WATER OBSERVED IN RED GIANT AND SUPERGIANT STARS – MANIFESTATION OF A NOVEL PICTURE OF THE STELLAR ATMOSPHERE OR ELSE EVIDENCE AGAINST THE CLASSICAL MODEL STELLAR PHOTOSPHERE

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ABSTRACT

We detected the H₂O 6.3 μ m bands in more than 30 red giants stars from K5III to M8III as well as in some early M supergiants on the SWS spectra retrieved from the ISO Data Archive. This result, however, shows serious inconsistency with the present model photospheres which predict H₂O only in the latest M (super)giant stars. Also H₂O was once discovered in the early M (super)giant stars nearly 40 years ago with the balloon-borne telescope named Stratoscope II. This discovery was so unexpected at that time that it was not understood correctly and overlooked for a long time. Now, we reflect on our ignorance of this important discovery during the 40 years and should consider more seriously the meaning of the rediscovery of water in so many red (super)giant stars with ISO.

 $Key\ words:\ ISOSWS-MOL sphere-Photosphere-Water$

1. INTRODUCTION

At this monumental epoch to celebrate the opening of the ISO active archive phase, it may be instructive to recall a short history of stellar spectroscopy in space. At the infancy of the infrared astronomy in the 1960's, an ambitious attempt to observe stellar spectra with a balloonborn telescope was undertaken and this mission named Stratoscope II, launched on March 1963, successfully observed infrared spectra ($0.8 - 3.1 \,\mu$ m) of several red giant and supergiant stars (and invaluable spectra of Jupiter). The results showed beautiful spectra of water in Mira variables *o* Cet and R Leo (Woolf et al. 1964). This result was well in accord with the theoretical prediction (Russell 1934) and thus was well appreciated at that time.

However, the Stratoscope observers reported a more surprising result that water was detected in the earlier M giants μ Gem (M3III) and ρ Per (M4II) as well as in the early M supergiants α Ori (M2Iab) (Woolf et al. 1964) and μ Cep (M2Ia) (Danielson et al. 1965). However, this discovery was not in accord with the understanding of cool stellar atmosphere at that time and it was finally reinterpreted that the absorption bands at 0.9, 1.1, 1.4, & 1.9 μ m identified with H₂O by the Stratoscope observers should instead be due to the CN Red System which also has band heads at about the same positions (Wing & Spinrad 1970).

This proposition was more easily accepted by the astronomical community since then, since CN had been observed in a wide range of oxygen-rich stars from the Sun to red supergiants, not to speak of carbon stars.

Meanwhile, the discovery of water, at least in the coolest Miras, confirmed the importance of water as a source of opacity in cool stars, and actual computation of the non-grey model photospheres revealed that this is true in red giant stars with $T_{\rm eff}$ cooler than about 3200 K (Tsuji 1978), which roughly corresponds to M6III (Ridgway et al. 1980). This result was well consistent with the detection of the strong H₂O bands in the Miras but was contradicting with the identification of H_2O in the M2 - M4 (super)giants by the Stratoscope II observers. Thus, this result lent further support to the Wing-Spinrad proposition. A blind spot in this apparently reasonable conclusion, however, was that we were not aware at that time that the model photosphere, often referred to inadvertently as model atmosphere, is simply a model of the photosphere $(0 \leq \tau < \infty)$ and not of the *atmosphere* $(-\infty < \tau < \infty)$. which may still involve unknown problems.

Since then, important infrared missions such as IRAS and COBE have been successfully undertaken, but few observations of the near infrared stellar spectra were done in space, except for continued efforts with KAO which provided fine low resolution stellar spectra (e.g. Strecker et al. 1979). Finally, ISO launched on November 1995 (Kessler et al. 1996) provided the means by which to observe astronomical spectra at higher resolutions for a wider spectral coverage at last. One of the unexpected results in the initial ISO observations with SWS (de Graauw et al. 1996) was a detection of water in the M2 giant β Peg (Tsuji et al. 1997) and in several early M supergiants in $h + \chi$ Per clusters (Tsuji et al. 1998). It took sometime before we recognized that the Stratoscope II observers correctly identified water in the M2 – M4 (super)giant stars and that the Wing-Spinrad proposition was not correct (Tsuji 2000a). Further, IRTS launched by ISAS on March 1995 detected H_2O bands at $1.9\,\mu m$ in several M (super)giants earlier than M6 (Matsuura et al. 1999). Also, ground-based midinfrared spectroscopy revealed H₂O pure-rotation lines in α Ori and α Sco (Jennings & Sada 1998).

