WATER IN EMISSION IN THE ISO SPECTRUM OF THE
EARLY M SUPERGIANT STAR $\mu$ CEPHEI

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ABSTRACT

We report a detection of water in emission in the spectrum of the M2 supergiant star \( \mu \) Cep (M2Ia) observed by the Short Wavelength Spectrometer (SWS) aboard Infrared Space Observatory (ISO) and now released as the ISO Archives. The emission first appears in the 6 \( \mu \)m region (\( \nu_2 \) fundamental bands), and then in the 40 \( \mu \)m region (pure rotation lines) despite the rather strong dust emission. The intensity ratios of the emission features are far from those of the optically thin gaseous emission. Instead, we could reproduce the major observed emission features by an optically thick water sphere of the inner radius about two stellar radii (\( 2R_* \approx 1300R_\odot \)), \( T_{\text{ex}} = 1500 \text{K} \), and \( N_{\text{col}}(\text{H}_2\text{O}) = 3 \times 10^{20} \text{ cm}^{-2} \). This model also accounts for the H\(_2\)O absorption bands in the near infrared (1.4, 1.9, and 2.7\( \mu \)m) as well. The detection of water in emission provides strong constraints on the nature of water in the early M supergiant star, and especially its origin in the outer atmosphere is confirmed against other models such as the large convective cell model. We finally confirm that the early M supergiant star is surrounded by a huge optically thick sphere of the warm water vapor, which may be referred to as MOLsphere for simplicity. Thus, the outer atmosphere of M supergiant stars should have a complicated hierarchical and/or hybrid structure with at least three major constituents including the warm MOLsphere (\( T \approx 10^3 \text{K} \)) together with the previously known hot chromosphere (\( T \approx 10^4 \text{K} \)) and cool expanding gas-dust envelope (\( T \approx 10^2 \text{K} \)).

Subject headings: infrared: stars – molecular processes – stars: individual (\( \mu \) Cep, \( \alpha \) Ori) – stars: late-type – stars: supergiants
1. INTRODUCTION

Presence of water in the stellar environment has been known since 1960’s, especially by the pioneering space observations with the balloon-borne telescope Stratoscope II (Woolf, Schwarzschild, & Rose 1964). However, it is the recent ISO mission (Kessler et al. 1996) that the infrared spectra unobscured by Earth’s atmosphere have finally been explored in full details. One of the important results of the highly successful ISO mission is that water exists everywhere in the universe and that the star is not an exception. In fact, water has been detected not only by absorption but also by emission in cool luminous variables such as W Hya (Barlow et al. 1996; Neuffeld et al. 1996), NML Cyg (Justtanont et al. 1996), S Per (Tsuji et al. 1998), SW Vir (Tsuji, Aoki, & Ohnaka 1999), R Cas (Truong-Bach et al. 1999), o Cet (Yamamura, de Jong, & Cami 1999), VY CMa (Neuffeld et al. 1999) etc. The exact nature of these emission features, however, is by no means clear yet.

On the other hand, water in the early M (super)giant stars has been paid little attention until recently, since water has not been detected in these objects nor expected to be abundant in their atmospheres. Nevertheless, water in absorption has finally been detected by ISO in the early M (super)giants (Tsuji et al. 1997, 1998) as well as by the ground based mid-infrared observation in the early M supergiant stars (Jennings & Sada 1998). More correctly, however, water in the early M supergiants had in fact been discovered in the spectra taken by Stratoscope II (Woolf et al. 1964; Danielson, Woolf, & Gaustad 1965) more than 30 years before the ISO mission, although this discovery has been overlooked until recently in favor of the opposing interpretation. We have shown that the Stratoscope observers had correctly identified water in the early M supergiant stars but that the water detected by them is not originating in the photosphere (Tsuji 2000).

To clarify the nature of water found in the early M supergiant stars, ISO should provide the best possibility. In fact, thanks to the recently released ISO Archives, we found water
in emission in $\mu$ Cep for the first time in such an early M supergiant star. This detection is somewhat unexpected, but this provides not only the definitive evidence for the presence of water in the outer atmosphere of the early M supergiant stars but also a new clue to understanding the nature of water in the stellar environment.

