Water in stellar atmospheres

”Is a novel picture required to explain the

atmospheric behavior of water in red giant stars?"

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Sammanfattning (Swedish summary)

Sedan 1960 talet har det visat sig att atmosfärer hos de största stjärngiganterna i vår galax, nämligen röda jättar och superjättar av spektralklass mellan K och M, påvisar starka bevis av att innehålla vattenånga. Detta var på 60-talet helt obegripligt då de enda stjärnatmosfärer som förutsågs kunna innehålla och hålla kvar vattenånga var av kallare karaktär. Sedan de första spektroskopiska detektionerna av vatten erhölls har denna gåta levt kvar och först de senaste två årtiondena har forskningen tagit seriös fart. En del förklaringar har framförts, den kanske mest spektakulära förklaringen involverar ny tjock molekylär atmosfärisk komponent som ligger som ett hölje kring den klassiska stjärnatmosfären. Denna teori är dessvärre baserad på allt mer föråldrad data med låg spektroskopisk upplösning och allt eftersom ny, mer högupplöst data erhålls, börjar teorin stöta på problem.

Nya förklaringar som baseras på att justera klassiska atmosfärsmodeller börjar mer och mer knuffa ner förklaringen baserad på det molekylära höljet från tronen som bästa förklaring. Däremot har nya upptäckter gjorts som tyder på att det trots allt verkar finnas någonting väldigt stort kring vissa stjärnor som onekligen får tankarna att gå tillbaka till den molekylära sfären. Forskningen ligger nu mellan två förslag som utan tvivel båda har grund att stå på och för att fortsättningsvis utföra en effektiv forskning inom detta ämne, bör en god förståelse för båda förslagen finnas som grund för forskningen. Denna artikel kommer innefatta en genomgång av de båda utgångspunkterna, samt innefatta en grundlig undersökning av klassiska atmosfärsmodeller för att utvärdera vad de faktiskt antyder och hur de kan förbättras.

Abstract

Water has been found to be an important molecule in stellar atmospheres of as hot stars as red (super)giant stars with a stellar class as early as K. Former model photospheres of these stars did not allow water to be present and although the presence of water has been proven countless times, no satisfactory explanation has yet been found. The subject is a hot field of research and is currently based on two different explanations. The first explanation is based on the assumption of a giant molecular sphere that encloses the classical stellar atmosphere, and the second is based on the assumption that found disagreements to former model atmospheres may be explained by correcting these classical model photosphere and also to take non-local thermodynamic equilibrium effects into account.

In this project, in order to deepen the knowledge of classical model photospheres, investigations of classical MARCS-model have been performed. These investigations have found that the effective temperature-dependence of relative gas pressure of water does not face some critical value but gently decreases with higher temperature. Relating this with synthetic spectra, the effective temperature for when the water lines disappear, was found to be 4000K, 4200K, 4400K, for a surface gravity of log g = 1, log g = 2 and log g = 3, respectively. Restrictions for the effective temperature and surface gravity certain stars should possess in order to be suitable for observationally testing the MARCS-models is presented.

Content

Introduction

Stellar spectroscopy is an important tool in the understanding of atmospheric properties of stars. It is a well known fact that the atmospheres of red giant- and supergiant stars includes a large range of different atoms, ions and molecules and by using spectroscopy, one can analyze how the interplay between atoms and molecules in a stellar atmosphere depends on certain properties of the star. Three such important properties are the surface gravity, effective temperature and the abundances and thus the depth of where the spectral lines are formed in the atmosphere. Knowing these properties, much information of the star's atmosphere can be obtained from long known theoretical models.

However, recent research of late K and M (super)giant star's has started to dispute the classical view of the atmospheres, and particularly the photosphere, and its properties. The background behind the questioning of classical model photospheres goes all the way back to a balloon born telescope, Stratoscope II, sent up in the early 60:s to observe e.g. atmospheres of M (super)giant stars. M stands for a certain spectral class, which stars often are divided into and often directly comparable to a certain temperature. Stars in spectral class M have a typical effective temperature of less than approximately 4000 K.

The Stratoscope observation discovered evidence for water vapor in the early supergiants α Ori and μ Cep (Woolf et al. 1964, Danielson et al. 1965). Water was at this time not expected in these types of stars and one could not explain why there should be water present in these atmospheres. The observed water lines were observed in absorption using low resolution spectra and since water was only expected in the coolest M giants, not earlier than M6, an alternative view to the spectra was generally more accepted, namely a interpretation of the lines as due to the CN red system.

The CN molecule is a much more common molecule in a wider range of stellar atmospheres, which also had band head at the same position as the water lines. These lines were predicted, so the water lines were finally reinterpreted as due to the CN red system (Wing and Spinrad 1970). The Wing and Spinrad proposal was much more easily accepted by the community since CN molecules had been observed in much warmer red giants and with no other satisfactory conclusion regarding water vapor, further investigation was not made.

The CN red system proposal received further support from the, at that time, newly developed model photospheres for red giant stars. These model photospheres of red giant stars showed that water can be abundant in ~M2-M5 giants with effective temperature not exceeding 3200 K, and that the known effective temperatures of M giants should be revised upward (T.Tsuji 2001).

The recently found evidences for a misinterpretation of the CN red system proposal are however eloquent. Water lines has been popping up in different detectors during observations of plenty of red (super)giant stars, even as early as K I stars. Few observations in mid-infrared stellar spectra were done since the Stratoscope observations until the ISO satellite was launched on November 1995 (Kessler et al. 1996), set to observe astronomical spectra at a higher resolution for a wider spectral coverage. It took some time before one recognized that the Stratoscope II observers correctly identified water in the M2-M4 (super)giants and that the Wing and Spinrad proposal was incorrect (Tsuji 2000a).

ISO was to confirm the water detection from Stratoscope II and to detect water vapor absorption lines in more than 30 red giant stars, ranging from K5 III – M8 III. Further evidence and detection of water vapor was made when the IRTS was launched by ISAS on March 1995. The IRTS detected water lines at 1.9 µm in several M (super)giants earlier than M6 (Matsuura et al. 1999). Also, ground-based mid-infrared spectroscopy revealed water in α Ori and α Sco (Jennings and Sada 1998).

Not only has water been observed in absorption but emission lines were detected at 6 and 40 µm in the ISO spectrum of µ Cep. This suggests the water to originate in the outer atmosphere rather than in starspots or in the temperature in-homogeneities due to convection shells. This too is in conflict with classical model photospheres.

All these newly found evidence of water and its observed behavior implies that there are some serious flaws in our view of stellar atmospheres for red (super)giant stars. Suggestions has been made of a large molecular cloud as a new component of the stellar atmosphere, often referred to as a MOLsphere, to be a general phenomenon to red giant and supergiant stars. This suggestion has offered satisfactory explanations to the spectrum of µ Cephei (Tsuji 2003), but it has also encountered refutation from observation made of spectra with even higher resolution at 12 µm (Ryde et al 2006). As with the spectrum of µ Cephei, water has been detected in strong absorption with same resolution in 12 µm for the K1.5 III red giant star Arcturus (α Boo) with an effective temperature of approximately 4200K (Ryde et al. 2002). In these two cases, they managed to reproduce the lines by making the change a classical MARCS-model photosphere to one with a cooler outer part.

