

Water in K and M giant stars unveiled by ISO*

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Received 29 May 2001 / Accepted 11 July 2001

Abstract. Based on the spectra obtained with Infrared Space Observatory, ISO, we detected the $6.3\ \mu\text{m}$ bands of water in the late K giant Aldebaran (α Tau) and several early M giant stars (between M0 and M3.5), which have been deemed to be too warm for tri-atomic H_2O molecule to reside in their photospheres. The water column densities range $(0.2\text{--}2)\times 10^{18}$ molecules cm^{-2} in our sample of K and M giant stars and the excitation temperatures are 1500 K or higher. Thus, the water bands are not originating in cool stellar winds either. The presence of water in the K and early M giant stars was quite unexpected from the traditional picture of the atmosphere of the red giant star consisting of the photosphere, hot chromosphere, and cool wind. We confirm that a rather warm molecule forming region should exist as a new component of the atmosphere of red giant stars and that this should be a general phenomenon in late-type stars.

Key words. infrared: stars – molecular processes – stars: atmospheres – stars: chromospheres – stars: individual: α Tau, β And, α Cet, β Peg, γ Cru – stars: late-type

1. Introduction

A pioneering attempt to observe stellar spectra from outside the Earth's atmosphere was undertaken more than 35 years ago with the balloon-borne telescope named Stratoscope II, and water was clearly detected in Mira variables σ Cet and R Leo (Woolf et al. 1964). Also, a possible presence of water in the normal M giants μ Gem (M3III) and ρ Per (M4II) as well as in the early M supergiant α Ori (M2Iab) was suggested. The presence of water in such non-Miras, however, was so unexpected at that time (and even today) that it has not been understood correctly for a long time. Instead, the absorption bands at 1.4 and $1.9\ \mu\text{m}$ attributed to H_2O by the Stratoscope II observers were re-interpreted as due to the CN red system which also has the bandheads at 1.4 and $1.9\ \mu\text{m}$ (Wing & Spinrad 1970). In fact, it was known at that time that water can be observed only in the coolest M giant stars later than about M6 (e.g. Johnson & Méndez 1970), while CN can be well observed in the warmer red giant stars.

Further support for the proposition by Wing & Spinrad (1970) was provided by the model photospheres of red giant stars developed at that time, which showed that water can be abundant in M giants with effective temperatures (T_{eff}) lower than about 3200 K and that T_{eff} 's of M giants should be revised upward against the ones known at that time (Tsuji 1978). This upward revision of the

effective temperature scale was well consistent with the empirical scale based on the angular diameter measurements which showed $T_{\text{eff}} \approx 3250\text{K}$ for M6III (Ridgway et al. 1980). Thus, theory and observations that water can be observed only in M giants later than about M6 appeared to be consistent. This result further made it difficult to accept the Stratoscope II result that water could be detected in the M giant stars as early as M3–4.

Nevertheless, we recently found the possible presence of water in the early M giant β Peg (M2.5II-III) (Tsuji et al. 1997) on the spectra we observed with the Short Wavelength Spectrometer, SWS (de Graauw et al. 1996), on board the ISO (Kessler et al. 1996). This result was based on the analysis of the $2.7\ \mu\text{m}$ region where the H_2O ν_1 and ν_3 bands can be found, but the overlapping OH and CO bands made it difficult to clearly demonstrate the presence of the H_2O bands, especially by the low resolution spectrum we had at that time. Also, possible presence of water in early M type stars was suggested by the low resolution data obtained with IRTS (Infrared Telescope in Space) of ISAS (Matsuura et al. 1999). By these results, however, it might still be difficult to convince the presence of water in non-Mira stars earlier than about M6 against the general belief that water should not exist in such stars. Now, it is possible to utilize a larger sample of high resolution ISO spectra recently released by ESA and, with the higher resolution, we detected the H_2O ν_2 bands in the $6.3\ \mu\text{m}$ region, where is little disturbed by other molecular bands. This observation finally provides convincing evidence for the presence of water in normal red giants including the late K and early M giant stars.

* Based on the data archives of ISO, an ESA project with instruments funded by ESA member states (especially the PI countries: France, Germany, The Netherlands, and the UK) and with the participation of ISAS and NASA.