2. OBSERVED EMISSION LINES OF WATER

We retrieved the spectra of $\mu$ Cep (M2Ia: observed on 1996 Dec.18 UT) and $\alpha$ Ori (M2Iab: observed on 1997 Oct.08 UT) from the ISO Archives. These spectra were observed with the SWS (de Graauw et al. 1996) by its highest resolution grating mode (resolution $R \approx 1600$ or about 188 km s$^{-1}$) in the region between 2.4 and 45 $\mu$m. The region of the $\text{H}_2\text{O}$ $\nu_1$ and $\nu_3$ fundamentals around 2.7 $\mu$m is somewhat complicated due to the photospheric CO and OH bands, but the ISO data of both $\alpha$ Ori and $\mu$ Cep show additional absorption features not predicted by the photospheric models. At least, part of these features should be the same origin as the 1.4 and 1.9 $\mu$m absorption bands, namely $\text{H}_2\text{O}$ of the non-photospheric origin (Tsuji 2000).

The region of the $\text{H}_2\text{O}$ $\nu_2$ fundamentals (the band origin at 6.3 $\mu$m) is shown in Fig. 1. First, the spectrum of $\alpha$ Ori shows only weak absorption features due to $\text{H}_2\text{O}$ (indicated by the dotted lines in Fig.1a), as can be confirmed by the comparison with the $\text{H}_2\text{O}$ data based on HITEMP (Rothman 1997) shown in Fig.1c, but this detection is the best evidence for water in $\alpha$ Ori at present. The spectrum of $\mu$ Cep shown in Fig.1b is quite different with complicated spectral features which show upturn at about 6.4 $\mu$m in contrast to a smooth decline typical of the Rayleigh-Jeans spectrum as in $\alpha$ Ori. This upturn is explained by the onset of emission due to the $P$ branch of the $\text{H}_2\text{O}$ $\nu_2$ fundamentals. Thus, the $\text{H}_2\text{O}$ bands
in absorption at 1.4, 1.9 and 2.7 µm turn to emission at 6 µm, and this can be regarded as definite evidence for the presence of water in the extended outer atmosphere of \( \mu \) Cep. Also, some emission features of the observed spectrum are well identified with the fine structures of \( \text{H}_2\text{O} \) bands by the comparison with the \( \text{H}_2\text{O} \) data (Fig.1c). The intensity ratios of the emission features do not agree with those of the optically thin emission represented by the absorption cross-section of \( \text{H}_2\text{O} \) at \( T = 1500\text{K} \) in Fig.1c, and the situation cannot be improved by changing the temperature.

The spectrum of \( \mu \) Cep has once been observed by the NASA Airborne Infrared Observatory (Russell, Soifer, & Forrest 1975), and non-grey behavior from 5 to 8 µm has been noted. The observers preferred to assume excess absorption in the 4-5 µm rather than excess flux in the 5-8 µm. Another interpretation was to attribute the observed 5-8 µm feature as due to emission of \( \text{H}_2\text{O} \nu_2 \) fundamentals, and this was also proposing that water, besides dust, should be an important constituent of the outer atmosphere of \( \mu \) Cep (Tsuji 1978). There has been no means by which to test such a proposition at that time, but this is now fully confirmed by the ISO SWS which clearly resolved the fine structure of the \( \text{H}_2\text{O} \) emission bands.

We already know that \( \text{H}_2\text{O} \) pure rotation lines were observed as absorption in \( \alpha \) Ori by the ground-based high resolution spectroscopy in the 12 µm region (Jennings & Sada 1998). However, the spectral resolution of the ISO SWS is not high enough to detect such faint lines. In the 40 µm region of \( \alpha \) Ori, some emission-like features can be seen (Fig.2a), but they cannot be identified with the known sources, except for an emission feature at 40.5 µm which roughly corresponds to \( \text{H}_2\text{O} \) lines as can be known by the comparison with the \( \text{H}_2\text{O} \) data (Fig.2c). However, it is still possible that the observed features are due to the mixture of absorption (including photospheric lines) and emission unresolved by the low resolution.
More distinct emission features appear in $\mu$ Cep (Fig.2b) and most of them can be identified with the H$_2$O pure rotation lines by the comparison with the H$_2$O data (Fig.2c). The intensity ratios of the emission features again suggest that the emission should be originating from an optically thick source. Such emission features are relatively well seen in the 40 $\mu$m region, but not so clear in the other mid-infrared region. One reason for this may be the presence of dust emission. To illustrate this, the entire spectrum of $\mu$ Cep observed by the ISO SWS is shown in Fig.3a by the red dots. It is clear that dust emission dominates the region longward of 8 $\mu$m.

