The Time Variation in the Water Vapor Bands in Oxygen-Rich Mira variables *†

Mikako Matsuura[1,2], Issei Yamamura[1], Teije de Jong[3,4], Takashi Onaka[2], Hiroshi Murakami[1], Jan Cami[4,5]

December 12, 2000

(1) *The Institute of Space and Astronautical Science (ISAS), Yoshino-dai 3-1-1, Sagamihara, Kanagawa 229-8510, Japan*
e-mail(M.M.):mikako@ir.isas.ac.jp
(2) *Department of Astronomy, School of Science, University of Tokyo, Hongo 7-3-1, Bunkyo, Tokyo 113-0033, Japan*
(3) *SRON-Utrecht, Sorbonnelaan 2, 3584 CA Utrecht, the Netherlands*
(4) *Astronomical Institute 'Anton Pannekoek', University of Amsterdam, Kruislaan 403, 1098 SJ, Amsterdam, the Netherlands*
(5) *SRON-Groningen, P.O. Box 800, 9700 AV Groningen, the Netherlands*

Abstract

We examine the time variation in the near-infrared H_2O bands in oxygen-rich Mira variables. We analyzed four Mira variables, which were monitored for longer than one period of their optical light curves with the ISO/SWS. In the wavelength range from ∼3.5 to 4.0 μm, all of the sample stars show absorption features of H_2O bands around minima and emission features around maxima. The model analysis shows that the H_2O layer with an excitation temperature of ∼2000 K is responsible for these features and that the layer is located at about 1 stellar radius around minima, and expands to about 2 stellar radii around maxima. These results are probably explained by high density region in the extended atmosphere caused by the pulsation shock.

*Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) with the participation of ISAS and NASA. The SWS is a joint project of SRON and MPE.

†Original draft is submitted to Proceedings of the workshop, 'POST-AGB OBJECTS (PROTO-PLANETARY NEBULAE), as a Phase of Stellar Evolution', eds. R. Szczerba, S.K.Gorny, in press

1 Introduction

Strong pulsations in AGB stars, especially in the Mira variables, extend their atmospheres. This extended atmosphere is enriched with various kinds of molecules. Its temperature ranges from ∼2000 to ∼1000 K (Woitke et al. [1999]). Recent infrared spectroscopic observations from the space enable us to carry out detailed studies of the molecules in the extended atmosphere, based on the data unaffected by the terrestrial atmosphere.

Using the Short-Wavelength Spectrometer (SWS; de Graauw et al. [1996]) onboard the Infrared Space Observatory (ISO; Kessler et al. [1996]), Yamamura et al. ([1999]) studied the near-infrared H_2O bands in the Mira variables. They found that H_2O bands in the ∼3.5–4.0 μm region were observed as emission in *o* Cet, which was observed at maximum in the visual light curve. In contrast, another star Z Cas, observed at minimum showed the bands in absorption at the same wavelengths. They analyzed the spectra of these stars in the 2.5–5.0 μm region with a simple 'slab' model. This model consists of two H_2O layers ('hot' and 'cool' layers) with independent excitation temperatures, column densities, and radii. The excitation temperature of the H_2O molecules responsible for the spectra in the ∼3.5–4.0 μm region was estimated as 2000 K in both stars. Yamamura et al. ([1999]) showed that the 'hot' layer is as large as ∼2 R_* in *o* Cet, while it was only ∼1 R_* in Z Cas, where R_* is the radius of the central star. They suggested that the difference between *o* Cet and Z Cas is mainly caused by the different radius of the 'hot' layer, and that the 'hot' water layer is more extended at maximum than at minimum.

2 The Time Variation in the H_2O bands

We examine the time variation in the H_2O bands in the 2.5–4.0 μm region in oxygen-rich Mira variables. We selected four stars (R Aql, R Cas, T Cep, and Z Cyg) from the ISO Data Archive. They were observed by the SWS several times over the period longer than one variable cycle (Onaka et al. [1999]; Loidl et al. [1999]). Fig. 1 shows an example of the time variation of the spectra between 2.5 and 4.0 μm.

We apply the same model as described in Yamamura et al ([1999]). The plane-parallel configuration and local thermodynamic equilibrium (LTE) were assumed in the model calculation. A disk-shaped background source and molecular layers were placed one over the other. The background source, which represents the stellar continuum, is assumed to be a 3000 K blackbody. In most cases only H_2O molecules are included in the model except for two spectra in R Aql and four spectra in T Cep, for which OH molecules are also taken into account to reproduce sharp absorption features. We calculated more than ten thousands of spectra, over a large parameter space of radius and column density of two layers, and the excitation temperature of the cool layer with sufficiently fine grid points. According to Yamamura et al. ([1999]), we fix the excitation temperature of the 'hot' layer as 2000 K. We apply the χ^2 test to find the best-

