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**Publication date**
1999

**Published in**
Astronomy & Astrophysics



**Citation for published version (APA):**
Matsuura, M., Yamamura, I., Murakami, H., Freund, M. M., & Tanaka, M. (1999). Water vapor absorption in early type M-type stars. *Astronomy & Astrophysics*, *348*, 579-583.

Astron. Astrophys. 348, 579–583 (1999)

ASTRONOMY AND ASTROPHYSICS

# Water vapor absorption in early M-type stars

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Received 27 October 1998 / Accepted 26 May 1999

**Abstract.** The spectrometers onboard the Infrared Telescope in Space (IRTS) reveal water vapor absorption in early M-type stars, as early as M2. Previous observations detected $H_2O$ vapor absorption only in stars later than M6, with the exception of the recent detection of $H_2O$ in $\beta$ Peg (M2.5 II-III). In our sample of 108 stars, 67 stars have spectral types earlier than M6. The spectral types are established by means of their near-infrared colors on a statistical basis. Among the 67 stars of spectral types earlier than M6, we find water vapor absorption in six stars. The observed absorption features are interpreted using a local thermodynamic equilibrium model. The features are reasonably fitted by model spectra with excitation temperatures of 1000–1500 K and water column densities of $5\times10^{19}$ to $1\times10^{20}$ cm$^{-2}$. These numbers imply that the $H_2O$ molecules are present in a region of the atmosphere, located above the photosphere. Furthermore, our analysis shows a good correlation between the $H_2O$ absorption band strength, and the mid-infrared excess due to the circumstellar dust. We discuss the relation between the outer atmosphere and the mass loss.

**Key words:** infrared: stars – stars: late-type – stars: atmospheres – stars: circumstellar matter – stars: variables: general – surveys

## 1. Introduction

Water is one of the most abundant molecules in the atmosphere of late M-giants, and it is a dominant absorber in the near-infrared (near-IR) region. Water vapor in stellar atmospheres has been studied by theoretical and observational methods. The strength of the $H_2O$ absorption possibly correlates with the spectral type, the effective temperature of the star, and the near-IR color (Kleinmann & Hall 1986; Lançon & Rocca-Volmerange 1992), even though such correlations were not clearly found by Hyland (1974). According to Spinrad & Wing (1969) and Hyland (1974), $H_2O$ could only be detected in giants with spectral type M6 or later. This was consistent with hydrostatic models of the atmosphere of red-giants (Tsuji 1978; Scargle & Strecker 1979). As a further complication, most late M-giants are long period variables, and in general, the band strength of the $H_2O$ absorption features depends on stellar variability. For example, Mira variables show very deep $H_2O$ absorption, and the depths of $H_2O$ features in Miras vary from phase to phase (Hyland 1974). High-resolution spectroscopic observations of the Mira variable R Leo by Hinkle & Barnes (1979) revealed that a significant fraction of the $H_2O$ molecules were in a component with a distinct velocity, and a cooler excitation temperature than molecules near the photosphere. They interpreted this 'cool component' as an overlying layer above the photosphere.

These previous studies were mostly based on ground or airborne observations, where the terrestrial $H_2O$ interferes with a detailed study of the center of the stellar water bands. In contrast, observations from space are ideal for investigations of stellar $H_2O$ features. Using the Infrared Space Observatory (ISO), Tsuji et al. (1997) discovered a weak $H_2O$ absorption in the early M-type star, $\beta$ Peg (M2.5II-III). They argued that the observed $H_2O$ is in a 'warm molecular layer' above the photosphere.

In this paper, we present the results of a study of $H_2O$ absorption features, using data from the Infrared Telescope in Space (IRTS, Murakami et al. 1996 and references therein).

## 2. Sample data

This study is based on data from the two grating spectrometers onboard the IRTS: the Near-Infrared Spectrometer (NIRS), and the Mid-Infrared Spectrometer (MIRS). The IRTS was launched in March 1995, and it surveyed about 7% of the sky with four instruments during its 26 day mission. The NIRS covers the wavelength region from 1.43 to 2.54 and from 2.88 to 3.98 $\mu$m in 24 channels with a spectral resolution for point sources of $\Delta\lambda = 0.10$–$0.12$ $\mu$m. The MIRS covers the range from 4.5 to 11.7 $\mu$m in 32 channels with a resolution of $\Delta\lambda = 0.23$–$0.36$ $\mu$m. Both spectrometers have a rectangular entrance aperture of $8' \times 8'$. The total number of detected point sources is about 50,000 for the NIRS (Freund et al. 1997) and about 1,000 for the MIRS (Yamamura et al. 1996). The estimated absolute calibration errors are 5% for the NIRS, and 10% for the MIRS. This may cause systematic errors in the colors and the $H_2O$ index discussed in this paper. The spectra are not color corrected.