EDITOR: PLACE FIGURE 3 HERE.

3. ORIGIN OF THE WATER EMISSION

We showed that a hypothetical absorption slab of H$_2$O with $T_{\text{ex}} = 1500$K and $N_{\text{col}} = 3.0 \times 10^{20}$ cm$^{-2}$ above the photosphere explains the 1.4 and 1.9 $\mu$m bands observed in the Stratoscope spectrum of $\mu$ Cep (Tsuji 2000). The presence of emission at the longer wavelength in the spectrum of $\mu$ Cep confirms that such a model of the non-photospheric origin of the water spectrum is basically correct, but we must now introduce geometrical extension of the water gas to explain the formation of emission features. For this purpose, we replace the simple absorption slab by a spherically symmetric isothermal gaseous envelope of water, whose inner and outer radii are $R_{\text{in}}$ and $R_{\text{out}}$, respectively. The density distribution in this envelope is assumed to be in hydrostatic equilibrium under the gravity field of the central star, and hence major contribution to the spectrum comes from the relatively dense region near $R_{\text{in}}$. For this reason, $R_{\text{in}}$ is more important than $R_{\text{out}}$.

We already suggested that the emission features may be originating from an optically thick source (Sect.2). In fact, the column density ($N_{\text{col}} = 3.0 \times 10^{20}$ cm$^{-2}$) and the
absorption cross-section of H$_2$O typically $10^{-17}$ cm$^2$ mol$^{-1}$ at $T = 1500$K (Figs. 1c and 2c) suggest that the optical depth of the strong lines should be as large as $10^3$. Thus, the water envelope is optically quite thick in the lines, and the warm molecular envelope can be referred to as molecular sphere, or MOLsphere for simplicity. Then, we must solve transfer equation in this MOLsphere and, since we are to interpret line spectra, the photospheric spectrum including the full details of the absorption lines should exactly be considered as the boundary condition. For this purpose, we apply the photospheric spectrum characterized by $M_* = 15 M_\odot$, $R_* = 650 R_\odot$, $L_* \approx 6 \times 10^4 L_\odot$ and $T_{\text{eff}} \approx 3600$ K (Fig. 1 of Tsuji 2000). The computation has been done with the spectral resolution of about 50000 by the use of the H$_2$O line database HITEMP (Rothman 1997). After a few trials, we found that $R_{in} \approx 2 R_* \approx 1300 R_\odot$ results in a spectrum that agrees with the observed one reasonably well. We also assumed $R_{out} \approx 4 R_*$, but this is of minor importance by the reason outlined above. The resulting emergent spectrum is shown by the green line in Fig. 3a.

In the spectral region shortward of 5 $\mu$m, the MOLsphere contributes only to absorption, and the upper boundary of the spectrum shown by the green line in Fig. 3a represents the photospheric continuum, below which CO, OH, and SiO bands of the photospheric origin can be seen together with the H$_2$O absorption produced anew in the MOLsphere (molecules other than H$_2$O are not considered in the MOLsphere). At the shorter and longer wavelength sides of 6.3 $\mu$m, the $R$ and $P$ branches, respectively, of the H$_2$O $\nu_2$ fundamentals are seen in emission above the photospheric continuum (which is not explicitly shown but can be extrapolated from the near infrared continuum). This emission of water due to the MOLsphere remains prominent throughout the mid infrared region because of the stronger H$_2$O pure rotation lines. The MOLsphere contributes only to emission in the mid-infrared region and the lower boundary of the spectrum shown by the green line represents the photospheric continuum, below which OH pure rotation lines of the photospheric origin can be seen. But most of these OH lines are weaker or some OH
lines are missing as compared with those in the photospheric spectrum because of the filling in by the overlapping H$_2$O emission lines from the MOLsphere.