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Table 1. Program stars observed with the ISO SWS.

Nos.	object	BS	Sp. type	T_{eff} (K)	ISO Obsno.
1	α CMa	2491	A1Vm	$\approx 10\,000$	689 01202
2	α Boo	5340	K1IIIb	4362 ^a	452 00101
3	γ Dra	6705	K5III	4095 ± 163^b	040 02405
4	α Tau	1457	K5III	3898 ^a	636 02102
5	β And	337	M0IIIa	4002 ± 178^b	795 01002
6	α Cet	911	M1.5IIIa	3869 ± 161^b	806 00924
7	β Peg	8775	M2.5II-III	3890 ± 174^b	551 00705
8	γ Cru	4763	M3.5III	3626 ^a	609 00804

^a Cohen et al. (1996). ^b Dyck et al. (1998).

2. Detection of water on ISO spectra

We used the spectra listed in Table 1 observed with the ISO SWS by its highest resolution grating mode, which gives a resolution of $R = \lambda/\Delta\lambda \approx 1600$ ($FWHM \approx 188 \text{ km s}^{-1}$). The sample shown in Table 1 is probably all the red giants earlier than M4III observed with the ISO SWS by this high resolution grating mode, even though more spectra were observed by the lower resolutions. Also, some spectra of late M giants were observed by the high resolution (e.g. Tsuji et al. 1997), but we concentrate in this Letter to the case of red giant stars earlier than about M4 for which the presence of water is not clear yet. The spectra are reduced with the use of OSIA¹ and the resulting spectra are shown in Fig. 1. For comparison, we show in Fig. 2 the spectra of H₂O in the form of $\log B_\nu(T_*)e^{-\tau_\nu}$ with $\tau_\nu = \kappa_\nu(T)N_{\text{col}}$, where $\kappa_\nu(T)$ is the absorption cross-section of H₂O and N_{col} is the column density of H₂O (assumed to be 10^{18} cm^{-2} throughout). The spectra for $T = 1000, 1500,$ and 2000 K are shown and some features to be used as signatures of H₂O absorption are indicated by $a - e$ in Fig. 2.

The spectrum of α CMa (A1Vm; $T_{\text{eff}} \approx 10\,000 \text{ K}$) shown at the top of Fig. 1 should show no stellar feature in this spectral region, and the features shown may simply be noise whose variations are within about 0.01 dex. ($\pm 1.2\%$). The next two spectra of K giant stars α Boo (K1IIIb) and γ Dra (K5III) may show some features which, however, do not agree with the signatures of water $a - e$ noted in Fig. 2. The features may be due to stellar CO lines (see Fig. 3) and/or to noise. The spectrum No. 4 of the K5 giant Aldebaran is quite different and shows, if very weak, most signatures $a - e$ of water against noise. Also, the overall pattern of the spectrum of α Tau is clearly different from that of the spectra Nos. 1–3, which are rather similar to each other. Then, the spectrum No. 5 of the M0 giant β And shows the H₂O signatures $a - e$ more clearly. The presence of water absorption in the spectra Nos. 6, 7, and 8 of α Cet (M1.5IIIa), β Peg (M2.5II-III), and γ Cru (M3.5III),

¹ OSIA (Observers SWS Interactive Analysis) is a joint development of the SWS consortium. Contributing institutes are SRON, MPE, KUL and the ESA Astrophysical Division.