All stars used in this study were observed both by the NIRS and the MIRS between April 9 and 24. We only include stars at high galactic latitudes ($|b| > 10^\circ$) in this sample, to mini-

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mize source confusion and interstellar extinction. Each selected star has a unique association with the IRAS Point Source Catalog (PSC, 1988), within 8′ from the nominal NIRS position, and each associated PSC entry has reliable 12 and 25 $\mu$m band fluxes (FQUAL=3; IRAS Explanatory Supplement 1988). Known carbon and S-type stars (Stephenson 1989, 1984), as well as non-stellar objects were discarded from the sample. The current sample contains 108 stars. The signal-to-noise ratio for all stars is larger than 5 in all NIRS bands.

Of the 108 stars used in this study, 43 have a unique association in the Bright Star Catalogue (BSC, Hoffleit & Jaschek 1991). The distribution of spectral types for these 43 stars are: 1 B, 2 F, 4 G, 22 K, and 14 M-types. A total of 31 M-giants are found in the General Catalogue of Variable Stars (GCVS, Kholopov et al. 1988), and the distribution of variable types in the GCVS is as follows: 10 Miras, 13 semi-regulars (SR, SRa or SRb, hereafter SR), and 8 irregulars (L or Lb, hereafter L). No M-dwarfs or M-supergiants were found in the BSC or the GCVS associations.

## 3. Results

In Fig. 1, we show the composite spectra of six representative M-giants observed by the NIRS and the MIRS. We indicate the position of the molecular absorption features due to CO (1.4, 2.3, 4.6 $\mu$m), $H_2O$ (1.5, 1.9, 2.7, 6.2 $\mu$m), and SiO (8.2 $\mu$m). The broad-band emission at 9.7 $\mu$m is due to silicate dust. The $H_2O$ bands at 1.9 and 2.7 $\mu$m are visible in two early M-giants, AK Cap (M2, Lb) and V Hor (M5, SRb), where no $H_2O$ in the photosphere was expected to be detectable.

One could argue that the early M-type stars with $H_2O$ absorption had spectral types later than M6 at the time of observation, because of their variability. However, this is not the case. We can estimate the spectral types, using the relation between the spectral type and color (Bessell & Brett 1988). We use the color $C_{2.2/1.7}$ instead of the photometric color $H-K$, where $C_{2.2/1.7}$ is defined as:

$$C_{2.2/1.7} = \log(F_{2.2}/F_{1.7}). \quad (1)$$

$F_{2.2}$ and $F_{1.7}$ are the IRTS/NIRS fluxes at 2.2 and 1.7 $\mu$m in units of Jy, respectively. For the NIRS wavelength region, the 2.2 and 1.7 $\mu$m bands are least affected by stellar $H_2O$ absorption bands. Fig. 2 shows $C_{2.2/1.7}$ versus the spectral types from BSC and GCVS of all the known K- and M-giants (59 giants) in the sample. There is a clear increase in $C_{2.2/1.7}$ toward later spectral type except for Miras. One M9 star (KP Lyr = ADS 11423) deviates from this relation, but we regard this star as M5, according to Abt (1988).

All stars of spectral type M6 and later are above $C_{2.2/1.7} = -0.085$. Thus, stars bluer than $-0.085$ are expected to have spectral types earlier than M6. There are 67 stars in the $<$ M6 region, defined by $C_{2.2/1.7} < -0.085$. $C_{2.2/1.7}$ for AK Cap and V Hor is $-0.130$ and $-0.102$, respectively. These numbers confirm that these 2 stars have spectral types earlier than M6 at the time of the IRTS observation, even though both stars show clear $H_2O$ absorption.

