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WATER ON THE EARLY M SUPERGIANT STARS α ORIONIS AND μ CEPHEI

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ABSTRACT

We reanalyze the spectra of α Ori (M2 Iab) and μ Cep (M2 Ia) observed with the balloon-borne telescope Stratoscope II more than 35 years ago, and we confirm the presence of water in these early M supergiant stars. This identification was first proposed by the Stratoscope observers themselves (Woolf, Schwarzschild, and Rose in 1964; and Danielson, Woolf, and Gaustad in 1965), but this important discovery was overlooked for a long time without any follow-up observation. Consequently, this finding has so far had little influence on the theory of the atmosphere of red supergiant stars. A reason for this may be due to an early criticism by Wing and Spinrad, who suggested CN instead of H_2O for the spectral features observed by Stratoscope II. This alternative proposition has more easily been accepted since CN has widely been observed from the Sun to red supergiants, while H_2O has been observed only in very cool stars such as Mira variables. In fact, we confirm that the self-consistent photospheric model of the early M supergiants shows CN bands but no H_2O band in the near-infrared. Nevertheless, we find that the contribution of CN is only minor and that H_2O should be the dominant absorber for the 1.4 and 1.9 μm features on the Stratoscope spectra of α Ori and μ Cep, a conclusion opposite to that of Wing and Spinrad. The observed spectra can best be interpreted by the water gas with the column density of the order of 10^{20} cm^{-2} and temperature about 1500 ± 500 K, but they cannot be originating in the photosphere. We suggest a possible presence of a gaseous component not as hot as the chromosphere but warmer than the cool expanding envelope. On the other hand, we notice that the mid-infrared pure-rotation lines of H_2O recently discovered on Betelgeuse (α Ori) and Antares (α Sco) by Jennings and Sada may partly be originating in the photosphere, even though the larger part should again be non-photospheric in origin. Thus, the presence of water possibly originating in the outer atmosphere of Betelgeuse is confirmed by the independent observation in the mid-infrared region. We now conclude that water should be an important new probe on the atmosphere of the early M supergiant stars, for which water has not been recognized as such until recently.

Subject headings: infrared: stars — molecular processes — stars: individual (μ Cephei, α Orionis) — stars: late-type — supergiants

1. INTRODUCTION

Presence of water in stellar photospheres was predicted a long time ago (Russell 1934), but its observational confirmation had to await the development of infrared (IR) astronomy in the 1960s. The most clear demonstration of the stellar water has been achieved by the observation from outside Earth's atmosphere by the balloon-borne telescope Stratoscope II, launched in 1963 (Woolf, Schwarzschild, & Rose 1964). The Stratoscope observers showed that water-vapor absorption bands appear in the spectrum of α Ori (M2 Iab) and that they are extremely strong in the spectra of Mira variables R Leo (M8) and *o* Cet (M9). Also, strong water bands were found in the M supergiant μ Cep (M2 Ia) on the spectra observed by the same flight. However, it seems that the significance of this discovery was not widely recognized, and the spectrum of μ Cep, for example, was used to discuss water ice in the interstellar medium (ISM) rather than gaseous water in the star (Danielson, Woolf, & Gaustad 1965).

Later observations, mostly ground based, confirmed the presence of water in cool Mira variable stars but failed to confirm water in non-Mira M giant and supergiant stars earlier than about M7 (e.g., Spinrad & Wing 1969; Johnson & Méndez 1970). Such a result apparently contradicted the Stratoscope finding, and this fact led Wing & Spinrad (1970) to suggest that most features attributed to water on the Stratoscope spectra should be the result of CN bands. In fact, the CN red system ($A\ ^2\Pi_i$–$X\ ^2\Sigma^+$) shows the band heads at 0.9, 1.1, 1.4, and 1.9 μm, which roughly agree with the positions of the combination bands of H_2O (which are known as ρ, φ, Ψ, and Ω bands, respectively, in the terrestrial absorption), and they can be confused in the identifications based on the band positions alone. A motivation of Wing & Spinrad (1970) was to provide a satisfactory and consistent account of the molecular bands observed in cool stars, and they concluded that CN should be the better candidate than H_2O since the presence of CN in the photosphere of red supergiants could be well understood (remember that the CN bands are pretty strong even in the oxygen-rich stars, including the Sun), but the presence of water in the early M supergiants was thought to be rather odd in view of the other known observations. For this reason, it is natural that the criticism by Wing & Spinrad (1970) was widely accepted by the astronomical community not only 30 years ago but also until recently. In fact, no debate of this criticism has been offered by the Stratoscope observers themselves nor by others, including the present author, who has in fact adopted the CN identification in his interpretation of the Betelgeuse spectrum (Tsuji 1976).

