate that the simultaneous occurence of the 13 μm dust feature and the CO_2 emission lines indicates the existence of a warm ($\sim$ 650-1250 K) gas layer close to the star where both the 13 μm dust and the CO_2 emission lines are formed.

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

1. Introduction

As part of the guaranteed time observing program presently carried out with instruments on board the Infrared Space Observatory (Kessler et al. 1996) we use the ISO/SWS (de Graauw et al. 1996) to study the infrared spectra of about 40 bright Asymptotic Giant Branch (AGB) stars (cf. Iben and Renzini 1983). The sample consists of stars with different chemical compositions (O-rich and C-rich) and a wide range of mass loss rates (optical Miras and Carbon stars, OH/IR stars, infrared Carbon stars). A few M-type supergiants are also included. Preliminary results of studies based on data obtained in this program have been reported by Justtanont et al. (1996, 1997), Cami et al. (1997) and Yamamura et al. (1997).

One of the surprising features in the AOT01 SWS spectra (resolution $\sim$ 250) of AGB stars were unresolved emission lines at 13.87 μm, 14.97 μm and 16.18 μm in the spectra of several O-rich Mira variables. When it turned out that all stars showing these lines also exhibited the 13 μm dust feature in their spectra we asked for and obtained additional observing time to study a larger sample of stars with the 13 μm dust emission feature using the ISO/SWS at higher spectral resolution (AOT06 and Fabry-Perot observing modes).

At the time of writing this Letter our dataset consists of five stars showing in total five emission lines: lines at 13.87 and 16.18 μm observed in emission in all stars, one at 14.97 sometimes seen in absorption (in R Cas and W Hya) and two additional emission lines at 13.48 and 15.40 μm in EP Aqr. None of these lines have ever been seen prior to the launch of ISO. This region of the spectrum is inaccessible from the ground due to atmospheric absorption and the IRAS/LRS could not detect these lines because its resolution was too low.

Initially, since they were unresolved at the AOT01 resolution, we speculated that these lines might be due to ions associated with chromospheric activity in the stellar atmosphere, possibly related to the onset of mass loss (Justtanont et al. 1997). However, based on the recent high-resolution observations which show that the lines are just resolved and based on a more careful analysis we are now able to report the identification of these lines as due to ro-vibrational transitions between

Send offprint requests to: K. Justtanont (e-mail: kay@sron.rug.nl)

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different vibrational bending modes of CO_2. Recently, Ryde et al. (1997) have independently proposed that the emission of the 14.97 μm line in their spectrum of R CrA is due to CO_2.

The correlation of the CO_2 lines with the 13 μm dust feature is quite significant. This feature was discovered by Vardya et al. (1986) in the IRAS/LRS spectra of Mira variables with symmetric light curves. Onaka et al. (1989) proposed that the 13 μm dust feature was due to Al_2O_3, a high-temperature condensate which is thought to be the first form of dust to condense in the outflow (Tielens 1990). However, optical properties of crystalline Al_2O_3 do not produce emission at 13 μm with a comparable width, but at a shorter wavelength and with a narrower profile (Sloan et al. 1996). Another possible candidate suggested by Begemann et al. (1997) is magnesium silicate. Kozasa and Sogawa (1997) have proposed the composite of an aluminum oxide core coated by silicate as a possible explanation for the 13 μm emission. Sloan et al. (1996) studied a large number of these stars and found that stars with the 13 μm emission tend to have bluer colour, i.e. lower mass loss rates ($\dot{M} \lesssim 10^{-6}$ $M_\odot$ yr^{-1}), and that about 50% of all O-rich AGB stars exhibit this emission feature. Many of the stars with 13 μm emission have been monitored for their light variations. The majority of them displays symmetric light curves indicative of a relatively weak pulsational shock wave.

2. Observations

For all stars in our sample of AGB stars we have full-grating ISO/SWS spectra with complete wavelength coverage from 2-45 μm (AOT01, speed 1 or 2) and on average a spectral resolution of 250. Recently, we acquired in our open time program high-resolution SWS spectra (AOT06) for a selected number of O-rich AGB stars with the 13 μm dust feature at the full-grating resolution of 1500 in the wavelength range 12-16.5 μm. For one star, W Hya, we obtained in addition a SWS Fabry-Perot measurement with a resolution of 30 000, centered on the emission line at 13.87 μm.