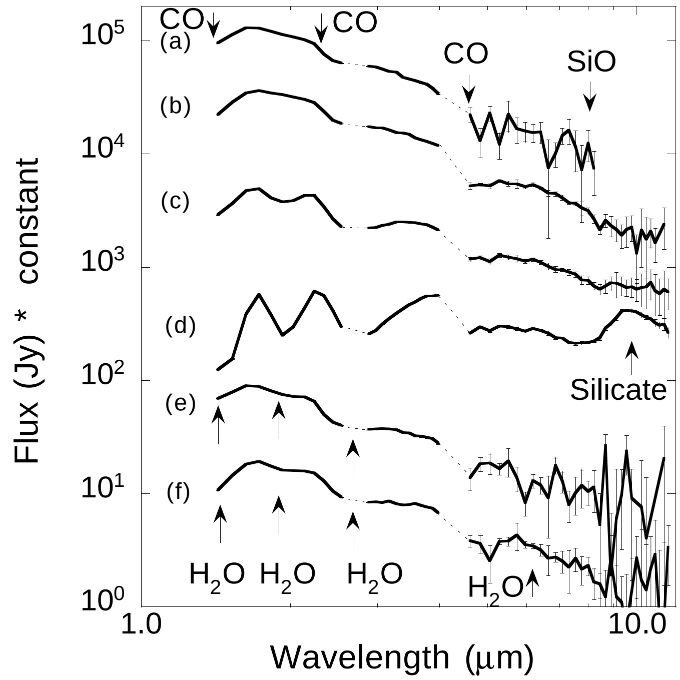


**Fig. 1.** The combined NIRS & MIRS spectra of M-giants are shown. From top to bottom: (a) HR 1667 (M2III), (b) HR 257 (M4III) (c) X Hor (M6-M8, SRa), (d) RR Aql (M6e-M9, Mira), (e) AK Cap (M2, Lb) and (f) V Hor (M5III, SRb). The error bars represent the noise in the subtracted background level. Water absorption bands at 1.9 and 2.7 $\mu$m are seen in the two early M-giants (e) AK Cap and (f) V Hor, in contrast to other early M-giants ((a) and (b)).

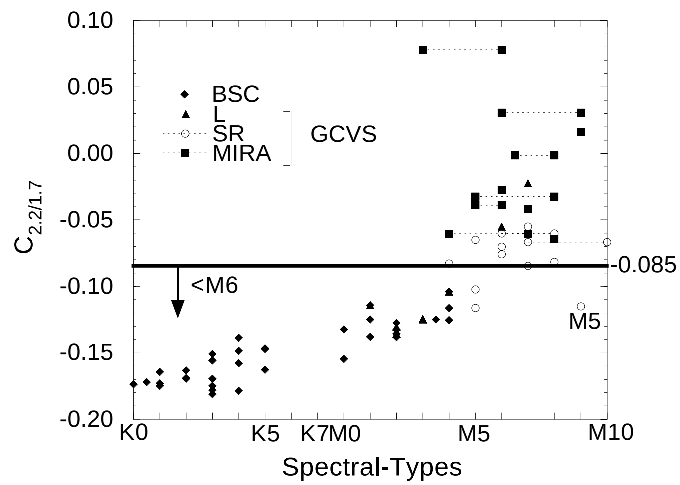


**Fig. 2.** The color $C_{2.2/1.7}$ is plotted against the spectral type derived from BSC and GCVS. Ranges of spectral types of some SRs and Miras are represented by dotted bars. The thick horizontal line indicates the boundary of stars with spectral types $<$ M6.

We now discuss the relationship between the $H_2O$ absorption strength and the spectral type. For this, we define the $H_2O$ index $I_{H_2O}$ as follows:

$$I_{H_2O} = \log(F_{cont}/F_{1.9}), \quad (2)$$

where $F_{\rm cont}$ is the continuum flux level at 1.9 $\mu$m in units of Jy, which is evaluated by linear interpolation between $F_{1.7}$ and $F_{2.2}$. $F_{1.9}$ is the observed flux (Jy) at 1.9 $\mu$m. In Fig. 3, we plot $I_{\rm H_2O}$ as a function of $C_{2.2/1.7}$. The dominant measurement errors for $C_{2.2/1.7}$ and $I_{\rm H_2O}$ are due to the slitless spectroscopy, and they are roughly 0.01 and 0.002 for stars $<$ M6, respectively.