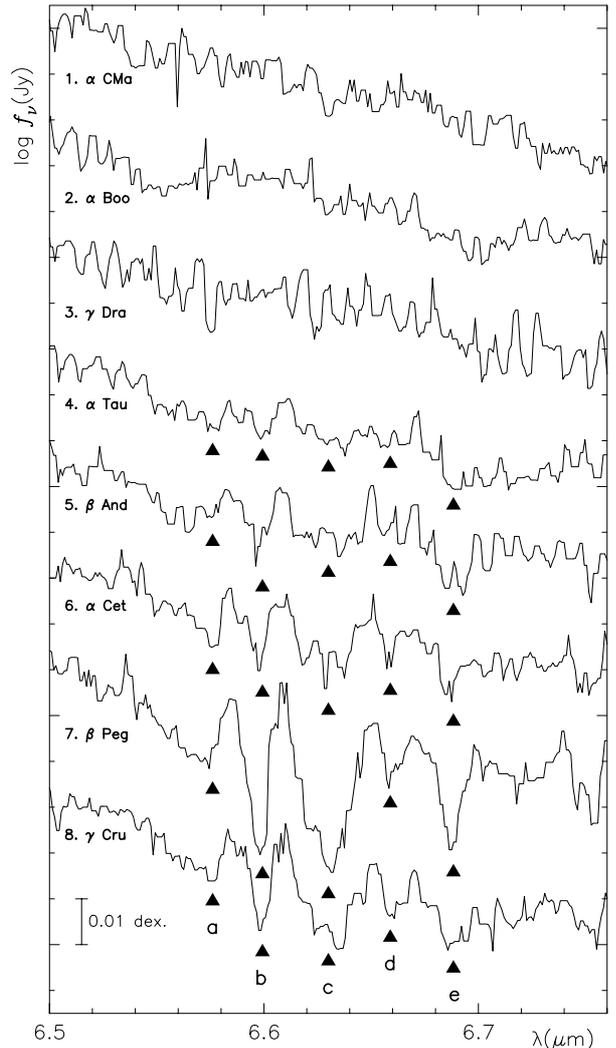


Fig. 1. Spectra observed with the ISO SWS. The first three stars may serve as references in which no signature of water can be seen. The other five objects all show the signatures of water $a - e$ predicted from the spectroscopic data of H₂O in Fig. 2.

respectively, is definite and we thus find convincing evidence for water in the early M giant stars. The water features are the strongest in β Peg rather than in γ Cru, the latest M giant in the present sample. The identification of molecular absorption on stellar spectra is a simple problem of pattern recognition, and the presence of water in α Tau can be convinced if we compare the spectrum No. 4 with the spectra Nos. 5–8.

The water spectra shown in Fig. 2 are well sensitive to temperature, since the features a and c are mainly contributed by the low excitation lines (typically L.E.P. $< 2000 \text{ cm}^{-1}$) while the features $b, d,$ and e by the higher excitation lines (L.E.P. $> 2000 \text{ cm}^{-1}$). For this reason, the relative intensities of $b + d + e$ against $a + c$ are larger at higher temperatures. We notice that the observed spectra in Fig. 1 do not agree with the trend of the predicted spectrum based on $T = 1000 \text{ K}$ in Fig. 2, and the excitation temperature of the water gas in the observed red giants

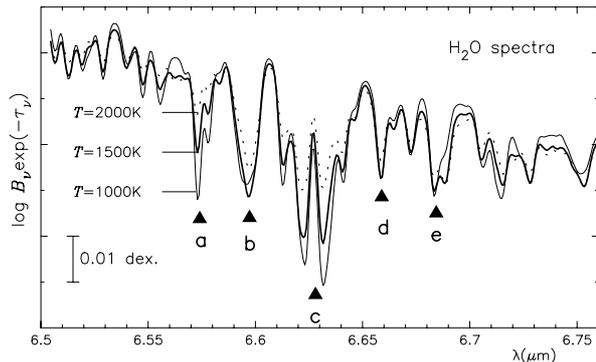


Fig. 2. Spectra of water evaluated at high resolution ($R \approx 10^5$) and convolved with the slit function of the ISO SWS (Gaussian with $FWHM \approx 188 \text{ km s}^{-1}$) are shown for three temperatures. The linelists by Rothman (1997) and by Schwenke & Partridge (1997) are used and the results are almost the same.

cannot be as low as 1000 K. Instead, the relative intensities of the observed features appear to be more consistent with $T \approx 1500 \text{ K}$ or somewhat higher. For evaluating water spectra shown in Fig. 2, we used a calculated water linelist HITEMP (Rothman 1997), but its accuracy is unknown. Then, we also used a more extensive linelist by Schwenke & Partridge (1997), and confirmed that the resulting spectra show little difference with those based on HITEMP at the resolution of Fig. 2. This consistency of the available linelists is encouraging, although the accuracy of the linelists of hot water should be verified by laboratory data in future. Once temperatures can be known, the column densities can be estimated by comparisons of the observed and calculated water spectra. We found N_{col} between 2×10^{17} (α Tau) and 2×10^{18} (β Peg) cm^{-2} .