The data were reduced using the SWS Interactive Analysis (SIA) data reduction software package using standard ISO pipeline data products (version 6.0). Although in principle flux levels may be affected by the uncertainty in the dark current measured during the observation, the high flux levels of our stars ensure that this effect can be neglected here. The main uncertainties in the observed flux come from the pointing uncertainty and the relative spectral response function (RSRF). The latter also introduces a few artifacts in the spectrum and some instrumental fringing between 12 and 16.5 μm. The flux level of the Fabry-Perot observation is scaled to the flux of the grating spectrum.

3. Discussion

The stars observed so far at high resolution in our sample are listed in Table 1, along with their spectral class, period, distance and expansion velocity. Since no CO measurements are available for R Cen, the expansion velocity as derived from the SiO maser lines is given here. The parameter f is a measure of the symmetry of the light curve, i.e., the ratio of the time it takes to reach the maximum and the period. Values for this parameter and for the period are taken from measurements available from the American Association of Variable Star Observers (AAVSO, Mattei private communication). Unfortunately, for EP Aqr both are unknown. All stars in Table 1 have relatively low mass loss rates. They tend to be type I OH maser sources, i.e. the OH 1665/1667 MHz main-line maser is stronger than the 1612 MHz maser (e.g. Szymczak et al. 1995, Chapman et al. 1994, Slootmaker et al. 1985). The CO J=1-0 lines are weak or not detected (Loup et al. 1993 and references therein). For most of them H_2O (Yates et al. 1995, Krocker and Hagen 1983, Lepine and Paes de Borres 1977) and SiO maser emission has been reported (Cho et al. 1996, Haikala et al. 1994).

Table 1. Stars observed at full-grating resolution.

Object	Sp class	P (days)	v_e (km s^{-1})	D (pc)	f
R Hya	M	388	7.5	130	0.50
W Hya	SRa	361	9.7	100	0.43
R Cen	M	546	7.0	376	0.54
RX Boo	SRb	340	11.5	225	0.46
R Cas	M	430	11.0	216	0.48
EP Aqr	SRb	-	11.0	250	-

We display the 7-16.5 μm section of the AOT01 SWS spectra for the stars in our sample in Fig. 1, including for comparison the spectrum of μ Cep which has no 13 μm dust emission feature. Note that the strength of the 13 μm dust feature varies from one object to another and that the 9.7 μm silicate feature also shows remarkable differences. Two emission features at 10.05 and 11.05 μm and an absorption dip at 9.35 μm are instrumental since they are present in the RSRF. The silicate profiles exhibit a shoulder on the red side compared to the "classical" silicate shape of μ Cep. Little and Little-Marenin (1990) studied a large number of IRAS/LRS spectra of Mira variables and noted variations in the shape of the silicate feature in many stars. It is possible that the profile is broadened by the presence of aluminum oxide which has a peak in its absorption efficiency around 11 μm (Eriksson et al. 1981, Begemann et al. 1997).

From Fig. 1 it is clear that all five objects show emission lines at 13.87 and 16.18 μm. RX Boo shows an additional emission line at 14.97 μm while W Hya and R Cas show absorption lines at the same wavelength. As a first step in the identification of these lines we note that the absorption line at 14.97 μm occurs at the wavelength of the fundamental ro-vibrational ν_2-band of gaseous CO_2, consistent with the fact that both W Hya and R Cas show a deep absorption line at 4.27 μm due to the fundamental ro-vibrational ν_3-band of CO_2 in our full grating scans (AOT1).

Fig. 2 shows the AOT06 spectra of W Hya and EP Aqr at a spectral resolution of 1500. In the spectrum of EP Aqr, we see two additional emission lines at 13.48 and 15.40 μm. On closer examination of the fast AOT01 grating spectra (Fig. 1) these two extra lines are also present in the spectrum of RX Boo. R Cen also exhibits the 13.48 μm line.