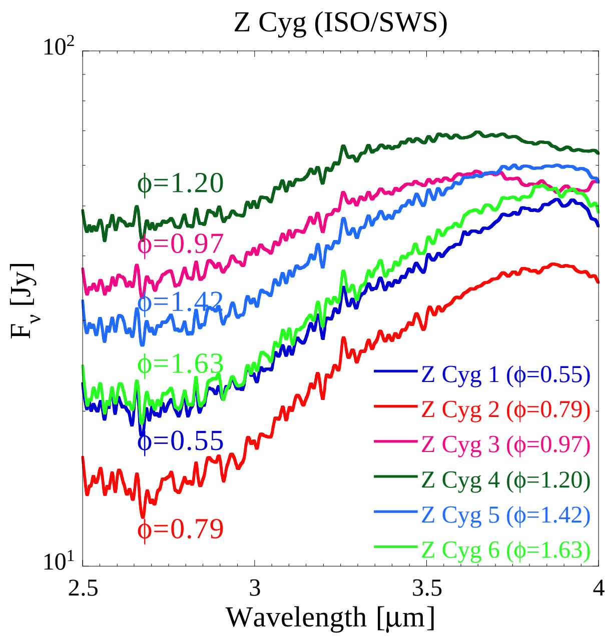

Figure 1: The time variation in the Z Cyg spectra obtained by the ISO/SWS. The optical variability phase (ϕ) at each observation, determined by the AAVSO light curve, is indicated in the figure by the labels. The '3.83 μm feature' (see text and Fig. 3) is marked by the vertical lines.

fit spectra. Fig. 2 indicates the best fitted results for Z Cyg corresponding to the observed spectra in Fig 1. Our simple 'slab' model satisfactorily reproduces the global shape as well as the small features in the observed spectra.

Here we focus on the most interesting parameter, the radius of the 'hot' layer (R_H). Other parameters are discussed in Matsuura et al. ([**?**]). The 'hot' layer has an excitation temperature of 2000 K. The radius of the 'hot' layer (R_H) affects the features in the wavelengths longer than $\sim$3.5 μm (Fig. 3). The overlaying 'cool' layer causes absorption features in the wavelengths shorter than $\sim$3.5 μm and masks features arising from the 'hot' layer. The features from the hot layer become in emission in the 3.8 μm region when R_H is larger than $\sim$1.6 R_*, while they are seen in absorption when R_H is smaller than that. This is clearly demonstrated by a sharp peak at 3.83 μm in Fig. 3. In the observed spectra in Fig. 1, this feature, marked by the lines, are seen in emission around maximum, and in absorption around minima. Thus, from Fig. 1, we estimate that R_H is larger than $\sim$1.6 R_* around maximum and smaller than that around minima.

The variation of R_H derived from the model fitting is plotted in Fig. 4. In

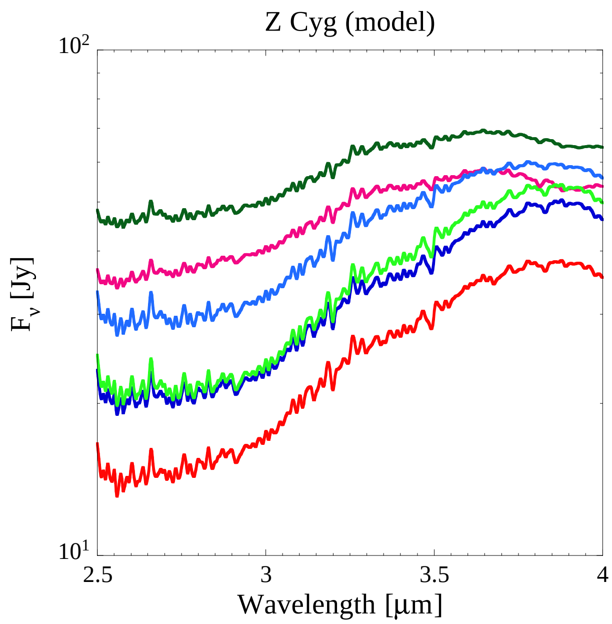

Figure 2: The synthesized spectra corresponding to Fig. 1 are indicated. Global shape and most of the small features in this wavelength range are reproduced by the model including only H_2O.

all of the four stars, R_H reaches about 2 R_* around maxima (ϕ=0.0, 1.0, and 2.0) and becomes $\sim$1 R_* around minima. These results are in agreement with Yamamura et al. ([1999]). The variation in R_H is calculated as the ratio to the radius of the stellar continuum. According to the interferometric observations by Tuthill et al. ([1995]), the variation in the 'stellar radius' of Mira is smaller than 7 %. Theoretical work (Bessell et al. [1996]) indicates the range of about 20 %. The amplitude of variation in the stellar radius is smaller than that of R_H. Thus the location of the 'hot' H_2O layer actually varies.

The periodical variations of the H_2O bands suggest that they are related to the pulsation. One possible explanation for this variation is that the high-density layers are produced by the shocks, and such regions contribute on the spectrum. The layers move as the shock propagates in the atmosphere. More detailed discussion is given in Matsuura et al. ([2000]).