The direct motivation to discuss this problem again is a recent finding of water on the spectra of the early M supergiants in h and χ Persei clusters (Tsuji et al. 1998) observed with the *Infrared Space Observatory* (*ISO*) launched more than 30 years after the Stratoscope flight (Kessler et al. 1996). However, it is again not certain if this unexpected result can be well accepted, so we looked for independent

evidence for water on the early M type stars. In this connection, we remembered that the above noted issue in the 1970s as to whether H_2O or CN is the dominant contributor to the infrared spectra of the early M supergiants has not yet been resolved so far as we are aware, and we think it useful to reanalyze the Stratoscope spectra of α Ori and μ Cep. The result clearly demonstrates the presence of water in these stars. In fact, we found that the Stratoscope spectra show the most clear evidence for water of the non-photospheric origin in the early M supergiant stars even after *ISO* and other space missions with advanced technology.

Recently, a unique attempt of the ground-based high-resolution spectroscopy in the 12 μm region by Jennings & Sada (1998) revealed clear evidence for water on the early M supergiant stars Betelgeuse and Antares. These authors pointed out that the detected pure-rotation lines of H_2O are high-temperature lines and originate from the atmospheres of the early M supergiants but not from their cool circumstellar envelope. To clarify the exact nature of these water lines is quite interesting, and we discuss them together with the near-infrared H_2O bands on the Stratoscope spectra. These spectra of water through the near- to mid-infrared, together with other observations such as the recent Very Large Array (VLA) imaging of Betelgeuse by the radio continuum (Lim et al. 1998), suggest a novel picture of the atmosphere of the red supergiant stars represented by Betelgeuse.

2. THE PHOTOSPHERE OF THE EARLY M SUPERGIANT STARS

In interpreting observed spectra, we apply the method of spectral synthesis, and for this purpose we have constructed a self-consistent model photosphere based on the so-called classical assumptions (LTE, hydrostatic, and radiative equilibria in the spherically symmetric configuration). Stellar photospheres can be relatively well modeled almost free from ad hoc assumption, and hence the model photosphere can be used as a reference by which any deviation from the classical assumptions can be examined. We must, however, assume turbulent velocity which influences the opacity through line broadening and also on the atmospheric extension through turbulent pressure. We constructed a photospheric model of $M_* = 15\ M_\odot$, $R_* = 650\ R_\odot$, and $L_* \approx 6 \times 10^4\ L_\odot$ ($T_{\rm eff} \approx 3600$ K defined by $L_* = 4\pi R_*^2 \sigma T_{\rm eff}^4$, where σ is the Stefan-Boltzmann constant) by the use of our code of the nongray spherical-model photosphere. These parameters are settled with α Ori in mind and assumed to be the same in μ Cep. For example, $T_{\rm eff} = 3605$ K is suggested based on the angular diameter by the interferometric measurement of α Ori (Dyck, van Belle, & Thompson 1998), and combined with the *Hipparcos* parallax (ESA 1997) we have $R_* = 637\ R_\odot$. We also applied the surface chemical compositions ($\log A_{\rm C} = 8.4$, $\log A_{\rm N} = 8.6$, $\log A_{\rm O} = 8.8$ on the scale of $\log A_{\rm H} = 12.0$) and the microturbulent velocity ($\xi_{\rm micro} = 4$ km s^{-1}) determined from the high-resolution FTS spectra of α Ori (Lambert et al. 1984).

The resulting photospheric model extends from $R_* = 650\ R_\odot$ at $\tau_{\rm cont} \approx 1$ to $R_0 = 711\ R_\odot$ at $\tau_{\rm cont} \approx 10^{-6}$, where $\tau_{\rm cont}$ is the optical depth defined by the continuous opacity at 0.81 μm. Thus, the extension of the photosphere defined by $d = (R_0 - R_*)/R_*$ is 0.094, or about 9% of the stellar radius. The column densities in this extended photosphere are as follows: 7.8×10^{22} cm^{-2} (CO), 1.2×10^{18} cm^{-2} (H_2O), 2.7×10^{20} cm^{-2} (OH), and 2.5×10^{18} cm^{-2} (CN). The surface temperature at $\tau_{\rm cont} = 10^{-6}$ is 2005 K.