However, results from observations made from the Very long baseline interferometry (VLA), have revealed many masering water clouds around red supergiants such as M3-M4 VY Canis majoris (Imai et al. 1997) and M3-M4 S Persei (Richards et al. 1999), with origin unknown. Also, radio observations of Betelgeuse with the VLA (Lim et al. 1998) revealed the presence of a new component of modest temperature of $T_{ex} \leq \sim 3500$ K, over the same height as the classical chromospheres, with $T_{ex} \geq \sim 5000$ K. However, this observation is obscure and needs a better interpretation.

As of today, a unified picture of how all new data should be interpreted and how the atmospheres of K-M stars actually look like is still to be found. Whether or not the answer is a MOLsphere as a general phenomenon or if the answer lies closer to the classical model photospheres, only with certain corrections, it is certain that there indeed needs more work on this subject. It is of great importance that knowledge of the work being made from both the research about MOLspheres and the opposing research since the correct answer may indeed be some unified picture resulting from of both camps.

In this report I will present the pros and cons of the two models to explain the water observed in red giant atmospheres. Related to this, an investigation of classical MARCS-model photospheres will be presented together with concluding remarks and discussions comparing the results with the two grounds of research; the MOLsphere and corrections of classical model photospheres. Related to this work, an article from Lunds Observatory by Mohsen Farzone (Master thesis 2012) presents a wide range of K1-M6 stars which all show strong water absorption lines at 12 µm. In his article he discusses the variation of the lines with spectral type and compares with classical model predictions and also with what would be expected if the lines were formed out of equilibrium. These two reports should contribute to a better understanding of the characteristics of classical model photospheres and thus hopefully reveal clues to what possible corrections and changes are encouraged.

Theory

Planck's law of radiation

Having an interest in astrophysics, it might be familiar that stars are commonly considered to be one of the closest real objects to be approximated with satisfaction with the theoretical model of a black body radiator. But what does the theoretical model of a black body radiator tell us and why does it work on stars?

Regular stars are big lumps of glowing gas, many times bigger than the size of our planet. This glowing gas consists mainly of plasma, which is a gas of charged particle – such as electrons and protons – which moves around fairly freely. These charged particles, together with ions, are common in stellar atmospheres and they will however from time to time collide or bend, in other words; change their velocities and paths. When a charged particle is accelerated in one way or another, it will either emit or absorb photons of some wavelength as a direct and fundamental consequence from the physical laws of quantum electro dynamics (QED). Considering this fact as an example and nothing more, one would expect the spectrum from a big ball of glowing plasma to be a continuous curve for the intensity as a function of wavelength. These two processes of free charges that either emit or absorb photons of certain wavelength are called "*bremsstrahlung*" and "*Compton scattering*" and both processes are common features in stellar atmospheres and gives us a mental picture of how a continuous spectra can be produced.

Planck's law of radiation is a theoretical prediction of the amount of electromagnetic radiation that a perfect black body radiates. The described intensity is a function of frequency and temperature and was introduced by Max Planck in the year 1900, with prospect to fit the intensities measured experimentally. Planck's law of radiation follows:

$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_BT}}-1} \quad (1)$$

where *h* is Planck's constant, v stands for frequency, *T* for temperature, *c* for light speed in vacuum and k_B is the Boltzmann's constant.

The Rayleigh-Jeans' law

$$B_\nu(T) = \frac{2\nu^2 k_B T}{c^2} \quad (2)$$

was based on classical assumptions and were therefore, as a consequence, expecting the intensities to increase up to infinity for high frequencies. It fits well for lower frequencies but at higher frequencies, this was clearly not the case. By introducing the concept of light quanta, Planck managed to control the curve and made it fit to empirical results satisfactorily.

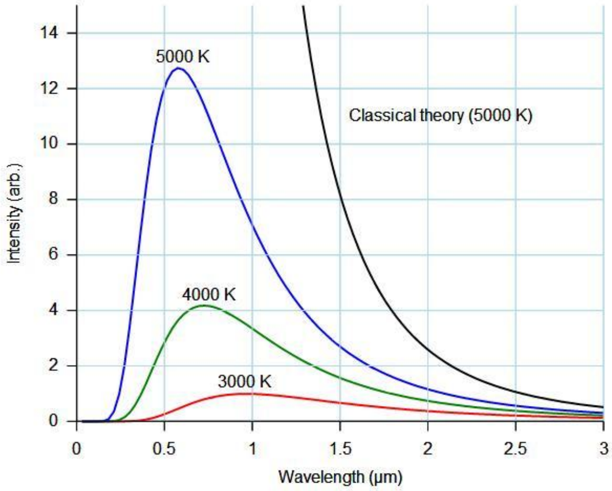


Fig 1) The three colored curves represent the Planck intensities for three different temperatures; 3000K, 4000K and 5000K, as a function of wavelength in μm. The black curve represents classical expectations of emitted radiation from a black body.

By using the Taylor series of $e^{\frac{h\nu}{k_BT}}$ for low frequencies, it is legitimate to make following approximation:

$$e^{\frac{h\nu}{k_BT}} \approx 1 + \frac{h\nu}{k_BT}$$

This leads to the fact that

$$\frac{1}{e^{\frac{h\nu}{k_BT}} - 1} \approx \frac{1}{\frac{h\nu}{k_BT}} = \frac{k_BT}{h\nu}$$

and using this approximation in Planck's law, one realizes that the law, at low frequencies, reduces to the Rayleigh-Jeans law (2):

$$I(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_BT}} - 1} \approx \frac{2h\nu^3}{c^2}\frac{k_BT}{h\nu} = \frac{2\nu^2 k_BT}{c^2}$$

Planck described the behavior for the higher frequencies as due to a quantization of the oscillation energy as multiples of $h\nu$ and that the mean energy for an oscillator, k_BT, was not enough to start the oscillations of the higher frequencies. This was the breakthrough of which gave birth to the concept of "photons" and indeed the world of quantum mechanics.

Looking at fig 1, one sees that the curves from the theory of Planck's law of radiation for black bodies indeed has the continuous profile for the intensity as a function of wavelength or frequency, as was expected from the discussion of a ball of plasma above. It was also mentioned that the behavior of stars is very closely related to the behavior of a theoretical black body. Looking closely at fig 1, one notices a small shift in frequency for the maximum intensity for different temperatures according to Wien's displacement law

$$\lambda_{max} = \frac{b}{T}$$

where b is Wien's displacement constant. This is also what we observe when analyzing stellar spectroscopy. It indeed looks very promising to say that a star spectrum follows the Planck curve perfectly but, in fact, this is not case.

Observing stellar spectra one can indeed recognize the shape of the Planck curve, but the true spectra is, especially for cooler stars such as red giant and red supergiant stars, crowded by absorption and emission lines at different frequencies. These lines exist as a consequence of the fact that these stars have atmospheres full of atoms and molecules of different kinds. As a consequence, the continuous curve of radiation faces different opacity depending on the frequency. This theory of light-matter interaction is what spectroscopy is all about and studying stellar spectroscopy, it is of great importance to understand what circumstances could appear in a stellar atmosphere, what the consequences may be and what we can learn and use from it.