All these results that H_2O exists in red (super)giants earlier than about M6, however, could not be understood with the present model photospheres. We now encounter

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Figure 1. Spectra of water for $N_{\rm col} = 10^{18} \ cm^{-2}$ and $T_{\rm ex} = 1000, 1500$, and 2000 K are shown for high ($R \approx 1600$; solid lines) and low ($R \approx 200$; dashed lines) resolutions of SWS.

a serious problem: are we confronting with a fall of the classical model stellar photosphere or else with a rise of a novel picture of the stellar atmosphere (including the photosphere as a part)? A rather intriguing story of water in red (super)giant stars still remains open, and we hope to utilize the extensive ISO Data Archive to extend and finalize this fascinating story.

2. A RED GIANT SAMPLE

Our initial detection of water was done with the H₂O $2.7 \,\mu\text{m}$ bands which, however, are contaminated by OH, CO, and other molecular bands. Then, we analyzed the H₂O $6.3 \,\mu\text{m}$ bands which are little disturbed by other molecular bands. The expected spectra of the H₂O ν_2 bands computed with the use of HITEMP (Rothman 1997) based on a single absorption slab model are shown in Fig.1.

We first examined a dozen of high resolution spectra of red giants in the ISO Data Archive. The H₂O 6.3 μ m bands are detected in the K5 giant Aldebaran (but not in other two K giants) as well as in all the M giants between M0III and M3.5III (Tsuji 2001), and also in the later M giants (M6-7III), as shown in Fig. 2. We found $T_{\rm ex} \approx 1500$ K (and log $N_{\rm col}$ noted on Fig. 2) by referring to the spectra such as shown in Fig.1. It is remarkable that SWS detected such faint water bands in the K giant star α Tau. This result is quite unexpected but confirmed recently in another K giant Arcturus (α Boo) with the high resolution groundbased spectroscopy in the 12 μ m region (Ryde et al. 2002).

Next, we extend our survey to a larger sample of the low resolution SWS spectra. We found dozens of spectra in this category from the ISO Data Archive. At the lower resolution, some details of the band structure seen at the higher resolution are smeared out (Fig.1). Nevertheless we can detect the dip at $6.63 \,\mu\text{m}$ due to the H₂O ν_2 bands in 25 M giants from M0III to M8III. Some examples are shown in Fig.3 and we estimated $N_{\rm col}$ values for these M giants, again with the single slab model of Fig.1.

The resulting values of $N_{\rm col}$ from the high and low resolution samples are plotted against spectral types in Fig.4. For comparison, the predicted values of $N_{\rm col}$ from



Figure 2. Observed high resolution SWS spectra (filled circles) are compared with the water spectra of Fig.1 (solid lines).



Figure 3. Observed low resolution SWS spectra (open circles) are compared with the water spectra of Fig.1 (solid lines).

the spherically extended non-grey model photospheres are shown by the dashed line. It is clear that the observed $N_{\rm col}$ values cannot be explained at all by the predicted ones. Thus, H₂O detected in M giants should be non-photospheric in origin, but where does it come from?

3. A RED SUPERGIANT SAMPLE

In red supergiant stars, the H₂O 6.3 μ m bands are found as absorption in α Ori (M2Iab) and α Sco (M2Ib), as in K - M giants. Further, water appears in absorption at $\lambda < 5 \,\mu$ m but in emission at $\lambda \gtrsim 5 \,\mu$ m throughout in μ Cep (M2Ia) (Tsuji 2000b). This detection of water in distinct emission should be an important clue to the origin of H₂O, since such emission should most probably originate in the outer atmosphere and not, for example, in the "starspots".



Figure 4. The observed $N_{\rm col}$ values from the high and low resolution SWS spectra (filled and open circles, respectively) plotted against spectral types are compared with the predicted $N_{\rm col}$ values based on the model photospheres (dashed line).