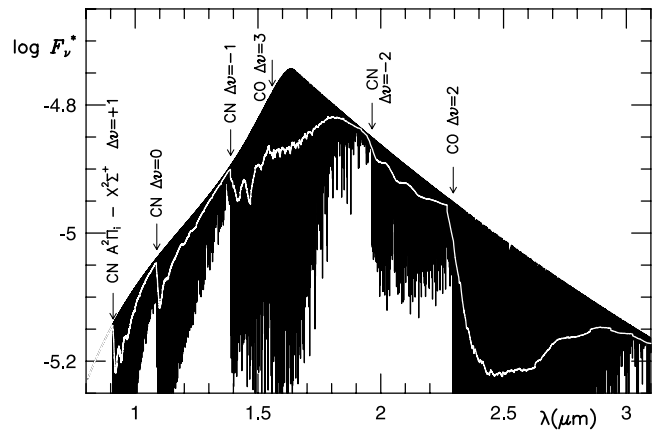

FIG. 1.—Predicted spectrum based on the model photosphere of $M_* = 15\ M_\odot$, $R_* = 650\ R_\odot$, and $L_* \approx 6 \times 10^4\ L_\odot$ ($T_{\rm eff} \approx 3600$ K) is shown on the scale of $\log F_\nu^*$ (ergs cm^{-2} s^{-1} Hz^{-1}). The black line is the result of computation with a mesh interval of 0.05 cm^{-1} (resolving power of about 10^5), and the white line is the result of convolution with the slit function corresponding to the resolution of the Stratoscope spectrometer (FWHM = 0.01 μm).

3. WATER BANDS IN THE NEAR-INFRARED SPECTRAL REGION

First, we computed the synthetic spectrum for the region observed by Stratoscope II. We used the spectral-line database including about a million lines of ^{12}CO, ^{13}CO, CN, OH, SiO, and H_2O, and the computation has been done with the mesh interval of 0.05 cm^{-1}. The resulting spectrum[1] is shown by the black line in Figure 1, and the major molecular bands responsible to the dominant spectral features are indicated. Note that all these results are consistent with a more or less similar computation by Kurcuz (1997). The band heads degraded to the red at 0.9, 1.1, 1.4, and near 2.0 μm are due to the $\Delta v = 1, 0, -1$, and -2 transitions of the CN red system, respectively. The strong band head at 2.294 μm is due to the CO first overtones (CO second overtones and OH first overtones have band heads at 1.558 and 1.391 μm, respectively). One noticeable fact is that H_2O bands never appear in the predicted spectrum shown in Figure 1, even though the H_2O lines based on HITEMP (Rothman 1997), the high-temperature adjunct to the well-known HITRAN (Rothman et al. 1992), are included in the computation of the synthetic spectrum. This is because the photosphere is too warm for ample amount of water to be formed, and the column density of H_2O is too small (only about 10^{18} cm^{-2} as noted in § 2) for the rovibration bands to be observed.

Finally, we convolved the synthetic spectrum with the slit function of the Stratoscope spectrometer, which we assumed to be the Gaussian with FWHM of 0.01 μm. The resulting low-resolution version of our synthetic spectrum is shown by the white line in Figure 1.

The spectra of α Ori and μ Cep were observed by the two different detectors of Stratoscope II, and the results of the

[1] From the flux $F_\nu(r)$ computed in the spherical configuration, we define the flux corrected for the dilution effect by $F_\nu^*(r) = r^2 F_\nu(r)/R_*^2$. The emergent spectrum is represented by $F_\nu^*(r = R_0)$ to remain consistent with the plane-parallel case, and this corrected flux is used in Figures 1–4. The total corrected flux $\int F_\nu^*(r) d\nu$ is conserved to be $\sigma T_{\rm eff}^4/\pi$ throughout the photosphere in our spherically symmetric models.

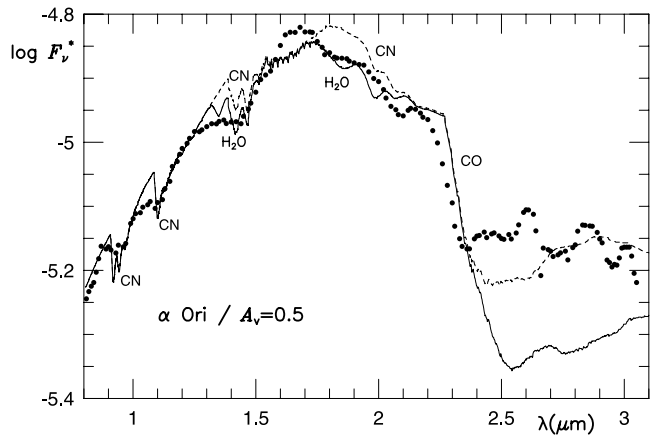

FIG. 2.—The Stratoscope spectrum of α Ori corrected for the interstellar reddening with $A_v = 0.5$ is shown by the dots (the original f_λ scale is converted to f_ν scale and shifted vertically to fit with model spectra). The dashed line is the predicted photospheric spectrum (identical with the white line in Fig. 1), but it cannot be matched with the observed spectrum. The solid line shows the predicted photospheric spectrum after passing a hypothetical H_2O absorption layer of $N_{col} = 10^{20}$ cm^{-2} ($T_{ex} = 1500$ K) situated above the photosphere, and the 1.4 and 1.9 μm features of the observed spectrum are roughly accounted for by this model.