Acknowledgments

The authors acknowledge the American Association of Variable Star Observers (AAVSO) to provide us the light curves. M.M. thanks the hospitality of the

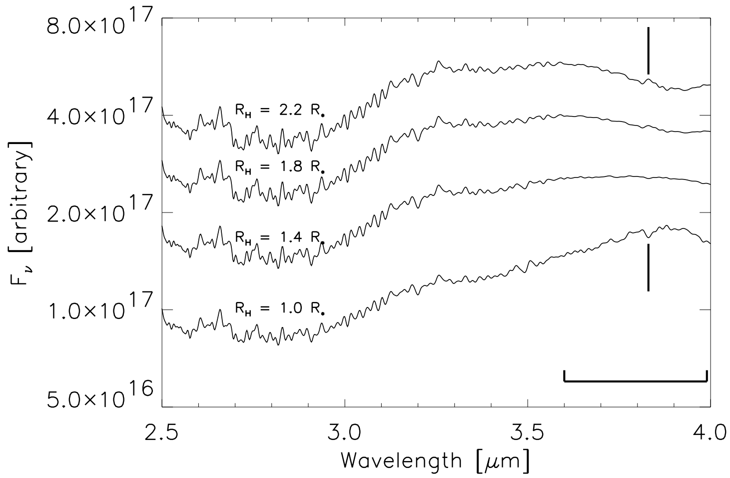

Figure 3: The effects of R_H on the synthesized spectra. From top to bottom, R_H is 2.2, 1.8, 1.4, 1.0 R_*. The features longer than $\sim$3.5 μm vary with R_H. The features become emission when R_H is larger than $\sim$1.6 R_*. The effects are prominently seen in the 3.83 μm feature which is either seen in emission or in absorption depending on R_H. The wavelengths shorter than $\sim$ 3.5 μm are subjected to the absorption feature from the overlaying 'cool' layer, and the features are insensitive to the parameters of the hot layer in this figure. The absolute flux varies owing to the variation of radius of the emitting region. Other parameters are fixed as $T_H = 2000$ K, $T_C = 1200$ K, $N_H = 1 \times 10^{22}$ cm^{-2}, $N_C = 1 \times 10^{21}$ cm^{-2}. In these calculations, R_C is given as $R_C^2 = R_H^2 + 1^2$ $[R_*^2]$.

Astronomical Institute, University of Amsterdam during her stay. M.M. is a Research Fellow of the Japan Society for the Promotion of Science for the Young Scientists.

References

[1996] Bessell M.S., Scholz M., Wood P.R., 1996, A&A 307, 481

[1996] de Graauw Th., Haser L.N., Beintema D.A., et al., 1996, A&A 315, L49

[1996] Kessler M., Steinz J.A., Anderegg M.E., et al., 1996, A&A 315, L27

[1999] Loidl R., Aringer B., Hron J., Kerschbaum F., Höfner S., Jørgensen U.G., Windsteig W., 1999, ESA-SP 427, 365

[2000] Matsuura M., Yamamura I., de Jong T., et al., 2001, A&A, in preparation

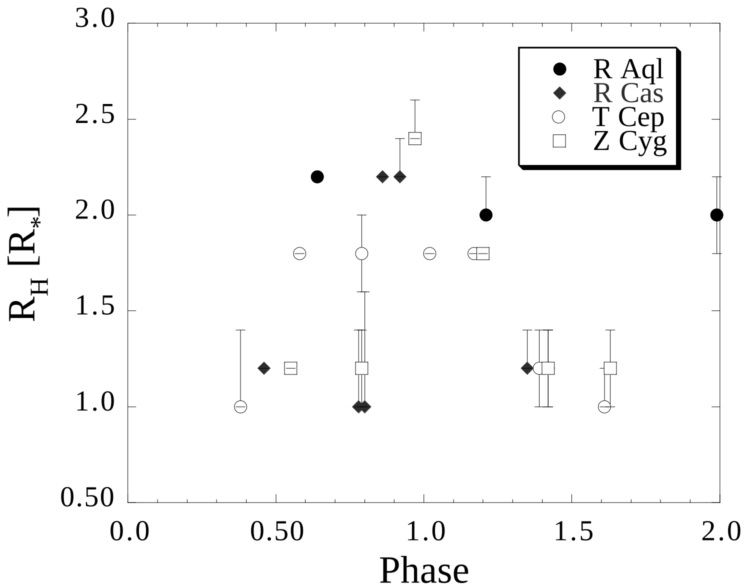

Figure 4: The derived R_H for four Mira variables are indicated against the optical phase. The radius of the 'hot' layer is about $\sim 1\ R_*$ around minimum, and about $\sim 2\ R_*$ around maximum.

[1999] Onaka T., de Jong T., Yamamura I., Cami J., Tanabé T., 1999, ESA-SP 427, 281

[1995] Tuthill P.G., Haniff C.A., Baldwin J.E., 1995, MNRAS 277, 1541

[1999] Woitke P., Helling Ch., Winters J.M., Jeong K.S., 1999, A&A 348, L17

[1999] Yamamura I., de Jong T., Cami J., 1999, A&A 348, L55