To account for the emission, we upgrade our single slab model to a spherically extended molecular sphere (MOLsphere for simplicity). Since we already know that $T_{\rm ex}\approx 1500\,{\rm K}$ and $N_{\rm col}\approx 3\times 10^{20}~{\rm cm}^{-2}$ from the Stratoscope II data (Tsuji 2000a), an additional free parameter is the inner radius of the MOLsphere r_i . For simplicity, we consider only H₂O whose absorption cross-section is as large as 10^{-18} cm² and thus the H₂O gas is optically thick. Then we solve the transfer equation with the photospheric radiation, resulting in $F_{\rm P}$, as a boundary condition, which shows absorption bands due to CO, CN, OH, SiO etc (Fig.5). We found that the resulting emergent flux from the MOLsphere $F_{\rm P+M}$ with $r_{\rm i} \approx 2R_*$ (R_* is the stellar radius) accounts for the prominent emission lines due to H₂O at $\lambda \gtrsim 5\,\mu\text{m}$ as well as the absorption bands at $\lambda < 5 \,\mu \mathrm{m}$ (Tsuji 2000b).

Further, we found that the huge infrared excess can be explained by an optically thin dust envelope with $\tau_{10\mu m}^{\rm d} \approx 0.1$ and $r_i^{\rm d} \approx 13.5 R_*$. Then the dust emission is simply added to $F_{\rm P+M}$. The entire spectra of μ Cep observed with the ISO SWS (corrected for $A_{\rm V} = 1.5$ mag.) can reasonably be explained by our final spectrum resulting from Photospher + MOLsphere + Dust Envelope, $F_{\rm P+M+D}$. Some details of the water emission in the 6 μ m and 40 μ m regions can be well reproduced by our model as shown in the inserted boxes of the left and right, respectively, in Fig.5. So far, the huge IR excess of μ Cep was thought to be due to dust alone, but now it is clear that it includes water emission originating in the MOLsphere.

4. DISCUSSION AND CONCLUDING REMARKS

Although we have assumed MOLsphere for μ Cep, this is not a theoretical model of the usual meaning but simply a kind of working hypothesis or an empirical model at best. We know nothing about the origin of the MOLsphere and it is a major challenge how to resolve this issue. Such a difficulty, however, may be shared with the origin of the chromosphere as well as of the mass-loss outflow (at least in



Figure 5. Photospheric spectrum $F_{\rm P}$ (bottom) based on the spherically symmetric non-grey model photosphere ($T_{\rm eff}$ = 3600 K, $M_* = 15 M_{\odot}$, $R_* = 650 R_{\odot}$) is used as the boundary condition for solving radiative transfer in the MOLsphere. The resulting emergent spectrum from the MOLsphere $F_{\rm P+M}$ (middle) is further diluted by the emission due to the optically thin dust envelope and $F_{\rm P+M+D}$ (top) is the final spectrum to be compared with the ISO spectrum $f_{\rm obs}$. The computations of $F_{\rm P}$ and $F_{\rm P+M}$ are done with a resolution of $R \approx 10^5$ and the results are convolved with the slit function of SWS (R = 1600).

non-pulsating stars). With this reservation, our empirical model for μ Cep is reasonably successful, and a problem is if such a model can be extended to other cases. Although we see no emission in the 6 μ m region in our large sample of red giant stars, it is interesting to notice that the H₂O column densities tend to lever-off at about M5 and then to be smaller than the predicted photospheric values (Fig.4). Moreover, water bands almost disappear in M7 giant EP Aqr. These results suggest that the photospheric H₂O bands may be filled in by the emission due to H₂O itself in the late M giants. Also, in the late M giants, H₂O appears as emission in the 40 μ m region (Tsuji et al. 1999), CO₂ shows prominent emission in the 15 μ m region (Jasttanont et al. 1998), and SO₂ shows emission as well as absorption in the 7 μ m region (Yamamura et al. 1999).



Figure 6. A working hypothesis on the evolution of the atmospheric structure of red giants with Sp. Type. Stellar radius R_* is defined by $\tau_{\text{Ross}} \approx 1$ but photosphere extends to where $\tau_{\text{Ross}} \approx 0$. Presently, self-consistent modelings are possible for the photosphere and interior ($0 < \tau < \infty$), but not at all for other components in the outer atmosphere ($-\infty < \tau < 0$).