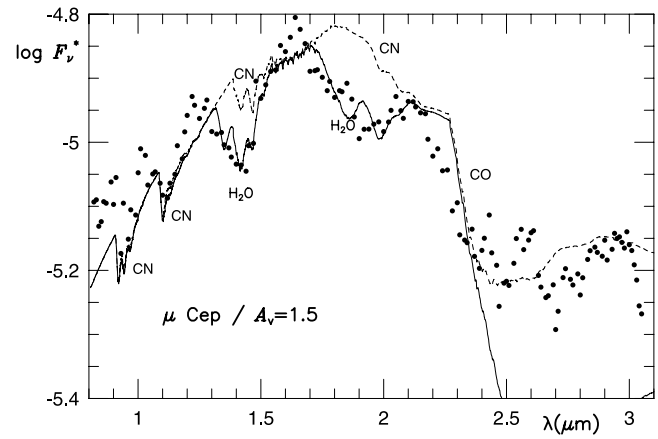

FIG. 3.—The same as Fig. 2 but for μ Cep. The observed spectrum shown by the dots is corrected for the interstellar reddening with $A_v = 1.5$. The solid line shows the predicted photospheric spectrum after passing an H_2O absorption layer with $N_{col} = 3 \times 10^{20}$ cm^{-2} ($T_{ex} = 1500$ K).

different detectors show some differences. Then, we co-added them with the hope of increasing the signal-to-noise ratio (S/N) somewhat. In correcting for the effect of the interstellar reddening, we assume $A_v = 0.5$ and 1.5 for α Ori and μ Cep, respectively (Lee 1970), and apply the reddening law suggested by Lee (1970). The resulting observed spectra are shown by the dots in Figures 2 and 3 for α Ori and μ Cep, respectively.

We compare the observed spectra shown by the dots with the predicted photospheric spectrum shown by the dashed lines (which are identical with the white line in Fig. 1) in Figures 2 and 3. The observed features at 0.9 (though rather noisy in Fig. 3) and 1.1 μm can be reasonably accounted for by the predicted CN bands, in agreement with Wing & Spinrad (1970). However, the observed feature at 1.4 μm is stronger and more shifted to the blue as compared with the predicted CN bands at 1.4 μm. Further, the observed feature at 1.9 μm extends to the shortward of 2 μm and is especially strong in μ Cep, while the predicted CN bands are too weak and extend to the longward of 2 μm. Thus it is evident that the observed 1.4 and 1.9 μm features cannot be explained by the CN bands. We conclude that the proposition by Wing & Spinrad (1970) to have attributed the major absorber for the 1.4 and 1.9 μm features to the CN bands cannot be supported.

Given the result that CN can no longer account for the 1.4 and 1.9 μm features in the observed spectra of α Ori and μ Cep, a plausible candidate can be H_2O even though it is not predicted by the photospheric model. Since the photosphere cannot be the seat for H_2O, we assume a presence of an absorption layer of H_2O above the photosphere as the simplest model for computing water spectra. Then the photospheric radiation will suffer an extinction by $e^{-\tau}$ with $\tau = \kappa(T_{ex})N_{col}$, where $\kappa(T_{ex})$ is the absorption cross section of H_2O evaluated from the HITEMP database (Rothman 1997), and N_{col} is the column density of H_2O in the hypothetical absorption layer. We assume $T_{ex} = 1500$ K and $N_{col} = 10^{20}$ cm^{-2} for α Ori, and the resulting spectrum after the extinction by the H_2O absorption layer is shown by the solid line in Figure 2. The observed features at 1.4 and 1.9 μm can now be reasonably well accounted for by the H_2O extinction model. We apply the same model to μ Cep but with $N_{col} = 3 \times 10^{20}$ cm^{-2}, and the resulting spectrum after the extinction is shown by the solid line in Figure 3. The agreement with the observed spectrum is significantly improved by our predicted spectrum based on the H_2O extinction model. In fact, the shape of the observed spectrum at 1.4 and 1.9 μm can now be reasonably reproduced by this model. Thus we confirm the original proposition by the Stratoscope observers that water should exist in the early M supergiants α Ori and μ Cep. It must be emphasized, however, that the water confirmed on α Ori and μ Cep should not be originating from the photosphere.

Still the question remains why such distinct water bands could not be recognized for such a long time, especially since bright objects like α Ori and μ Cep have been well observed in the near-infrared. Certainly ground-based observations are severely limited by the water bands originating in Earth's atmosphere, and only some hot bands extending outside the terrestrial bands can be observed. Such observations have been successful to Mira variables but not to non-Mira M-type stars. A reason for this may be that the water bands in Mira variables are originating from the photosphere, which is relatively hot, and hence the hot bands can be excited, while those in non-Mira variables are formed in the cooler layer above the photosphere where the hot bands cannot be excited so well. Nevertheless, careful observers noticed the presence of the 1.9 μm feature in the infrared spectra of cool stars. For example, Johnson & Méndez (1970) found a broad-absorption feature at around 1.8 μm on the spectrum of μ Cep corrected for the effect of the terrestrial absorption, although they did not propose it to be the result of water and left it as unidentified. This observation nevertheless confirmed the reality of the 1.9 μm feature observed by Stratoscope II. On the other hand, Wallace & Hinkle (1996) did not detect H_2O lines but found many CN lines on their high-resolution FTS spectrum of α Ori in the K-band region. This may be because the region covered by them was limited to the region longward of 2 μm where CN dominates (see Fig. 2), and this result does not necessarily conflict with our detection of water on the Stratoscope spectrum in the region shortward of 2 μm, which is more difficult to observe from the ground.

