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DOI

[10.1007/BF00667868](https://doi.org/10.1007/BF00667868)

Publication date

1995

Published in

Astrophysics and Space Science

[Link to publication](#)

Citation for published version (APA):

Bakker, E. J., Lamers, H. J. G. L. M., Waters, L. B. F. M., & Schoenmaker, A. M. (1995). Circumstellar molecular line absorption and emission in the optical spectra of post-AGB stars. *Astrophysics and Space Science*, 224, 335-338. <https://doi.org/10.1007/BF00667868>

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CIRCUMSTELLAR MOLECULAR LINE ABSORPTION AND EMISSION IN THE OPTICAL SPECTRA OF POST-AGB STARS *

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Abstract. We present a list of post-AGB stars showing molecular line absorption and emission in the optical spectrum. Two objects show CH^+ , one in emission and one in absorption, and 10 stars show C_2 and CN in absorption. The Doppler velocities of the C_2 lines and the rotational temperatures indicate that the line forming region is the AGB remnant. An analysis of the post-AGB stars of which CO millimeter data is available suggests that the C_2 expansion velocity is of the same order as the CO expansion velocity. HD 56126 has been studied in detail and we find a mass-loss rate of $\dot{M}=2.8 \times 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1}$, $f_{\text{C}_2} = 2.4 \times 10^{-8}$ and $f_{\text{CN}} = 1.3 \times 10^{-8}$. The mass-loss derived from C_2 is significantly larger than $\dot{M}=1.2 \times 10^{-5} \text{ M}_{\odot} \text{ yr}^{-1}$ derived from CO. We find that all objects with the $21\mu\text{m}$ feature in emission show C_2 and CN absorption, but not all objects with C_2 and CN detections show a $21\mu\text{m}$ feature.

Key words: molecules – physical conditions in AGB remnant – mass-loss history on AGB

1. Introduction

The study of molecular lines in the optical spectra of post-AGB stars started with the paper by Waelkens *et al.* (1992) in which they presented a band of narrow emission lines in the spectrum of the Red Rectangle (HD 44179). These emission lines were identified as the $(0,0) \text{ A}^1\Pi_u - \text{X}^1\Sigma_g^+$ band of CH^+ by Balm and Jura (1992). The presence of the Swan and Phillips bands of C_2 (Fig. 1) and red system bands of CN (Fig. 2) in the spectrum of HD 56126 studied by Bakker (1994), showed that the outflow velocity and the excitation conditions of C_2 suggest that these lines are formed in the AGB remnant. This opens new possibilities to study the physical conditions in AGB remnants. Hrivnak (1995) presents a list of post-AGB stars showing C_2 and C_3 in absorption. Here we present the observations of post-AGB stars that show molecular lines in the optical spectrum. For several stars

* Based on observations with the WHT/UES

TABLE I
Expansion velocities of the AGB remnant

Object	Id*	$\delta V_{optical}$ [km s ⁻¹]	δV^+ [km s ⁻¹]	T_{rot} [K]	$N10^{14}$ [cm ⁻²]	Remark
IRAS 04296+3429	C ₂	-7.5	-12	138	14	
IRAS 05113+1347	C ₂	-5.2	no	198	12	not observed in CO
HD 56126	C ₂	-8.8	-10.0	240	20	
IRAS 08005-2356	C ₂	-38.1	-50.0	150	31	OH maser
IRC +10216	C ₂	-17.9	-15.7			AGB star
AFGL 2688	C ₂	-15.0	-22.8	56	26	
HD 44179	CH ⁺	-4.5 em.	-3	267	2	
HD 213985	CH ⁺	-5.4 abs.	nd			not detected in CO

* all stars with C₂ do also show CN absorption.

+ from CO millimeter emission. For IRAS 08005-2356 there is no CO data available and we used the velocities from the OH maser line.

the excitation temperature and outflow velocity have been determined. The C₂ absorption in HD 56126 is studied in detail by modeling the population density over the rotational quantum number (Section 3).

2. Detection of Molecules

In Table 1 we list the first results of our work. For each star the 3th and 4th column give the expansion velocity derived from respectively the optical (C₂,CN,CH⁺) and the CO millimeter or OH maser line. The 5th and 6th column give the rotational temperature and column density derived from C₂ (3,0) or CH⁺(0,0) band. Negative velocities are due to outflow of material. The C₂ line absorption is formed closer to the star than the CO line emission, the two different molecules trace different material and hence different stages of the AGB evolution. Our data may indicate that the expansion velocity decreases as the star evolves along the AGB (Table 1). However a larger sample is needed to quantify this result. Stars showing the unidentified 21 μ m emission feature all exhibit C₂ and CN absorption, strongly suggesting that the 21 μ m feature is from carbon-rich material, but not all stars with C₂ absorption show the 21 μ m feature.