Fig. 3 can be used to find candidate stars ($<$ M6) with $H_2O$ absorption. Since we estimated $F_{\rm cont}$ by linear interpolation, $I_{\rm H_2O}$ is not zero even in the absence of $H_2O$. We evaluate the relation between $I_{\rm H_2O}$ and $C_{2.2/1.7}$ for stars without $H_2O$, using a linear fit for the 67 stars in the $<$ M6 region, by minimizing a merit function $\sum_i^n |y_i - a - bx_i|$ for $n$ data points $(x_i, y_i)$ (Press et al. 1986). This fit is robust against outliers, i.e. stars with $H_2O$. The result is indicated as a thick line. The thin lines indicate $\pm 2\sigma$ level from the fit, where $\sigma$ is standard deviation of $I_{\rm H_2O}$. Here, we use the $+2\sigma$ level as a threshold to find candidate stars with $H_2O$, because no star appears below the $-2\sigma$ line. The stars above the $+2\sigma$ are supposed to be stars with $H_2O$ absorptions. There are 6 such stars in the region of $<$ M6. The value of $2\sigma$ is almost equal to that of 3 standard deviations after the outliers are excluded. The spectra of the stars are shown in Fig. 4. These 6 stars above the $+2\sigma$ line show clear evidence of $H_2O$ absorption bands at 1.9 and 2.7 $\mu$m. Only AK Cap and V Hor have identifications of spectral type in BSC or GCVS. On the basis of their $C_{2.2/1.7}$ (ranging from $-0.113$ to $-0.086$), the other four stars are probably M-type stars, and not K-type stars (see Fig. 2).

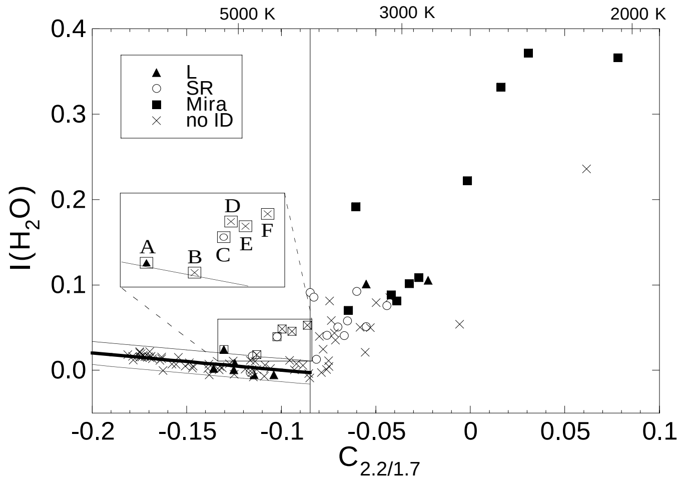


**Fig. 3.** $I_{\rm H_2O}$ is plotted as a function of near-IR color $C_{2.2/1.7}$. Symbols represent variable types in GCVS. The blackbody color temperatures corresponding to $C_{2.2/1.7}$ are indicated on the upper x-axis. Left of the vertical line at $-0.085$ is the region of stars $<$ M6. The thick horizontal line indicates $I_{\rm H_2O}$ v.s. $C_{2.2/1.7}$ relation for stars with spectral type $<$ M6. Six stars above the upper thin line ($+2\sigma$) with spectral types $<$ M6 are supposed to have $H_2O$ absorption. Two stars from the sample lie outside of this plot at $(C_{2.2/1.7}, I_{\rm H_2O}) = (0.888, 0.301), (-0.213, 0.025)$.

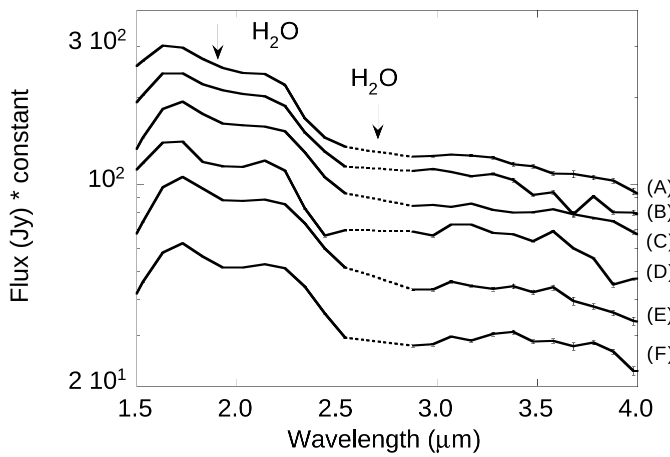


**Fig. 4.** The six early M-type stars with clear $H_2O$ absorption bands, which are above the $+2\sigma$ line in Fig. 3. From top to bottom: (A) AK Cap, (B) IRAS 21222−4155, (C) V Hor, (D) IRAS 21269−3711, (E) IRAS 20073−1041, and (F) IRAS 05124−4936.