Then what about other space observations? After the Stratoscope flight, major space observations were made by NASA's airborne observatories. For example, Nordh, Olofsson, & Augason (1978) observed several late-type stars using five filter band photometry aboard the Lear Jet Infrared Observatory and found possible evidence for water in the middle M giants μ Gem (M3 III) and α Her (M5 II). This interesting result, however, has also been overlooked without any follow-up observation. More extensive data by the Kuiper Airborne Observatory have recently been recalibrated by Cohen et al. (1995), and we noticed a possible presence of water bands on the spectrum of the M2 giant β Peg (Tsuji, Aoki, & Ohnaka 1997a). More recently, an unbiased survey by the *Infrared Telescope in Space* (*IRTS*) of the Institute of Space and Astronautical Science (ISAS) revealed a depression at 1.9 μm in many M stars, including the early M, and the absorption has been attributed to water (Matsuura et al. 1999). A higher potentiality to explore the water bands in the early M stars may be provided by the *ISO* spectra, but reports on the early M (super)giant stars are rather minor yet. Certainly, further effort is needed to obtain a more general conclusion from the *ISO* data.

4. WATER LINES IN THE MID-INFRARED SPECTRAL REGION

Recently, the pure-rotation lines of water have been detected for the first time in the mid-infrared spectra of Betelgeuse and Antares by Jennings & Sada (1998), and this result provides an interesting possibility of comparing the water spectra in the different spectral regions. For this purpose, we again compute the synthetic spectrum of the region observed by them, and the resulting spectrum between 810 and 820 cm^{-1} computed with the mesh interval of 0.01 cm^{-1} is shown by the thin line, while the spectrum degraded to the resolution of the observed spectrum (0.1 cm^{-1}) is shown by the heavy line (see Fig. 4). The strong quartet is due to the pure-rotation transitions of OH ($X\ ^2\Pi$), and we are using the line list based on the transition probabilities well extended to the high-lying rotational levels by Holtzclaw, Person, & Green (1993).[2] Other weak features are all due to the pure-rotational lines of water included in the HITEMP database (Rothman 1997). These water lines are rather weak, but it was unexpected that the H_2O lines could be predicted to be observable by the model photosphere of the early M supergiant stars. However, the intrinsic intensities of the pure-rotational lines of H_2O are pretty large and more than an order of magnitude larger than those of the rovibration lines in the near-infrared as noted by Jennings & Sada (1998). Thus, it can be possible in principle to observe the H_2O pure-rotation lines of the photospheric origin in the early M supergiant stars and probably in other late-type stars not necessarily very cool.

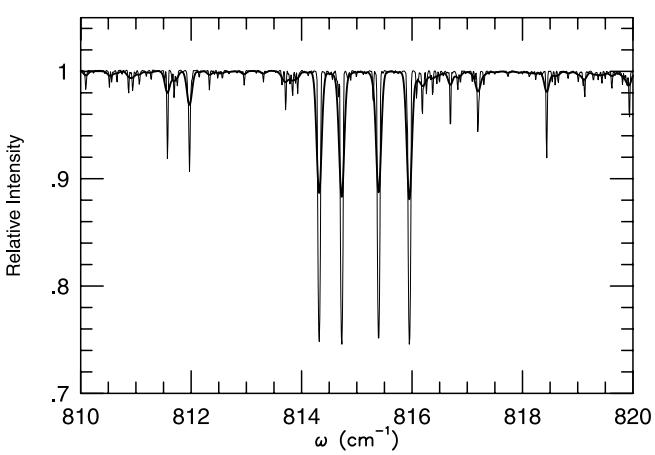

FIG. 4.—Predicted spectrum (normalized by the local continuum) based on the same model photosphere used in Figs. 1–3 but for the mid-infrared region around 12.3 μm. The thin line is the result of computation with a mesh interval of 0.01 cm^{-1} (resolving power of about 8×10^4), and the heavy line is the result of convolution with the slit function corresponding to the resolution of the spectrometer used by Jennings & Sada (1998) (FWHM = 0.1 cm^{-1}). The strong quartet is the OH pure-rotation lines, while all the other weak features are due to the pure-rotation lines of H_2O (for details, see Table 1).