Basic stellar spectroscopy

A stellar atmosphere is commonly interpreted as built up by several different layers with different properties. These layers may differ from different spectral classes, but the main structure for red (super)giant stars includes a photosphere, a chromosphere and a dust envelope followed by wind. This is the current model, which generally works well. These different layers have different properties, such as pressure and temperature and are thus composed differently. Going outwards, starting at the stellar surface, the hierarchy is photosphere, chromosphere, dust and wind.

The photosphere lies at an optical depth of approximately 2/3 and as will be proven later; this is where most of the light that one collects in a detector on Earth originates. It is thus of great importance to know what the conditions inside the photosphere looks like, what ions, atoms and molecules are present and to which extent. Using stellar spectroscopy, all information received from our observations is indirectly extracted from what the photons with photospheric origin have told us.

The following layer – the chromosphere – is a much less dense layer which in our Sun being only 10^{-4} times the density of the photosphere. Since the light we collect from the star originates within the photosphere, it implies that the chromosphere is more or less transparent for light with optical and IR wavelengths, which fits well with the low density. The temperature of the chromosphere varies with spatial distance from the inner boundary to the outer. The Sun's chromosphere has a temperature of approximately 6000 K at its inner boundary, and decreases as the distance increases outwards to a minimum of ~3800 K. Continuing outwards, the temperature gradient changes sign and the temperature drastically increases to extremely high temperatures, ~35 000 K in our Sun.

The next layer – the circumstellar dust envelope – is a region where the temperature has decreased and dust formation has started. This layer may be responsible for much or less extinction, depending on the properties of the dust envelope, and is usually the explanation when stars is observed with a high infrared light excess.

It is important to realize that these structures and numbers are not exact and may differ from different stellar classes. It is helpful however, to have this mental picture of atmospheric composition and hierarchy when pursuing reading this report.

As mentioned, light collected in our detectors originates from within the photosphere and at an optical depth of approximately $\tau = 2/3$. This fact, which will be explained later, implies that the structure of our spectrum will depend on the circumstances at these regions in space. The reason to why I have written regions and not region is because photons of different wavelength discover different opacities and will thus have an optical depth equal to 2/3 at different spatial regions. The value of optical depth τ is frequency dependent. The definition of the monochromatic optical depth at a geometrical location z_0 is:

$$\tau_\nu(z_0) = \int_\infty^{z_0} -\alpha_\nu \, dz = \int_{z_0}^\infty \alpha_\nu \, dz \quad (3)$$

where α_ν is the monochromatic linear extinction coefficient, having the observer's eye located at $z = \infty$.

For a frequency within the frequency range of a spectral line, the total optical depth is given by

$$d\tau_{\nu}^{tot} = -(\alpha_{\nu}^{c} + \alpha_{\nu}^{l})dz \ (4)$$

where α^c and α^l is the linear extinction coefficient for the continuum and the line, respectively.

Microscopic effects

The interplay between the atmospheric elements at the optical depth of 2/3, relates to the conditions of the atmospheric surroundings which, in turn, relates directly to both macroscopic and microscopic circumstances. A typical shape of either an absorption line or emission line is described by what is often called as the "line profile". The shape of a line profile is a result of different processes on a microscopic scale and most common processes that occur in all gases are the natural broadening, Doppler broadening, and pressure broadening.

The natural broadening process relates directly to one of the most fundamental principles in the quantum mechanical domain – the Heisenberg's uncertainty principle. This principle implies that the energy and frequency relation must obey the relation:

$$\Delta E \cdot \Delta t \geq \hbar \ (5)$$

This relation gives us that the time it takes for an atom or molecule to spontaneously emit a photon will have a directly implicate which energy, and thus what frequency, the emitted photon will have. This uncertainty in frequency is described by a Lorentz profile and plays a fundamental role in shapes of spectral lines, but is generally very small and negligible.

Doppler broadening relates to the Doppler – effect of which describes how waves appear different for different observers due to relative velocities of the source and observers. On a microscopic scale, the atoms and molecules of a gas may possess lots of different velocities and directions. These different thermal velocities will have different relative motions as to the observer and will, as in the example of an ambulance moving either away or towards the observer, according to the observer, appear either shifted to lower or higher frequencies. On a macroscopic scale, this effect can shift an entire spectrum, with lots of lines, to either lower frequencies (red-shifted) or higher frequencies (blue-shifted) depending on if the star moves away or towards the observer. However, on a microscopic scale, which is of interest in line profiling, the Doppler – effect affects how much the line will broaden from the line center as due to these relative motions. The effect is described by

$$\Delta\nu_D = \frac{\nu_0}{c}\sqrt{\frac{2k_BT}{m}}$$

Another spectroscopic broadening process is something called "collision broadening" or "pressure broadening". This broadening mechanism is related to the presence of other perturbing atoms, ions or molecules. These other neighboring elements may perturb the radiating atom or molecule due to Coulomb interaction, and thus affect the frequency of the radiation. The concept of how collision broadening affects a spectral line can be divided into two groups; impact approximation and quasi-static approximation.

The *impact approximation* is described by a Lorentz profile, just like in the case of natural broadening. This approximation relates to when the perturber comes by with high velocity and when the collisions can be assumed to be short and isolated. The time of impact should be considerably shorter than the time between two collisions. This approximation is valid when the main source of disruption is due to free electrons of high thermal speed. Even neutral atoms can work as perturbers since they are to some extent polarizable. Neutral hydrogen is the most important perturber of these polarizable neutral atoms in stellar atmospheres because of the electron's bad shielding of the proton. Disruptions caused by neutral hydrogen are also well described by the impact approximation even though their thermal motions are slower. This fact becomes nevertheless valid because the spatial extent of the interactions is short. The impact approximation at a frequency difference of $|\nu_0 - \nu|$ from line centre is valid when

$$|\nu_0 - \nu| < \frac{\bar{v}}{2\pi\rho}$$

Where, $\bar{v}$ is the relative velocity of the two particles of impact and ρ is the distance of closest approach.

On the other hand, if a gas or an atmospheric surrounding has few high speed perturbers, having the surrounding particles almost at rest, the *Quasi-static approximation* becomes valid. This approximation finds its applications when describing broadening by slow ions and the collisions can be regarded as an almost constant perturbation. The slow moving ions then define an electric field that perturbs the radiating atom or molecule.

Macroscopic effects

As we have seen above, microscopic effects affect the line profiles, in other words, the shape of a spectral line. Macroscopic effects on the other hand, affect entire spectral regions and the most common and well known macroscopic effects in stellar spectroscopy is what is known as blue and red shifts of stars. This again, has to do with the Doppler-effect, but now on the entire star's radial velocity relative the observer. If a star has a radial velocity towards the observer, the entire star's spectrum will be shifted to higher frequencies and have a bluer color. Analyzing stellar atmospheres and its environment, macroscopic effects such as non – local thermodynamic equilibriums is of interest since our models often suggests that the atmosphere behaves pleasantly and is in thermodynamic equilibrium. We do know however that star spots can make up a great part of a stellar surface and that each star spot can have a great temperature difference relative the effective temperature. Relating the temperature differences with the theory of black body radiation, one realizes that the intensity of emitted radiation will not be constant throughout the entire atmosphere and depending on the spatial region of a line's origin; the depth or peak of the line may certainly be affected.