3. Discussion

In Fig. 3, we examine the predicted synthetic spectra based on the model photospheres, which are essentially the same with those discussed before (Tsuji 1978) except that the photosphere is now assumed to be spherically symmetric rather than plane-parallel. Also, the opacity data are largely updated by the use of the HITEMP linelist, whose $\log gf$ values agree with those by Schwenke & Partridge (1997) within 0.05 dex. The weak absorption features in the models of T_{eff} between 4000 and 3400 K are due to high excitation tails of the CO fundamental bands whose band origin is at $4.6 \mu\text{m}$. H_2O features appear first in the model of $T_{\text{eff}} = 3300 \text{ K}$ and strengthen in the model of $T_{\text{eff}} = 3200 \text{ K}$. On the other hand, T_{eff} 's of the early M giant stars (M0–M3.5) are between 3600 and 4000 K as shown in Table 1. However, H_2O features can never be predicted from the models of $T_{\text{eff}} = 3600\text{--}4000 \text{ K}$. Does this imply that our classical model photospheres are so useless?

It is true that model photospheres of cool stars are not yet perfect. However, stellar photospheres can be relatively well modeled based on few ad-hoc assumptions except possibly for the treatments of convection and

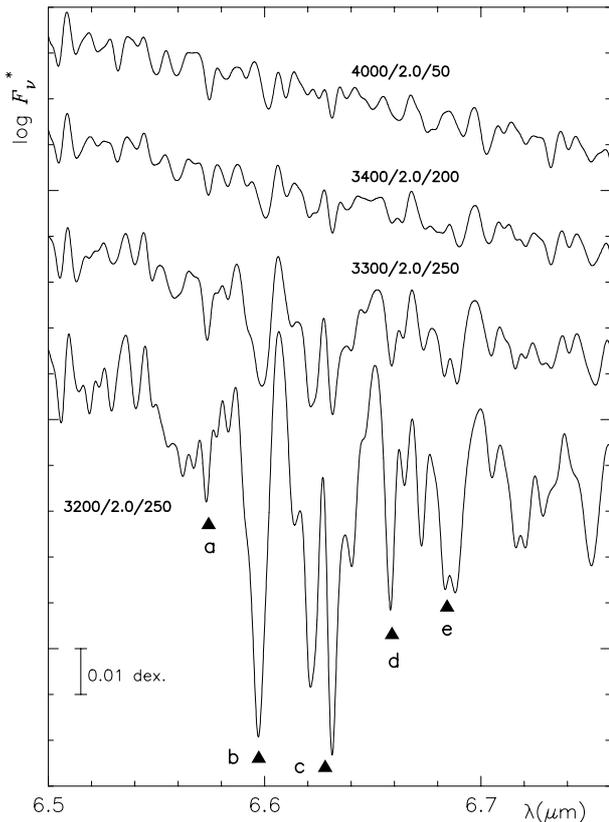


Fig. 3. Predicted spectra by model photospheres whose basic parameters (T_{eff} /mass in unit of M_{\odot} /radius in unit of R_{\odot}) are indicated. The synthetic spectra are evaluated with the spectral line database including about a million of lines of CO, OH, CN, SiO, H_2O etc., and reduced to the resolution of the observed spectra as in Fig. 2.

turbulence, and there is no reason why cool stars are exception only if molecular opacities are properly taken into account. In fact, the present model photospheres of red giant stars have been tested by the fact that the empirical effective temperature scale and the predicted one based on our models show reasonable agreement as noted in Sect. 1. We believe that the photosphere of red giant stars can be modeled at least approximately within the framework of the so-called classical assumptions and that the model photospheres of cool stars cannot be so wrong as to not able to predict the major molecular features originating in the photosphere. However, we should notice that the stellar atmosphere, which represents all the observable outer layers, could not necessarily be represented by the model photosphere. In other words, it should still be possible that some new component remains unrecognized in the atmosphere of red giant stars beside the known ones including the photosphere, chromosphere and wind.