This result suggests that the H_2O lines observed by Jennings & Sada (1998) should be originating from the photosphere at least partly, in marked contrast to the case of the near-infrared rovibration bands whose intrinsic intensities are too weak to appear in the photospheric spectrum. In fact, this was the explanation of the observed pure-rotation H_2O lines by Jennings & Sada (1998), who did not expect H_2O lines to be observed in the near-infrared. However, it seems that the observed water lines are stronger than those predicted from our photospheric model. To examine this in more detail, we compare the observed equivalent widths (EWs) given by Jennings & Sada (1998) with the predicted ones by our model photosphere, and the results are summarized in Table 1. Note that the effect of the circumstellar-dust emission is already corrected for in the observed equivalent widths, and hence no correction is applied to the predicted ones. Inspection of Table 1 reveals that the observed equivalent widths of H_2O are about factors of 2–3 larger than those predicted. This fact suggests that there should be contributions other than the photospheric absorption in the observed H_2O lines. However, there is a possibility that our classical-model photosphere is not realistic enough, and the nearby OH lines can be used to examine this problem.

For this purpose, we also show the OH lines observed by Jennings & Sada (1998) in Table 1, and we found that our predicted equivalent widths of the OH lines are about a factor of 2 larger than those observed. These OH lines were previously observed and analyzed by Jennings et al. (1986), who have already noted that their predicted equivalent widths are larger by about a factor of 2 compared with their observed values. Thus, our result fully agrees with theirs. The model photospheres used by them and by us are more or less similar classical LTE models, but Jennings et al. (1986) found that the discrepancy can be resolved if they employ the semiempirical model of photosphere-chromosphere by Basri, Linsky, & Eriksson (1981), which has higher surface temperatures. This might be a fine solution for OH, but the H_2O lines should also be weakened by this semiempirical model, which shows $T_{\rm min} = 2700$ K (Basri et al. 1981) compared to $T_0 = 2005$ K of the classical LTE model (§ 2). This result strengthens our conclusion that the pure-rotation lines of H_2O should mostly not be originating in the photosphere, especially if we further take into account the temperature minimum and the subsequent temperature upturn of the empirical model.

[2] Digital data made available by Dr. Holtzclaw.

TABLE 1

PURE-ROTATION LINES OF H_2O AND OH IN BETELGEUSE (α ORI)

Obs. Freq.[a] (cm^{-1})	Identified[b] (cm^{-1})	Transition $J'K'_aK'_c$–$J''K''_aK''_c$	Vib. State ($v_1 v_2 v_3$)	log gf	L.E.P. (cm^{-1})	EW(Obs.)[c] (cm^{-1})	EW(Pred.)[d] (cm^{-1})
H_2O:							
811.53.....	811.571	22 15 07–21 14 08	(000)	−2.33	7999.36	0.0080	0.0034
	811.572	22 15 08–21 14 07	(000)	−1.85	7999.36		
811.95.....	811.966	21 15 06–20 14 07	(010)	−1.86	9406.69	0.0114	0.0035
	811.972	25 10 15–24 09 16	(000)	−2.15	8229.36		
	811.973	23 13 10–22 12 11	(000)	−1.94	7929.41		
815.35.....	815.296	18 07 12–17 04 13	(000)	−3.15	4017.91	0.0094	0.0006
818.42.....	818.438	22 16 07–21 15 06	(000)	−1.81	8297.72	0.0048	0.0022
	818.439	22 16 06–21 15 07	(000)	−2.29	8297.72		
OH:							
815.41.....	815.395	$R_{2e}(23.5)$	$v = 0$	−1.54	10500.14	0.0052	0.0127
815.95.....	815.953	$R_{1f}(24.5)$	$v = 0$	−1.49	10482.57	0.0052	0.0137

[a] Observed by Jennings & Sada 1998.

[b] H_2O lines whose intrinsic strengths are larger than 3×10^{-21} cm molecule^{-1} at $T = 2500$ K by the HITEMP database (Rothman 1997), which is also the source of the transition assignments, gf values (converted from the integrated line strengths), and lower excitation potentials (L. E. P.), and the identifications mostly agree with those by Jennings & Sada 1998.

[c] Observed equivalent widths corrected for circumstellar emission by Jennings & Sada 1998.

[d] Predicted equivalent widths measured from Fig. 4. A large discrepancy with the observed EW for the line at 815.35 cm^{-1} may be due to unknown line(s) of the higher excitation or due to difficulty in correcting for the effect of the nearby OH line.