For comparing the predicted spectrum from the MOLsphere discussed above with observations, we convolve it with the slit function of SWS which is assumed to be the Gaussian of FWHM = 187.5 km s$^{-1}$ and the resulting low resolution spectrum is shown by the blue line in Fig.3a. The result can directly be compared with the observed spectrum in the region shortward of 8 $\mu$m where dust emission is negligible, and is shifted vertically to fit the observed spectrum of $\mu$ Cep shown by the red dots. A close-up of the region around 6.3 $\mu$m is shown in Fig.3b, where the red dots represent the observed spectrum and the blue line the predicted spectrum from the MOLsphere, as in Fig.3a. The agreements between the observed and predicted spectra appear to be fine if not perfect.

For interpreting the spectrum longward of 8 $\mu$m, effect of dust emission on our predicted spectrum should be taken into account. Since dust envelope of $\mu$ Cep is optically thin (e.g. Tsuji 1978), we simply add the dust emission to the spectrum by the MOLsphere. The region near 40 $\mu$m is shown by an expanded scale in Fig.3c, where the red dots represent the observed spectrum and the black line the predicted spectrum which is the sum of the spectrum from the MOLsphere (the blue line in Fig.3a) and dust emission represented by the Rayleigh-Jeans spectrum normalized to 162 Jy at 40 $\mu$m. The agreements between the observed and predicted spectra appear to be reasonable. This result also shows that the mid-infrared flux of apparently dusty stars such as $\mu$ Cep consists not only of dust emission but also of gaseous emission of water. The contribution of water to the thermal balance in the outer atmosphere as a whole is not very large (only 10 % or so in the case of $\mu$ Cep), yet water may be the dominant coolant in the inner part of the outer atmosphere.

In the above analysis, we apply $T_{\text{ex}}$ and $N_{\text{col}}$ for H$_2$O in the MOLsphere determined by the previous analysis of the Stratoscope spectra (Tsuji 2000). We confirmed that
these parameters explain the ISO spectra as well and no improvement is gained if these parameters are changed. Certainly, these parameters are better determined from absorption rather than from emission spectra. Also, the near infrared spectrum predicted from the MOLSphere agrees well with the Stratoscope spectrum, which was interpreted by the simpler slab model in our previous analysis. The new constraint imposed by the ISO spectra is essentially the inner radius of the MOLSphere, $R_{in}$. In fact, the emission features are quite sensitive to $R_{in}$, and the emission tends to be much stronger for $R_{in}$ larger than $R_{in} \approx 2R_*$ we have adopted. Further, the 6 $\mu$m emission turns to absorption for the smaller values, e.g. $R_{in} \approx 1000R_\odot \approx 1.5R_*$. The weak 6 $\mu$m absorption seen in $\alpha$ Ori (Fig.1a) can be explained this way. Also, neither emission nor absorption will appear from the MOLSphere for some intermediate values of $R_{in}$ and the mid-infrared region of $\alpha$ Ori (Fig.2a) may be such a case. Returning to $\mu$ Cep, the value of $R_{in} \approx 2R_* \approx 1300R_\odot$ we have suggested should have important implications. Especially, this result suggests that water is absent in the region between $r \approx R_*$ and $2R_*$, and water of the MOLSphere may be formed anew somewhere at about $R_*$ above the photosphere rather than the region very close to the photosphere. This fact should be kept in mind in considering the origin of water in the MOLSphere.

4. CONCLUDING REMARKS

We found distinct emission of water at 6 $\mu$m and 40 $\mu$m regions in the ISO spectrum of $\mu$ Cep in addition to the absorption bands at 1.4, 1.9 and 2.7 $\mu$m in the near infrared. We showed that all these observed features can be explained consistently by a simple model of the optically thick molecular sphere with modest temperature (e.g. 1500K) at modest distance above the photosphere (e.g. about one stellar radius). What we have proposed, however, is not a model of the usual meaning but simply an intuitive interpretation on the observed data, since our “model” cannot yet be constructed based on the first principle.
In fact, the presence of the optically thick molecular envelope, which we referred to as the MOLsphere for simplicity, has never been predicted by any theory of stellar atmospheres so far as we are aware. Thus, despite the simplicity of the picture we propose, the physics behind the apparently simple phenomenon remains obscure and offers a challenging problem to the theory of stellar atmospheres.