## 4. Discussion

In Fig. 5, we plot $I_{\rm H_2O}$ versus the color defined by the NIRS 2.2 $\mu$m band flux and IRAS 12 $\mu$m flux ($F_{12}$) as:

$$C_{12/2.2} = \log(F_{12}/F_{2.2}). \quad (3)$$

$C_{12/2.2}$ is a measure of the IR excess due to circumstellar dust, and is roughly equivalent to $K - [12]$, which is an indicator of mass-loss rate in Miras (Whitelock et al. 1994). Fig. 5 shows boundary at $C_{12/2.2} \approx -1.0$ between early M-type stars with $H_2O$ and those without $H_2O$ (we regard all stars below the $+2\sigma$ line in Fig. 3 as early M-type stars without $H_2O$). Furthermore, there is a clear correlation between $I_{\rm H_2O}$ and $C_{12/2.2}$, which implies that the $H_2O$ absorption is related to the circumstellar dust emission. However, as we show below, the $H_2O$ molecules are not necessarily located in the circumstellar envelope.

We estimate the excitation temperature ($T_{\rm ex}$), and the column density ($N$) of $H_2O$ molecules in early M-type stars. The spectrum of a representative star, AK Cap is normalized with respect to the spectra of two early M-type stars, which have the same spectral types and similar near-IR color ($C_{2.2/1.7}$), but do not show $H_2O$ absorption ($I_{\rm H_2O}$), or dust excess ($C_{12/2.2}$). The resulting normalized spectrum of AK Cap is fitted by a simple plane-parallel model with a uniform molecular layer assuming local thermodynamic equilibrium (LTE) (Fig. 6). The $H_2O$ line list is taken from Partridge & Schwenke (1997). The turbulent velocity is assumed to be 3 $\rm km\ s^{-1}$. For AK Cap, we obtain a reasonable fit for $T_{\rm ex} \approx 1000$–1500 K and $N \approx 5 \times 10^{19}$ cm$^{-2}$. A similar analysis for V Hor (M5III) results in $T_{\rm ex} \approx 1000$–1500 K and $N \approx 1 \times 10^{20}$ cm$^{-2}$. If we assume that the $H_2O$ molecules were in the circumstellar envelope, the mass-loss rate obtained from these column densities would exceed $10^{-6}$ $M_\odot$ yr$^{-1}$ (assuming an abundance ratio of $H_2O/H_2 = 8 \times 10^{-4}$; Barlow et al. 1996), which is about a factor of 10–100 larger than those expected for Ls and SRs ($10^{-7}$–$10^{-8}$ $M_\odot$ yr$^{-1}$, Jura & Kleinmann 1992). Thus, the $H_2O$ molecules responsible for observed feature cannot be in the circumstellar shell.

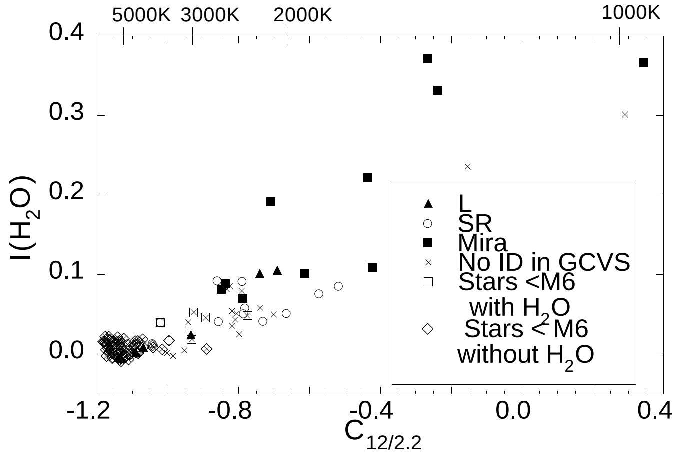


**Fig. 5.** $I_{\mathrm{H_2O}}$ correlates well with $C_{12/2.2}$. The color temperatures are indicated on the upper x-axis. The open rectangles denote the six stars (< M6) with $H_2O$. The early M-type stars without $H_2O$ are overlapped by diamonds. There is a systematic dependence of $C_{12/2.2}$ on variable types: Miras show the deepest $H_2O$ absorption, as well as reddest $C_{12/2.2}$, and the SRs are second. Ls are scattered in a regime from no-$H_2O$ to lower end of the $H_2O$ absorption in Miras (see also Fig. 3 for variable-type dependence).