Based on these observations, it should be reasonable to assume the presence of MOLsphere in late M giants.

However, a possibility that there are some serious flaws in the present model photospheres cannot be excluded, especially for K (see Ryde et al. 2002) and early M giants for which there is no direct evidence for MOLsphere. This case offers a more serious problem, since our present stellar spectroscopy (e.g. abundance analysis) loses its basis. Also, if this is the case, we must give up to have a unified picture for cool luminous stars including K and early M giants. We are yet tempted to have a unified picture, ISO's innovation of which may be illustrated as in Fig.6. The presence of the high excited molecular gas has been known for late (super)giants from the H₂O and SiO masers for a long time, but ISO revealed that the presence of such a warm molecular gas, including not only H₂O and SiO but also CO_2 and SO_2 , may be a general phenomenon in red giant and supergiant stars.

In concluding, we summarize our present viewpoint:

1. Water was discovered in several early M (super)giants nearly 40 years ago with Stratoscope II, but this discovery has been mis-interpreted and overlooked until recently. We regret that this important discovery did not provide major impact on the theory of cool stellar atmosphere during these 40 years. We certainly hope that such an unfortunate history should not be repeated with the ISO data.

2. After 40 years, we confirmed H_2O absorption bands in more than 30 red giant stars from K5III to M8III with the use of the ISO Data Archive. Thus ISO finally established that the presence of water is a general phenomenon in red giant stars including K and early M types.

3. With ISO SWS, we detected water in emission in the M2 supergiant μ Cep. This fact suggests that water should be in the outer atmosphere rather than in the photosphere. Also, emission not only of H₂O but also of CO₂ and SO₂ are detected in late M giants with ISO and, by implication, water in all the red giant stars may also be originating in the outer atmosphere.

4. We conclude that the presence of a rather warm molecular sphere – MOLsphere – may be a general feature in red giant and supergiant stars. Thus ISO revealed a novel picture of the atmosphere consisting not only of the photospher, chromosphere, and wind so far known but also of a new component – MOLsphere. Certainly, the ISO Data Archive should be an invaluable tool by which to explore the fundamental problem on the atmospheric structure of red giant and supergiant stars.

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REFERENCES

- Danielson, R. E., Woolf, N. J., Gaustad, J. E. 1965, ApJ 141, 116
- de Graauw, Th., Haser, L. N., Beintema, D. A., et al. 1996, A&A 315, L49
- Jasttanont, K., Feuchtgruber, H., de Jong, T., et al. 1998, A&A 330, L17
- Jennings, D. E., Sada, P. V. 1998, Science 279, 844
- Kessler, M. F., Steinz, J. A., Anderegg, M. E., et al. 1996, A&A 315, L27
- Matsuura, M., Yamamura, I., Murakami, H., et al. 1999, A&A 348, 579
- Ridgway, S. T., Joyce, R. R., White, N. M., Wing, R. F. 1980, ApJ 235, 126
- Rothman, L. S. 1997, High-temperature molecular spectroscopic database (CD-ROM) (Andover: ONTAR Co.)
- Russell, H. N. 1934, ApJ 79, 317
- Ryde, N., Lambert, D., Richter, M. J., Lacy, H. 2002, preprint (astro-ph 0207368)
- Strecker, D. W., Erickson, E. F., Witteborn, F. C. 1979, ApJS 41, 501
- Tsuji, T. 1978, A&A 62, 29
- Tsuji, T. 2000a, ApJ 538, 801
- Tsuji, T. 2000b, ApJ 540, L99
- Tsuji, T. 2001, A&A 376, L1
- Tsuji, T., Ohnaka, K., Aoki, W., Yamamura, I. 1997, A&A 320, L1
- Tsuji, T., Ohnaka, K., Aoki, W., Yamamura, I. 1998, Ap&SS 255, 293
- Tsuji, T., Aoki, W., Ohnaka, K. 1999, ESA SP-427 229
- Wing, R. F., Spinrad, H. 1970, ApJ 159, 973
- Woolf, N. J., Schwarzschild, M., Rose, W. K. 1964, ApJ 140, 833
- Yamamura, I., de Jong, T., Onaka, T., et al. 1999, A&A 341, L9