Recently, presence of water has been shown in several cool stars by ISO (Sect.1), but interpretation of the observed spectra is by no means clear. On the other hand, we could present a simple but consistent interpretation for the case of $\mu$ Cep and this may be due to fortunate situations as follow. First, $\mu$ Cep is unique in that water could be observed through the near- to mid-infrared (including the Stratoscope data) and not only in absorption but also in emission. Second, $\mu$ Cep has the MOLsphere which has just developed to an adequate size. For comparison, $\alpha$ Ori may be the case in which the MOLsphere is not yet developed enough to give clear observed features, or emission and absorption (including the photospheric contributions) may be nearly canceled. On the contrary, the cooler supergiants may have well developed MOLsphere, the observed features from which may be heavily saturated and more difficult to interpret. Third, the spectrum of $\mu$ Cep shows almost no photospheric water band, unlike the case of the cooler objects which show strong photospheric water bands difficult to discriminate from those originating in the MOLsphere. Fourth, the MOLsphere of $\mu$ Cep may be relatively free from complexities due to the dynamical effect such as by a large amplitude pulsation. For all these reasons, the spectra of $\mu$ Cep could be interpreted relatively well and this may provide the proto-type of the MOLsphere, which should most probably exist in the outer atmosphere of cool luminous stars in general.

We finally confirmed that water exists not only in very cool luminous variables, but also in the early M supergiants and possibly in most M (super)giant stars. This fact implies
that the presence of water is not due to some secondary effect such as a large amplitude
pulsation but may be due to a more intrinsic property of cool stars. For example, the
MOLsphere may have some connection with the chromosphere which also exists in the outer
atmosphere of the most cool stars, but its origin is by no means clear yet. By the opening
of the infrared spectral region by ISO, we have now a means by which to explore the new
component of the outer atmosphere which is rather warm (MOLsphere), in addition to the
hot chromosphere and the cool expanding gas-dust envelope known so far. The problem
is how to understand these multiple components of different thermal and kinematical
properties in a unified model, and we now have a possibility to arrive at a more balanced
view of the stellar outer atmosphere by considering all its major constituents.

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Fig. 1.— (a) Spectrum of α Ori by the ISO SWS (resolution $R \approx 1600$) and corrected for the interstellar reddening with $A_v = 0.5$ mag (Lee 1970). (b) The same but for μ Cep corrected for the interstellar reddening with $A_v = 1.5$ mag (Lee 1970). (c) Absorption cross-section (cm$^2$ molecule$^{-1}$) of H$_2$O at $T = 1500$K based on HITEMP (Rothman 1997). The black line is by high resolution $(R \approx 50000)$ and the white line by low resolution $(R \approx 1600)$.

Fig. 2.— (a) Spectrum of α Ori. (b) Spectrum of μ Cep. (c) Absorption cross-section of water at $T = 1500$K. As for details, see the legend to Fig.1.

Fig. 3.— (a) The full spectrum of μ Cep by the ISO SWS (corrected for the interstellar reddening) is shown by the red dots. The gaps around 4, 7, 12, 20, 29 μm are instrumental effect not yet corrected for. The predicted spectrum based on the MOLsphere (optically thick isothermal sphere of the water gas with $T_{ex} = 1500$K, $N_{col} = 3.0 \times 10^{20}$ cm$^{-2}$, and located at $R_* = 650 R_\odot$ above the photosphere) computed with the photospheric spectrum as the boundary condition is shown by the green line (resolution $R \approx 50000$) and by the blue line $(R \approx 1600)$, after being shifted vertically to fit the observed spectrum. For comparison with observation, the effect of dust emission should be added for $\lambda > 8 \mu$m. The molecular bands indicated are originating in the photosphere except for H$_2$O formed anew in the MOLsphere. (b) A close-up of Fig.3a around H$_2$O $\nu_2$ fundamentals. The observed spectrum is shown by the red dots (identical with the ones in Fig.3a) and the predicted one based on the MOLsphere by the blue line (identical with the one in Fig.3a). (c) The region of the H$_2$O pure rotation lines in an expanded scale. Now the dust emission is added to the predicted spectrum from the MOLsphere (the blue line in Fig.3a), and the resulting spectrum is shown by the black line for comparison with the observed one (the red dots).
(a) $\alpha$ Ori/Av=0.5

(b) $\mu$ Cep/Av=1.5

(c) H$_2$O