3. Modeling the C₂ absorption Bands of HD 56126

From the rotational diagram of the C₂ bands (Fig. 3) we find $T_{rot}=240$ K and for the CN (1,0) band we find $T_{rot}=24$ K with a column density of $N_{C_2} = 20 \times 10^{14}$ cm⁻² and $N_{CN} = 11 \times 10^{14}$ cm⁻². Unlike CN, C₂ is a homo nuclear molecule having no permanent dipole moment and the rotation

Fig. 1. Left: The Phillips (2,0) band in the spectrum of HD 56126. The C_2 absorption lines are not resolved

Fig. 2. Right: The CN $A^2\Pi - X^2\Sigma^+$ (1,0) band in the spectrum of HD 56126. The computed synthetic spectrum is shifted down by 0.5

Fig. 3. Left: Rotational Diagram of the C_2 $A^1\Pi_u - X^1\Sigma_g^+$ (1,0), (2,0), and (3,0) absorption band. The P, Q, and R branches are denoted by respectively a plus, asterisk, and a square. Only the weakest rotational band (3,0) is optically thin and gives an almost linear relation in the rotational diagram with $T_{rot}=240K$ and $N=20 \times 10^{14} \text{ cm}^{-2}$

Fig. 4. Right: Relative rotational diagram of the C_2 $A^1\Pi_u - X^1\Sigma_g^+$ (1,0), (2,0), and (3,0) absorption band of HD 56126 with the model fit for $T_{kin}=24K$ superimposed

temperature is not a good indicator of the kinetic temperature because of pumping by the stellar radiation field. We use the CN rotational temperature as a measure of the kinetic temperature of the gas.

We have tried to fit the relative rotational diagram (Fig. 4) with the population density distribution derived from modeling the C_2 excitation by taking into account radiative pumping and collisional de-excitation (Van Dishoeck and Black 1982). The best fit is reached for $n_c\sigma/I = 3.25 \cdot 10^{-14}$. Taking the latest H_2 - C_2 cross section of $\sigma = 7.8 \times 10^{-16} \text{ cm}^{-2}$ (Phillips 1994) the mass-loss rate can be calculated using Eq. 1. This gives a mass-loss rate

TABLE II
Overview of derived mass-loss rates for HD 56126

Modeling C ₂ excitation	$2.8 \times 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1}$	this study
Infrared excess from dust	$1.9 \times 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1}$	this study; gas/dust=100
CO millimeter emission	$1.2 \times 10^{-5} \text{ M}_{\odot} \text{ yr}^{-1}$	¹² CO(2-1) Omont <i>et al.</i> 1993

of $\dot{M}_{C_2} = 2.8 \times 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1}$.

$$\dot{M} = 2.8 \times 10^{-4} \cdot \left(\frac{v_{exp}}{8.8} \cdot \frac{n_c}{1.7 \times 10^7} \cdot \frac{\sigma}{7.8 \times 10^{-16}} \cdot \frac{4.1 \times 10^5}{I} \right) \text{ M}_{\odot} \text{ yr}^{-1} \quad (1)$$

Fitting an optically thin dust model (Waters *et al.* 1988) to the the spectral energy distribution of HD 56126 yields a dust inner radius of $2 \times 10^3 R_{\star}$ and $\dot{M} = 1.9 \times 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1}$. Assuming that the molecular line absorption originates at this dust inner radius we find a particle abundance relative to H₂ of $f_{C_2} = 2.4 \times 10^{-8}$ and $f_{CN} = 1.3 \times 10^{-8}$. Table 2 summarizes the mass-loss rates derived for HD 56126, where we have scaled the different mass-loss rates to $R_{\star} = 50 R_{\odot}$, $T_{eff} = 6500 \text{ K}$ ($\log L = 3.6$) and $D = 2.7 \text{ kpc}$. The mass-loss rate derived from C₂ and from the IR excess are significantly higher than that derived from the CO millimeter emission, which might indicate that the mass loss rate increased dramatically towards the end of the AGB.

Acknowledgements

The authors want to thank Ewine van Dishoeck and Christoffel Waelkens for the stimulating and constructive discussions on this work. EJB was supported by grant no. 782-371-040 by ASTRON, which receives funds from NWO. LBFMW acknowledges financial support from the Royal Dutch Academy of Arts and Sciences. This research has made use of the Simbad database, operated at CDS, Strasbourg, France.

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