Transport equation

Measuring radiation along a ray of monochromatic light, the mathematical expression of how the intensity varies by unit length follows the radiation transport equation, which goes as follows:

$$dI_\nu(s) = I_\nu(s+ds) - I_\nu(s) = j_\nu(s) - \alpha_\nu I_\nu(s)ds \ (6)$$

In this equation, a new variable is introduced which stands for the monochromatic emissivity, $j_\nu(s)$. This variable gives the value of how the medium adds "new" energy, in other words photons, into the beam of radiation, per unit volume, unit time, frequency bandwidth and per solid angle. The mathematical definition is:

$$j_\nu = \frac{dE_\nu}{dVdtd\nu d\Omega} \ (7)$$

Consequently, the intensity contribution to the beam from medium's emission is:

$$dI_\nu(s) = j_\nu ds$$

The extinction from a beam of light was explained above and the corresponding variable is denoted as α_ν and the loss of intensity for a beam that faces extinction per a geometric length of ds is:

$$dI_\nu(s) = -\alpha_\nu I_\nu(s)ds$$

From these two variables, the emissivity and extinction, one can derive a new, very useful function – the source function S_ν. The source function has the same unit as the intensity ($cm^{-2}s^{-1}Hz^{-1}ster^{-1}$) and the mathematical formulation of the source function is:

$$S_\nu = \frac{j_\nu}{\alpha_\nu} \ (8)$$

It should be noted that in the case of local thermodynamic equilibrium, the source function becomes equal to the Planck intensity.

Knowing this new function, equation (6) can be rewritten as

$$\frac{dI_\nu}{\alpha_\nu ds} = S_\nu - I_\nu \ (9)$$

or in a more formal way

$$cos\theta \frac{dI_\nu}{\alpha_\nu ds} = \mu \cdot \frac{dI_\nu}{d\tau_\nu} = S_\nu - I_\nu \ (10)$$

The cosine factor is necessary when the beam of light is not propagating parallel to the line of sight and the angle $0<|\theta|\leq\pi/2$. When θ goes to zero, equation (10) goes to equation (9) since cos 0 = 1. This equation is generally known as the *Transport equation*.

The formal solution to equation (10) has in fact two solutions, which come logical when realizing that depending on the sign of μ, the propagation of light can either be inwards or outwards. From axial symmetry, using the τ_ν-like integration variable t_ν, defined as:

$$t_\nu \equiv \int_{\infty}^{z} -\alpha_\nu \, dz \ (11)$$

the solution for the inward directed intensity becomes:

$$I_\nu^-(\tau_\nu, \mu) = -\int_0^{\tau_\nu} \frac{S_\nu(t_\nu) e^{\frac{-(t_\nu - \tau_\nu)}{\mu}}}{\mu} dt_\nu \ (12a)$$

and the outward directed intensity becomes:

$$I_\nu^+(\tau_\nu, \mu) = +\int_0^{\infty} \frac{S_\nu(t_\nu) e^{\frac{-(t_\nu - \tau_\nu)}{\mu}}}{\mu} dt_\nu \ (12b)$$

The transport equation and thus the solutions to the transport equation are the fundamental tool when modeling stellar atmospheres and is our key to understanding the processes of importance in stellar spectroscopy. These mathematical solutions are true to the extent of which we can manage to have good and trustworthy values of all involved variables. This is always the case when describing concepts of any sort with mathematical descriptions.

Eddington-Barbier

It was earlier mentioned that the light collected by the detectors on earth, has its origin at an optical depth of approximately 2/3. It was never explained why one could make this assumption but the reason comes from what is known as the *Eddington-Barbier approximation*. This approximation is a derivation based on the transport equation and the derivation goes as follows. From the outward directed solution to the transport equation, equation (12b), the emergent intensity at the stellar surface (τ_ν=0, μ>0) is:

$$I_\nu^+(\tau_\nu = 0, \mu) = \int_0^\infty \frac{S_\nu(t_\nu)e^{\frac{-t_\nu}{\mu}}}{\mu} dt_\nu$$

If substituting the source function as

$$S_\nu(\tau_\nu) = \sum_{n=0}^{\infty} a_n \tau_\nu^n = a_0 + a_1\tau_\nu + a_2{\tau_\nu}^2 + \ldots + a_n{\tau_\nu}^n \ (13)$$

and uses the Taylor expansion

$$\int_0^\infty x^n e^{-x} dx = n!$$

one receives, for the emergent intensity:

$$I_\nu^+(\tau_\nu = 0, \mu) = \int_0^\infty \frac{S_\nu(t_\nu)e^{\frac{-t_\nu}{\mu}}}{\mu} dt_\nu = a_0 + a_1\mu + 2a_2\mu^2 + \ldots + n!\, a_n\mu^n = \sum_{n=0}^{N} n!\, a_n\, \mu^n \ (14)$$

From this sum, by assuming that the intensity has more or less a linear dependence, neglecting the terms of higher order than two, we get the Eddington-Barbier approximation:

$$I_\nu^+(\tau_\nu = 0, \mu) \approx S_\nu(\tau_\nu = \mu) \ (15)$$

This approximation gets better the more linearly S_ν varies with τ_ν and equation (15) becomes exact when the dependence is indeed linear. One defines the emergent flux as

$$F_\nu(\tau_\nu) = F_\nu^+(\tau_\nu) - F_\nu^-(\tau_\nu) = 2\pi \int_0^1 \mu I_\nu d\mu - 2\pi \int_0^{-1} \mu I_\nu d\mu \ (16)$$

Since we are only interested in the flux corresponding to μ≥0, only F_ν^+ is of interest and we want to know at which optical depth the light originates, we solve the following integral, assuming a linear dependent source function:

$$F_\nu^+(0) = 2\pi \int_0^1 \mu I_\nu^+(0,\mu) d\mu \xleftrightarrow[\text{Assuming linear } S_\nu]{} 2\pi \int_0^1 \mu(a_0 + a_1\mu) d\mu = 2\pi \left[\frac{a_0}{2}\mu^2 + \frac{a_1}{3}\mu^3\right]_0^1 =$$

$$\pi\left(a_0 + \frac{2}{3}a_1\right) \xleftrightarrow[\text{equation (13)}]{} \pi\, S_\nu\left(\tau_\nu = \frac{2}{3}\right)$$

Theories of stellar atmospheres

Super giants include the most massive and largest stars in the universe and the stars of interest in this article, such as Betelgeuse (α Orion), Arcturus (α Boo), Aldebaran (α Taurus) and Herchel's Garnet star (μ Cephei) are either red giants or red super giants and indeed among the brightest celestial objects on the sky. Red (super)giant stars are stars suited for spectroscopic research due to the fact that their atmospheres include lots of atoms and molecules. The interplay between these atmospheric elements is of most importance when investigating spectra which has its origin from within a stellar atmosphere.

As of today, research of stellar atmospheres of cool red (super)giant stars with spectral class between K and M, deals with a severe problem. Water has been detected all around in (super)giant stars of spectral class K – M even though our theories tells us this should be impossible. At the beginning, when the first detections of water was observed, faulty explanations were made, suggesting low resolution evidence of water was actually misinterpret, motivating the spectra as due to the CN-red system. Since then, water has been detected countless times and there is absolutely no doubt that the presence of water in atmospheres of red (super)giant stars with spectral class K – M is a fact and has to be taken account of.