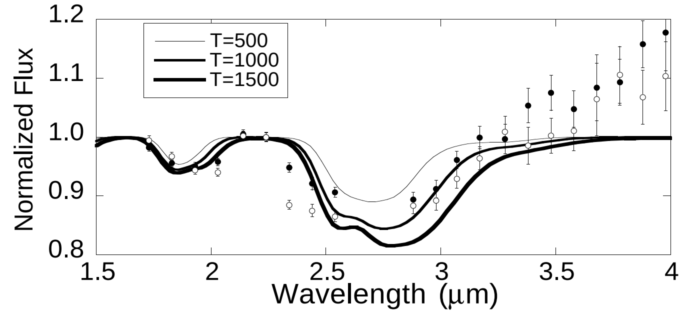


**Fig. 6.** The observed spectral profile of $H_2O$ in AK Cap (M2), divided by the spectra of HR 1667 (M2; open circle) and HR 6306 (M2; filled circle), and normalized to 1 at 2.2 $\mu$m. Both HR 1667 and HR 6306 have no $H_2O$ absorption bands and no dust emission. The three lines indicate LTE model spectra with a column density of $5\times10^{19}$ cm$^{-2}$, and temperatures of 500, 1000, and 1500 K. The excess at longer wavelength is possibly due to dust emission.

In contrast, our measured values for $T_{\mathrm{ex}}$ and $N$ are in good agreement with results by Tsuji et al. (1997), who suggested that the $H_2O$ molecules in M-type stars are located in the layer above the photosphere. Our numbers $T_{\mathrm{ex}}$ are also consistent with $T_{\mathrm{ex}} \approx 1150 \pm 200$ K by Hinkle & Barnes (1979) for the ‘cool component’ of the Mira variable R Leo, which is an overlaying layer of photosphere. Because the $H_2O$ molecules responsible for the near-IR absorption cannot be in the circumstellar shell, and because our results are consistent with Tsuji et al. (1997) and Hinkle & Barnes (1979), we conclude that they are in an outer atmosphere, i.e. the layer above the photosphere, but below the circumstellar envelope.

Numerical calculations of the atmospheres of Miras (e.g. Bowen 1988; Bessell et al. 1996) show that the pulsation of the star extends the stellar atmosphere. Our observations show that such an extended region could also be present in some SRs and Ls. The dependence of $H_2O$ intensity on variable types as seen in Fig. 3 and 5 may result from differences in the physics of pulsation. Not all Ls and SRs show $H_2O$ absorption, which is not surprising, because of their complexity (e.g. Jura & Kleinmann 1992). Using the light curve of V Hor (Mattei 1998), we confirm that V Hor is probably an SR, although it shows a sudden increase of its visual magnitude before the IRTS observation. Unfortunately, no light curve is available for AK Cap.

Hinkle & Barnes (1979) found that in Miras the $H_2O$ in an outer layer is responsible for the near-IR absorption, and we find the same situation in some early M-type stars. If we assume a constant abundance ratio of $H_2O/H_2$, then $I_{\mathrm{H_2O}}$ is a measure of the total column density in the outer layer. Furthermore, $C_{12/2.2}$ is a measure of the amount of the hot circumstellar dust, if the circumstellar shells of the stars in Fig. 5 have a similar dust composition. Therefore, the total column density of the outer layer correlates with the thickness of the circumstellar shell. This may suggest that the outer layer influences the mass loss of the star.

In conclusion, we demonstrate that $H_2O$ absorption can be seen in early M-type stars, and that the $H_2O$ molecules are located in the outer atmosphere. The observed correlation between the intensity of the $H_2O$ absorption and the mid-infrared excess implies that the extended atmosphere is connected to the mass loss of the stars.

*Acknowledgements.* The authors acknowledge Drs. M. Cohen and M. Noda for their efforts on the NIRS calibration. M.M. thanks the Research Fellowships of the Japan Society for the Promotion of Science for the Young Scientists. I.Y. acknowledges financial support from a NWO PIONIER grant. M.M.F. thanks Dr. H.A. Thronson at NASA Headquarters for discretionary funding, as well as the Center of Excellency of the Japanese Ministry of Education.

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