The emission lines are quite strong and resolved at this resolution, suggestive of molecular bands. However, this region of

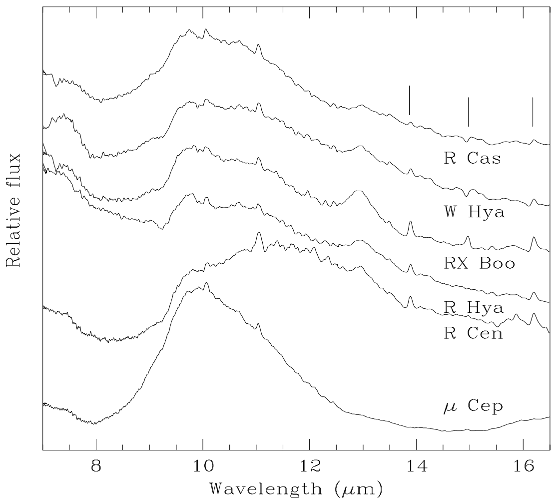

Fig. 1. The 7-16.5 μm section of the SWS/AOT01 spectra for the stars in our sample. Flux levels are in arbitrary units and spectra are shifted for clarity of presentation. Vertical tick marks indicate the positions of emission lines detected. The spectrum of μ Cep is plotted for comparison.

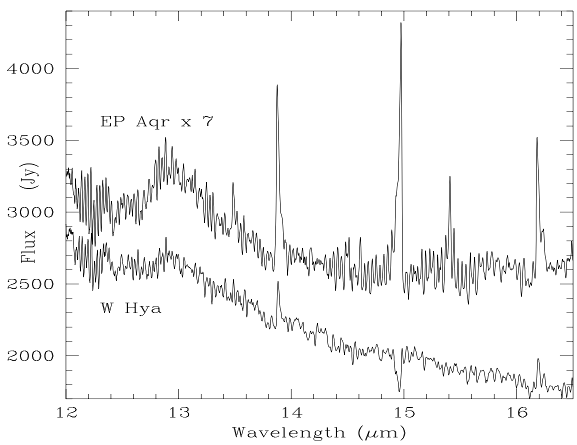

Fig. 2. High-resolution (AOT6) spectra of W Hya, showing two ro-vibrational bands of CO_2 in emission and one in absorption, and of EP Aqr, showing five bands in emission.

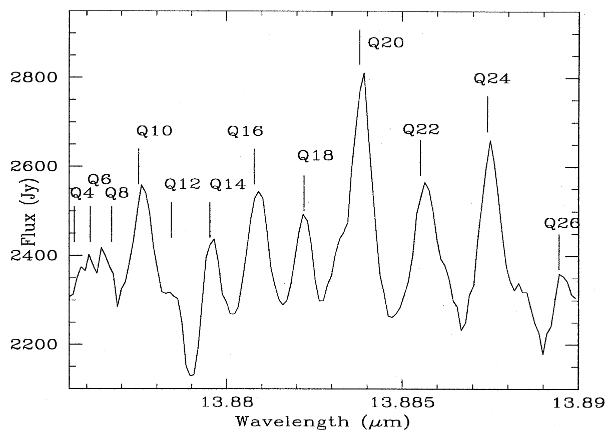

Fig. 3. Preliminary SWS Fabry-Perot spectrum of W Hya at 13.87 μm showing individual lines of the Q-branch of the $10^00 - 00^00$ band of CO_2. Note that the lines have not been corrected to the heliocentric rest frame.

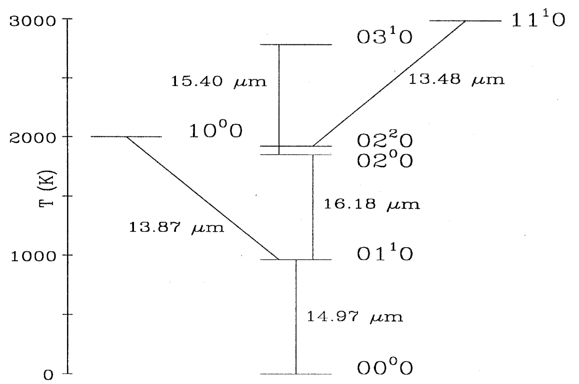

Fig. 4. Energy level diagram of CO_2 indicating the ro-vibrational bands observed in our program stars (adapted from Fig. 84 of Herzberg (1966)).

the spectrum is heavily contaminated by fringes in the RSRF making it difficult to be more positive.