Since the first observations, detection of water has been found in both emission and absorption. Not only is it difficult to explain the presence of water molecules to such an extent as are detected in as hot stars as K-stars, it is certainly much harder to understand why some detection has been done in emission. This emission implies that it has its origin in the outer parts of the atmosphere, and modeling from this fact, a theory of large molecular spheres as a new atmospheric component of these red (super)giants was presented by T.Tsuji et al. in 1997.The molecular sphere gave promising explanations to a number of stars, but the fact that the model was based on spectra of low resolution was later going to be a big setback for the prospect of having a molecular sphere as a general phenomenon to explain the detected water and its behavior.

The low resolution spectra could not manage to resolve individual spectral lines, so what was observed was a resulting curve from overlapping lines. These low resolution spectra were mainly done by the ISO SWS in the 6 μm band. As the technology has improved, other observations capable of resolving individual lines has been done for e.g. the 12μm band and these observations detected strong water absorption lines instead of emission lines, which was expected from the molecular sphere model. This was the big setback, since the promising model completely failed to explain the 12μm band for several stars.

Further work on the model of a molecular sphere should however indeed be encouraged since the model can explain certain stars well, such as μ Cephei. Furthermore, other interferometric observations has revealed many masering water clouds around VY Cma and S Per, indicating that there might be something more to the model to be found.

The presence of water, and indeed the strength of the absorption lines for the 12 μm band, can also be explained by correcting and making small changes in e.g. the temperature on the classical model photospheres. These corrections may indeed allow synthetic spectra to fit the observations but to motivate the corrections is more difficult.

This is where we are at the moment, with these two bases of starting point for which the research build upon, with a common goal – to find the correct model and atmospheric structure that hopefully could be considered to be a general feature for these red (super)giants between stellar class K-M. It may indeed be that the answer lies somewhere in between the two presented explanations, or there could be some important fact or property that has still to be found. A good way to continue the pursue of the correct answer is to get a deeper understanding of both bases of research and their arguments and motivate; what speaks for a novel picture of a stellar atmosphere, involving a molecular sphere or what does not, as well as what speaks for and against small corrections of the already present model atmospheres. In this report, both bases will be investigated, starting with the MOLsphere model, with the goal to better understand what the two can tell us.

Molecular sphere: the MOLsphere model

The large molecular cloud, suggested by Tsuji for the red supergiant star μ Cephei (Tsuji 2003), generated a satisfactory explanation for the received spectrum and gave us a new picture of the atmospheric structure. This suggestion may be right, and a few observations for other red (super)giant stars point in the MOLsphere direction, but whether or not a MOLsphere is a general phenomenon is definitely not something we can draw any confident conclusions about. To motivate if MOLspheres are common features of the atmospheres of red (super)giant stars, one must know how the MOLsphere model looks like and what features it has, and compare this to empirical data.

The MOLsphere created to fit the observed data of water vapor in μ Cephei, was essential when explaining the fact that water was observed in absorption at $\lambda < 5$ µm and in emission at $\lambda \geq 5$ µm. In order to start the modeling, Tsuji upgraded a single slab model to a spherically extended molecular sphere, which he called a MOLsphere (Tsuji 2003). The fact that water was detected in emission implied that the water found, should have originated from the outer part of the atmosphere. This suggestion relies on the physical fact that the flux curve created at the scenery of where water molecule emission takes place, must be greater than the flux curve of the continuum. Since the T_{ex} and the N_{col} already was known to be $T_{ex} \approx 1500$K and $N_{col} \approx 3 \cdot 10^{20}$ cm^{-2} from the Stratoscope II data (Tsuji 2000a), the additionally free parameter to use in order to raise the value of the flux became the radius of the MOLsphere. For simplicity, H_2O was only considered with absorption cross-section as large as 10^{-18} cm^2 and thus, the modeled H_2O gas was optically thick.

When having the transfer equation solved for the photospheric radiation, required absorption lines of molecules as e.g. CN, OH, SiO etc, was found. When adding the emergent flux calculated from a MOLsphere with an inner radius of 2 stellar radii, the observed emission lines at $\lambda \geq 5$ µm where in fact theoretically found, as well as the absorptions bands at λ 5 < µm (Tsuji 2000b).

However, there was a huge excess of infrared light that needed an explanation and to solve that problem it was explained as due to an optically thin dust envelope with $\tau_{10\mu m} \approx 0.1$ and $r_i \approx 13.5$ stellar radiuses. This flux contribution due to the optically thin dust envelope was also added to the total flux and the resulting flux, and thus the entire modeled spectra of μ Cephei, was considered to be a reasonably good fit with the observed data recorded by the ISO SWS.

Using this model, one has to rethink the hierarchy of the considered stellar atmospheres. We are used to believe the atmosphere to consist of mainly three components, starting with the photospheres closest to the star and then the chromosphere followed by wind. However, with the novel picture Tsuji presents, the new molecular cloud should step in as a component between the chromospheres and the wind. Using sensitive infrared survey with the ISO (ISOGAL), it was revealed that efficient dust formation already starts in K giant stars with weak mass-loss rates (Omont et al. 1999). Tsuji draws a certainly fascinating relation about this fact and a possible MOLsphere, saying that an interesting possibility is that the outer part of the MOLsphere is cool enough for dust to form (Tsuji 2001). According to this ideal connection, it could give an explanation to why dust formation starts in the red giant stage prior to the phase of the asymptotic giant branch and also to the onset of the wind as due to the dust being pushed outward by the radiation pressure.

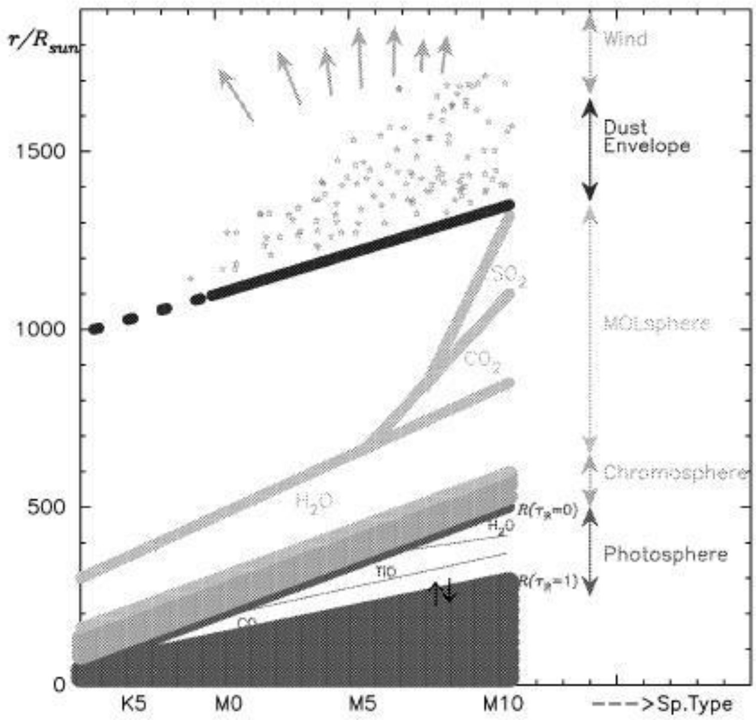


Fig 2) Hypothetic picture on the atmospheric evolution for red giant stars (Tsuji 2003).