There are, however, serious discrepancies between the results from the near- and mid-infrared spectra. In particular, the H_2O column density suggested from the mid-infrared spectrum by Jennings & Sada (1998) is $(3 \pm 2) \times 10^{18}$ cm^{-2} for Betelgeuse, while that from the near-infrared spectrum by us is as large as 10^{20} cm^{-2} (§ 3). Thus, if the column density estimated from the near-infrared spectrum is correct, stronger absorption of the H_2O pure-rotation lines might appear in the mid-infrared. However, we must remember that the large column density from the near-infrared spectrum is due to H_2O not in the photosphere but possibly in the outer atmosphere. Then, if this outer atmosphere is well extended above the classical photosphere, the mid-infrared lines will suffer a large weakening as a result of the emission component from the extended part of the outer atmosphere. Such an effect is important only in the Rayleigh-Jeans region, and thus the near-infrared spectrum may suffer little effect. In other words, estimation of the column density from the mid-infrared spectral lines is more difficult if the absorption is partly canceled by the emission from the extended atmosphere. Such an effect should be taken into account in future modelings. Also, Jennings & Sada (1998) suggested the upper limit of the excitation temperature to be 2800 K for the pure-rotation H_2O lines. On the other hand, we assumed $T_{ex} \approx 1500$ K for the near-infrared H_2O bands, but such an estimation from the low-resolution spectra cannot be very accurate, and we can explain the observed spectra with T_{ex} values between 1000 and 2000 K as well. Within the present limit of accuracy, we suggest $T_{ex} \approx 1500 \pm 500$ K, and this can be regarded as not being in serious conflict with the upper limit based on the pure-rotation lines.

5. DISCUSSION

We have shown that the observed near-infrared spectra of the early M supergiant stars cannot be understood by the predicted spectrum based on the self-consistent photospheric model but can be accounted for by a model with a hypothetical H_2O absorption layer above the photosphere. In the case of the pure-rotation lines recently detected by Jennings & Sada (1998), the discrepancy between the observed and the predicted photospheric spectra is apparently not as serious as in the case of the near-infrared spectra, but we should look for a consistent picture for the different spectral regions. Our ad hoc model with the H_2O absorption layer is certainly not a unique solution. We should also consider some other possibilities, and the major problem is how to understand the presence of water that cannot be predicted from the classical-model photosphere.

An interesting possibility in this regard is a large temperature inhomogeneity induced by large convective elements as proposed by Schwarzschild (1975). Since the pressure scale height is comparable with the dimension of the photosphere itself in the case of supergiants, only a modest number of the convective elements exist at any one time. Also, the plausible temperature differences between the upgoing and the downgoing convective elements would be as large as ± 1000 K. Therefore, Schwarzschild suggested that the motions of a few convective elements will produce local brightness variation and anisotropy of the light on the stellar surface, and they in turn can explain the observed irregular light variation and polarization. Although Schwarzschild himself did not mention the possibility of his convective model explaining his own discovery of water in the red supergiant stars (Woolf et al. 1964), it would be worthwhile to examine this possibility in more detail. In fact, the convective elements cooler by 1000 K from the mean photospheric temperatures represented by our model of $T_{eff} \approx 3600$ K will easily produce water-absorption bands.

A more extreme possibility is to assume large starspots analogous to sunspots. In fact, water is actually observed in sunspots (Oka 1997; Polyansky et al. 1997). However, it would be difficult to observe water on the integrated stellar and/or solar spectra, although it may be possible to detect changes in the spectra as the star rotates (Jennings & Sada 1998). Probably, such a "starspots" model cannot be extended so easily to supergiants in which formation of spots may be more difficult. Also, recent interferometric imaging of α Ori revealed instead the presence of hotspots,

which are identified with the large convective elements noted above (e.g., Tuthill, Haniff, & Baldwin 1997).

We have already used the simple-slab model of the water gas above the photosphere, partly for convenience of evaluating the model spectra shown in Figures 2 and 3, but such a model should be considered more seriously. We have also suggested that the apparent inconsistency in the column densities estimated from the near- and mid-infrared spectra may be reconciled if the water gas is found in the extended outer atmosphere. Thus, the simple-slab model should be extended to the spherically extended outer-envelope model. A support for such an outer-atmosphere model is that the observed water bands are stronger in μ Cep, which shows larger infrared excess as a result of silicate emission as compared with those in α Ori. Although our sample includes only two objects, similar correlation between the 1.9 μm depression and the infrared excess is noted on a larger sample by Matsuura et al. (1999). This correlation with dust suggests that the observed water may also be originating from the outer atmosphere.

Also, from the analysis of the high-resolution FTS spectra of CO, we found an extra CO component represented by $T_{ex} \approx 1000$–1500 K and $N_{col}(CO) \approx 10^{20}$ cm^{-2} both in α Ori and μ Cep (Tsuji 1987). This extra CO component shows little velocity shift against the photosphere and should be originating from a quasi-static layer distinct from the expanding cool CO shells known in these stars (Bernat et al. 1979; Ryde et al. 1999). Given the similarities of T_{ex} and of N_{col} between CO and H_2O, the H_2O bands should also be originating from the quasi-static layer in the outer atmosphere. Presence of such a CO component is confirmed by the independent observation with the *Hubble Space Telescope* (*HST*) in the far-ultraviolet (FUV) by Carpenter et al. (1994), who analyzed several bands as a result of the fourth positive A–X system of CO and suggested $T_{ex} = 500$ K and $N_{col}(CO) = 10^{18}$ cm^{-2}. The column densities and the excitation temperatures estimated in the IR and FUV show some differences, but they may be probing somewhat different regions of the same phenomenon.