Very recently, we have been able to obtain a SWS Fabry-Perot scan of the 13.87 μm line in W Hya shown in Fig. 3. The spectrum shows a series of individual lines of the Q-branch of the $10^00\,\Sigma_g^+ - 01^10\,\Pi_u$ ro-vibrational transition of CO_2. This establishes beyond any doubt the identification of gaseous CO_2 as the carrier of these lines.

The position of the 15.40 μm line is very close to the $03^10 - 02^20$ band of $^{12}CO_2$ but the peak position is better matched by the $01^10 - 00^00$ band of $^{13}CO_2$. In view of the strength of the 14.97 μm band (the equivalent band for $^{12}CO_2$) it is probable that the 15.40 μm line is due to $^{13}CO_2$.

Upon further examination of the Hitran database (Rothman et al. 1986), we have been able to identify all observed emission lines with the Q-branches of ro-vibrational bands of CO_2. The energy level diagram which summarizes the observed transitions is shown in Fig. 4. The notation used is that from Herzberg (1966).

Preliminary attempts to fit the observed emission lines of EP Aqr with emission from optically thin thermally populated CO_2 gas indicate that the emission lines are formed in a warm gas layer, probably located at a few stellar radii above the photosphere. The excitation temperature can be estimated by fitting the width of the lines: the higher the temperature, the broader the line due to the contribution from high-excitation lines. For all $^{12}CO_2$ lines, we obtain the same excitation temperature of $\sim$ 650 K. The existence of such a warm layer of molecular gas in AGB stars has recently been proposed by Tsuji et al. (1997).

For stars with relatively high mass loss rates in our sample, i.e. R Cas and W Hya, the 14.97 μm line appears in absorption. On close inspection of the spectra in Fig. 1 we note that the line at 14.97 μm when seen in emission is exactly coincident in wavelength with that expected from the lowest ro-vibrational transition in the ν_2-band of CO_2. However, when in absorption

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Table 2. Equivalent widths of the 13 μm dust feature and the detected emission lines.

Source	Equivalent widths (μm)			
	13 μm	13.87 μm	14.97 μm	16.18 μm
R Cas	0.0117	0.0021	0.0044[a]	0.0040
W Hya	0.0153	0.0032	0.0064[a]	0.0053
R Hya	0.0243	0.0051	-	0.0064
R Cen	0.0283	0.0092	0.0027	0.0064
RX Boo	0.0341	0.0115	0.0061	0.0138
EP Aqr	0.0468	0.0109	0.0183	0.0145

[a] CO_2 in absorption

it is shifted to the blue by 0.02 μm, both in W Hya and in R Cas. This cannot be explained by a Doppler shift because this would require a velocity of the order of 400 km s^{-1}, not seen in any of the other lines. A more probable explanation is the contribution from hot ν_2-bands. We have been able to satisfactorily reproduce the shape of the absorption line by including three hotbands and assuming thermal equilibrium population at a temperature of 1250 K, again consistent with the existence of a warm molecular layer in the stellar envelope. More detailed modeling is obviously required.

From the data in Table 2 we conclude that the strengths of the CO_2 emission lines and of the 13 μm dust feature are well-correlated. This suggests that both are produced at the same location in the circumstellar envelope under similar physical conditions. For stars with substantial mass loss rate ($\dot{M} \gtrsim 10^{-5}$ $M_\odot$ yr^{-1}) the 13 μm dust feature is no longer detectable while the 10 μm silicate dust feature starts dominating the spectrum. This could be understood if the enhanced mass loss rate would stimulate the formation of silicate dust and/or prevent the formation of 13 μm dust and at the same time would quench the formation and/or excitation of CO_2 so that we do not observe the CO_2 emission lines in stars without the 13 μm dust feature. More extensive observational studies and detailed models are required to further study the implications of this correlation.

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