As mentioned, other observations has been done showing features that could be interpret to have connection with a possible MOLsphere. The Very long baseline interferometry founding of many mastering water clouds around red supergiants such as M3-M5 VY CMa (Imai et al. 1997) and S Per (Richards et al. 1999) together with the revelation of a new component of Betelgeuse does certainly point in the MOLsphere direction.

Even though this sounds revolutionary and great in many ways, there are numerous of newly presented data that proves this hypothesis wrong, and more competing data emerge as instruments gets better and better in the sense of resolution, sensitivity and wave length coverage. These new observations are done mainly by higher resolution spectroscopy than the ones that the MOLsphere model relies on. More about this alternative picture is presented in Ryde et al. 2002 and 2006ab and will be discussed later in this report.

As of today, the spectroscopic data obtained by new instruments are of such good quality that many of the lines that, in the past, were irresolvable, now are and these lines of e.g. water vapor are not in good match with the MOLsphere model, as we will see.

Classical model photosphere

Running classical model photospheres for different stellar properties, such as surface gravity and effective temperature, one can extract important facts and knowledge about the characteristics and behaviors of stellar atmospheres for certain stellar classes. Such properties can for example be the interplay between the different atmospherically bound atoms and molecules. Spectroscopic observations have been an important tool when analyzing the interplay between atoms and molecules in a stellar atmosphere for many years. However, these kinds of observations, and more importantly – the interpretation of the data extracted from the observations – depend deeply on how our theoretical models are built up and how reliable they are.

The micro- or macroscopic circumstances in a stellar atmosphere, along with other theoretical assumptions, are made up from experimental and theoretical work of observations made on earth. These theories are nonetheless extremely well tested and the newly found contradictions to our classical theories of stellar atmospheres of red (super)giant stars are certainly not questioning these well known and tested theories. We then rule out the possibility of some mysterious kind of answers to why the water lines have revealed themselves and to why there has to be more water vapor in atmospheres that are hotter than previously was thought possible.

We are left to answer the question to why we until now have used an incomplete picture and theory of stellar atmospheres, and photospheres. One way to answer this has been presented using the MOLsphere proposal, where one suggests that we have been more or less right in our picture of the stellar atmosphere, apart from the new component – a molecular sphere. Another way to find the correct answer is to really dig into the classical models and investigate what they in fact tells us with a prospect to rule out what are unlikely to be wrong or on the contrary; find possible defects.

In the investigation being done, classical MARCS models of stellar photospheres were run in order to receive information about how the molecular abundances relates to different parameters. Using different values for parameters such as surface gravity and effective temperature in the MARC models, molecular abundances are calculated and presented in columns with corresponding columns of optical depth for the wavelengths of interest. By comparing the behavior of these different parameters, interesting associations may be found and could give us a hint of what may or may not be right with the classical models.

First relation of examination to discuss, namely how the molecular pressure of H_2O and the most important molecules that relates to H_2O, at $\tau = 1$, relates to surface temperature and how these curves change with different values of the surface gravity, is of big interest. Again, the reason to why τ was chosen to be equal to 1, which is approximately equal to 2/3, comes from the Eddington-Barbier, which mathematically tells us that the photons that manage to travel through the atmosphere and later collapses in our detectors has their origin within the spatial region where the optical depth is equal to 2/3.

The results of this examination are show in fig 3 a, b and c and one can see that, on a logarithmic scale, the relative water pressure relates linearly to the effective temperature, while the other molecules CO, OH, CH and CN has a more changing behavior when varying T_{eff}. As expected, the amount of water increases with lower temperature and decreases when the temperature increases. One can also see that when the surface gravity increases, the relative water pressure curve does not have an important change in behavior more than it shifts upwards allowing a higher concentration (in the order of 10) for same effective temperature

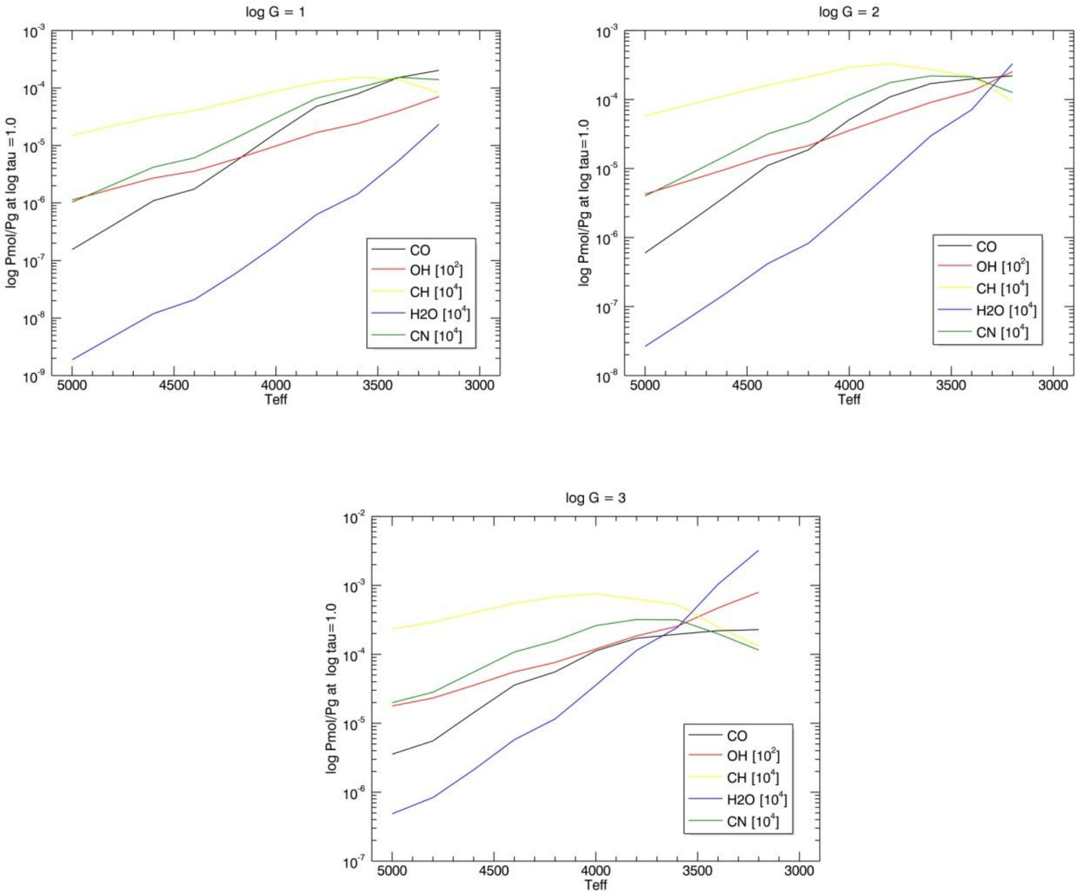
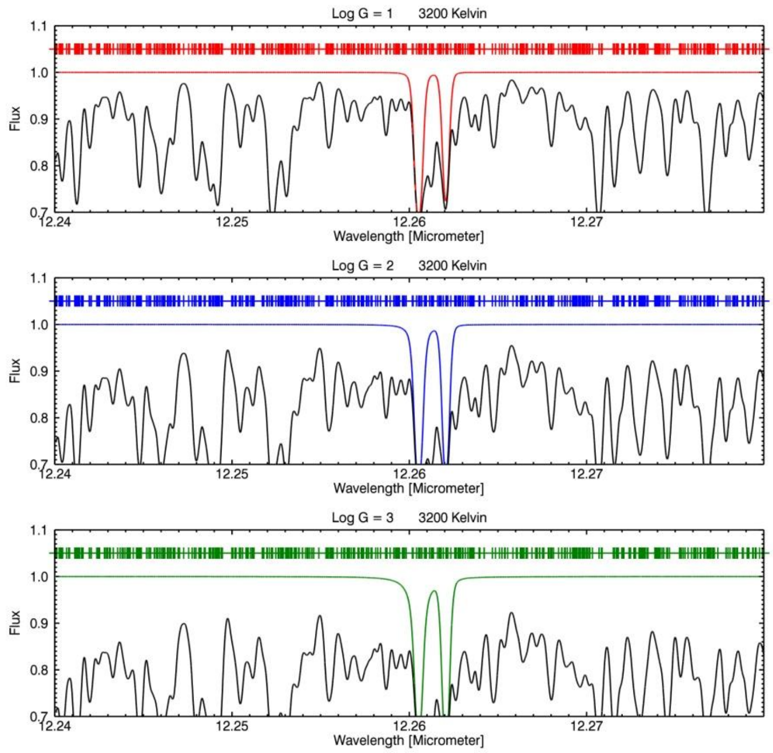
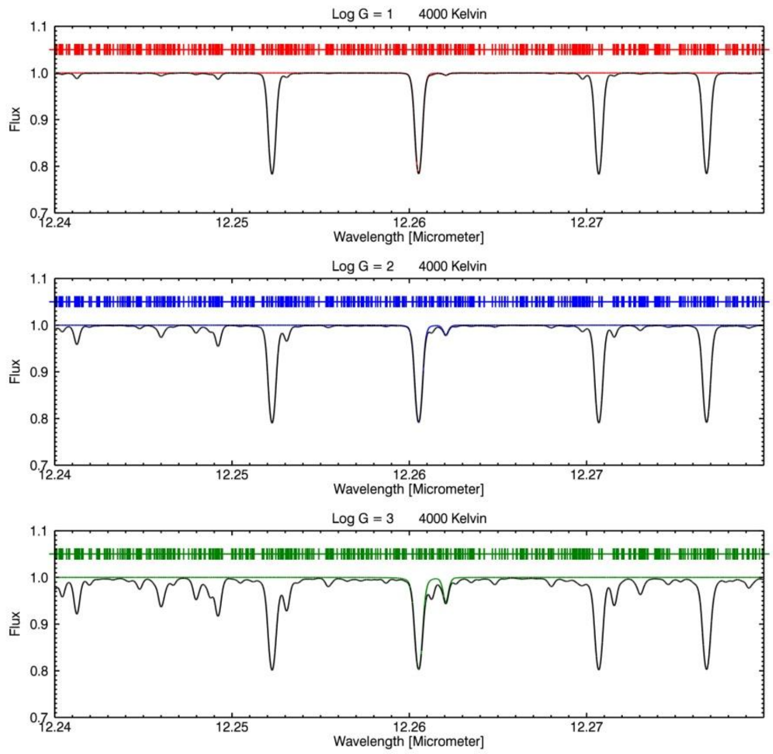