One possibility may be to assume the presence of large starspots, but such large starspots should give noticeable effects on other observables such as the spectral energy distributions, spectra, variabilities, activities etc. However, we know little evidence for such effects in the normal red giant stars. Another possibility is to assume that the red

giant stars are veiled by a cloud of water vapor. In fact, we found clear evidence for such a case in the M supergiant star μ Cep (M2Ia) by detecting the H₂O 6.3 μ m bands in emission on the ISO spectrum (Tsuji 2000) and by confirming the 1.4 and 1.9 μ m bands in absorption on the Stratoscope data (Tsuji 2000). In another M supergiant star α Ori, the H₂O 6.3 μ m bands appear in absorption (Tsuji 2000) and also absorption lines due to the H₂O pure-rotation transitions were detected by the high resolution ground-based spectroscopy (Jennings & Sada 1998). The nature of water in the red giant stars is rather similar to that in the red supergiant stars (e.g. $T_{\text{ex}} \approx 1500$ K in the both cases), and we propose that the similar model of a rather warm molecular sphere (MOLsphere) as for supergiants should be applied to the normal red giant stars.

In this connection, it is interesting that the molecular cloud referred to as “CO-mosphere” was found recently in the Sun by detecting CO emission beyond the solar limb (Solanski et al. 1994). Thus, the presence of the rather warm molecular sphere (MOLsphere) may be a common phenomenon in late-type stars including the Sun, red giants and supergiants, and we hope that future detailed studies of the MOLsphere as well as of the CO-mosphere will clarify the physical basis of such a phenomenon. Also, high excited water gas around very cool (super)giants has been known from water masers for a long time (Knowles et al. 1969). But it now turns out that such warm water gas already exists in the late K and early M giants even though H₂O masers are not observed. This fact implies that the cradle for maser activity may have already been germinating in K and M giant stars.

So far, the presence of the hot chromosphere ($T \approx 10^4$ K) is known in K and M giant stars but no evidence for the solar-type corona (Linsky & Haisch 1979). On the other hand, steady stellar wind already starts in K giant stars (Reimers 1977), but the origin of the wind is unknown yet. Recently, high sensitive infrared survey with the ISO (ISOGAL) revealed that efficient dust formation already starts in red giant stars with weak mass-loss rates (Omont et al. 1999). An interesting possibility is that the outer part of the MOLsphere is cool enough for dust to form, and this may explain why dust formation starts in the red giant stage prior to the AGB phase. Further, dust formed this way may be pushed outward by the radiation pressure and thus may explain the onset of the wind. This is of course not a solution to the origin of the dust and/or of the wind so long as the origin of the MOLsphere is unknown. But now it appears that the atmosphere of red giant stars is composed of the newly recognized MOLsphere in addition to the previously known photosphere, chromosphere and wind. With this new component, a more unified picture and self-consistent theory for the atmospheric structure of red giant stars could be developed.

4. Concluding remarks

The presence of water in the early M giants was once noticed more than 35 years ago (Woolf et al. 1964), but

this important discovery has not been understood properly and overlooked for a long time. We had to wait ISO to confirm the presence of water in normal red giant stars including the late K and early M giant stars. By hindsight, this may partly be due to confusion not to have realized the difference of the photosphere and the atmosphere. For example, stellar photosphere could be modeled rather easily but it has often been referred to as a *model atmosphere*. However, what we had this way is only a *model photosphere* and we have no self-consistent *model atmosphere* of red giant stars yet. What Stratoscope II suggested and what ISO finally unveiled is that the infrared spectra of red giant stars involve a new problem that cannot be represented by the photospheric model, and that the atmosphere and the photosphere should be clearly distinguished. Certainly a more unified understanding of the stellar atmosphere should be required to properly interpret the infrared spectra of red giant stars.

Acknowledgements. I thank I. Yamamura for making available his fine tools in applying OSIA, T. Tanabé for helpful advice on OSIA, and the anonymous referee for valuable comments. This work is supported by the Grant-in-Aid for Scientific Research of the Ministry of Education & Science No. 11640227.

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