It is generally believed that the outer atmosphere of red supergiants is dominated by the hot chromosphere, as is exemplified by the recent *HST* imaging of Betelgeuse (Gilliland & Dupree 1996). Recently, however, presence of a relatively cool gaseous component extending out to several stellar radii is recognized by radio observations of Betelgeuse with the VLA (Lim et al. 1998). The observed radio emission is purely thermal and optically thick and directly measures the temperature structure of the outer atmosphere of Betelgeuse. The resulting temperature measured over the same height range as the chromosphere shows clear differences with that generally known for the chromosphere. This means that the extended outer atmosphere of Betelgeuse should be inhomogeneous, consisting of the hot chromospheric component ($T_e \approx 4000$–$10{,}000$ K) and the cooler but still warm gaseous component ($T_{ex} \approx 1000$–4000 K). This cooler but still warm component should be what we have recognized from H_2O and CO as noted above. To distinguish from the cooler expanding shells known in cool supergiant stars, it may be appropriate to refer to the new component as the warm gaseous envelope.

The origin of the warm envelope was attributed to the elevation of photospheric material into the outer atmosphere by convection (Lim et al. 1998), and more detailed studies of such a possibility, both theoretically and empirically, are needed. For example, the dynamical structure of the new molecule-forming region can now be probed with spectroscopy of the water lines not only in the near-infrared but also in the mid-infrared regions (note that the FTS CO spectra have already served for this purpose as noted above). Also, it is interesting that the line profiles seen by the high resolution show (macro)turbulent velocities as large as 12 km s^{-1} in Betelgeuse (Jennings & Sada 1998). Such large turbulence works to extend the atmosphere appreciably and hence can be a driving mechanism to levitate the matter above the photosphere.

Even in the Sun, hot components represented by the chromosphere and corona have been extensively observed, but it is only recently that the extended CO envelope above the photosphere was discovered (Solanski, Livingston, & Ayres 1994) and the importance of the cooler component in the outer atmosphere has been recognized (Ayres 1998). Also, water is found in the early M giant stars (Tsuji et al. 1997b), and the quasi-static CO layer is known in M giant stars (Tsuji 1988). Thus, the presence of the warm gaseous component in the outer atmosphere may be a general phenomenon in late-type stars from the Sun to red supergiants, even though it is not certain if the exact nature should be the same. For example, the convective origin proposed for supergiants cannot be directly extended to giants and dwarfs, even if convection may play some role in these cases.

6. CONCLUDING REMARKS

We are now convinced of the presence of water on the early M supergiants from the Stratoscope spectra observed 35 years ago, and this result is supported by the detection of the pure-rotation H_2O lines in the mid-infrared region, by the presence of the extra CO component originating neither in the photosphere nor in the cool expanding shells, and by the high-resolution imaging of Betelgeuse with VLT. The detection of water in the early M supergiants is not a simple problem of spectral identification, but it should have an important bearing on our understanding of the whole atmosphere of red supergiant stars, covering from the subphotospheric convective zone to the outer atmosphere where stellar mass loss initiates. For example, the molecular lines of the nonphotospheric origin suggest the presence of the warm and nonexpanding gaseous envelope, which may serve as the "reservoir" for mass-loss outflow and will provide a new light on the mechanism of mass loss in these stars. Also, such a warm gaseous envelope of the modest temperatures may provide an ideal site for various chemical processes, including photochemical reactions under the presence of UV radiation fields from the coexisting hot chromosphere, to take place and hence for the molecular formations in the outer atmosphere of the red supergiant stars.

A brief history on the detection of water on the early M supergiants shows how difficult it is to recognize the spectral features of nonphotospheric origin, especially when they are confused with the photospheric spectrum. The case of water in the early M supergiants is relatively fortunate in that water of the photospheric origin is almost negligible except for the case of the pure-rotation lines of the large intrinsic intensities, while the case of CO IR lines required very high resolution spectra to recognize the nonphotospheric components against the stronger photospheric lines. Recent progress in observations finally

revealed the rather subtle spectral features that cannot be explained by the classical photosphere-chromosphere and hence the presence of the new component of the outer atmosphere. Now, the major problem is how to understand the origin of the new component which we referred to as the warm gaseous envelope. In particular, the mechanism to transport a considerable amount of mass to the "reservoir" in the outer atmosphere is not yet identified, even if this may not be very difficult under the low-gravity environment of the supergiant stars.

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