Fig 3a,b,c) These three plots describes how the relative molecular gas pressure within a stellar atmosphere behaves with respect to effective temperature. What separates the three plots is the logarithmic value of surface gravity, whichin fig a, b and c corresponds to 1,2 and 3, respectively.

Synthetic spectra of how the water lines, together with OH-lines, in the band around 12.26 µm can be found in fig 4: a-d. As one can see, there are plenty of lines and the spectrum is very crowded for lower temperatures. Every line is found in absorption and holding the temperature fixed, one sees that the higher surface gravity, the stronger are the lines. This relates directly to what was found in fig.3: a, b and c where the relative water pressure increased when lowering the temperature, and hence more absorption occurs. One should notice that at the lower temperatures, the absorption lines are that many and that strong that they overlap to such an extent that the continuum is completely gone within the presented wavelength interval. When increasing the temperature, the lines start to decrease and the overlaps consequently decrease and this result in that the continuum slowly reveals itself. When raising T_{eff}, the water lines decreases sooner and faster than the OH line, which also follows from fig 3 a – c where one can see that the change in concentration of water has a derivative of higher order than the OH concentration.

Raising the temperature, suddenly one reaches the point of where even the strongest H_2O-line disappears. Since the concentration of water molecules depends on the surface gravity, so does the point of where the last H_2O-line disappears. Looking at the spectrum for log g = 1, the last H_2O-line disappears at an effective temperature of 4000 Kelvin. As for the log g = 2 and 3, the critical point lies at T_{eff} = 4200 and T_{eff} = 4400, respectively. This fact that the synthetic spectra have these three critical temperature values is precisely the reason to why one have started to questioning the classical model atmospheres and photospheres since observations show lines for temperatures exceeding these critical values.




Log G = 1 4000 Kelvin
Log G = 2 4000 Kelvin
Log G = 3 4000 Kelvin
Flux
Wavelength [Micrometer]
1.1
1.0
0.9
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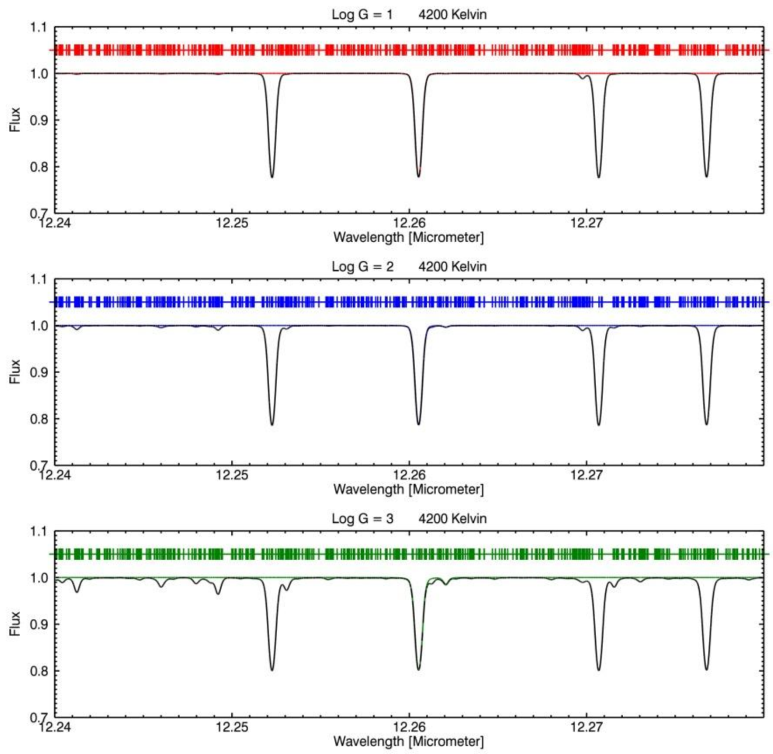
12.25
12.26
12.27


Log G = 1 4200 Kelvin
Log G = 2 4200 Kelvin
Log G = 3 4200 Kelvin
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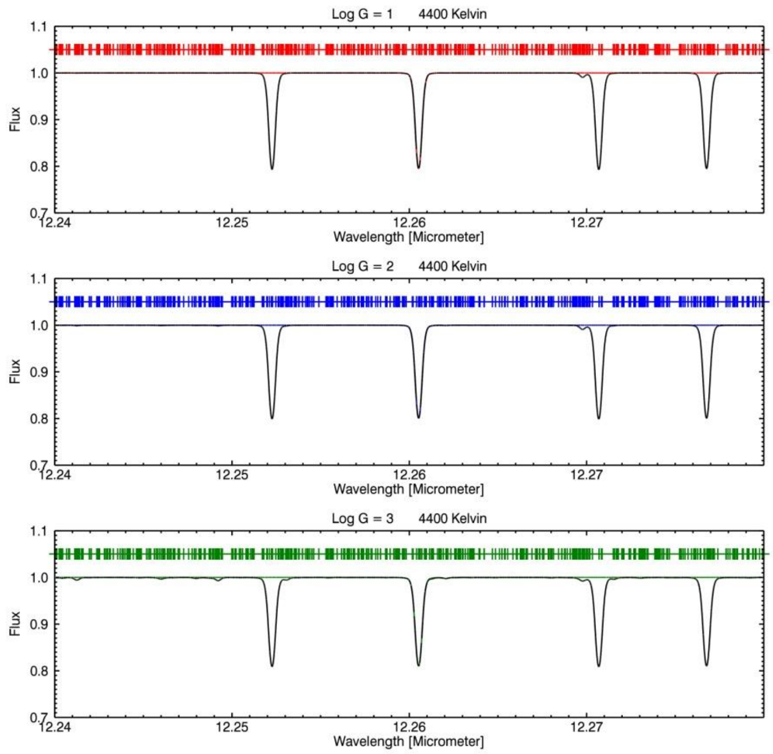
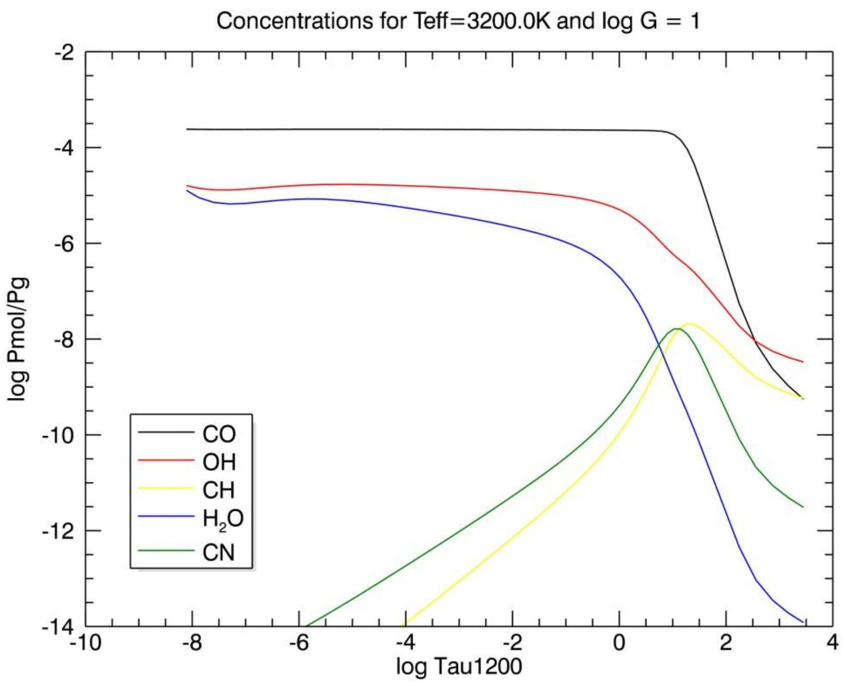


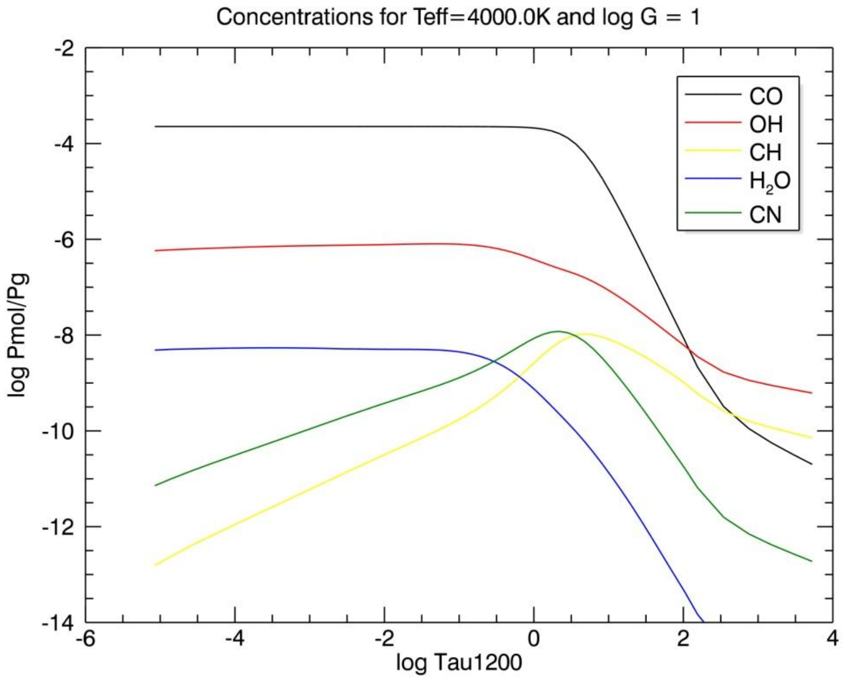
Fig 4 a-d) In these figures one can see how the water lines behaves according to effective temperature and surface gravity. It is clear that the water molecules dissolve when raising the effective temperature but one can see that atmospheres of stars with higher effective temperature manage to keep the lines better. The vertical lines indicate where the water lines are located. The strongest four lines that are presented relates to OH – molecules.

These spectra are theoretically calculated and the lines shown are analytical curves of what we are expecting from our observations. However, real observations and detections being done by spectrometers do not show any analytical curves but discrete data points of detections, of which our theoretically built analytical curve has the prospect of fitting as good as possible. It is of great importance that, when to interpret the data, one is aware and respects the quality of the observation being done, in other words; considers the resolution. Until recently, many of the mid infrared observations have been done in lower resolution and do accordingly not show these individual lines but a spectrum that will be theoretically compared with a resulting curve of all the lines within. Due to this fact, much information gets lost within this resulting curve and the interpretation may only be considered as a good educational guess. Although, as mentioned, higher resolution spectroscopic observations have been done, even for the red supergiant star μ Cephei (Ryde et al. 2006), which was the main argument against the vnewly introduced MOLsphere. According to the work being done, building up a molecular sphere to fit the lower resolution spectrum of μ Cephei, the water lines were expected to show up in emission in the 12 µm band, as for the 6 µm. Ryde et al. did not detect any water emission in the 12 µm band but the water lines was instead found in distinct absorption, even stronger absorption lines than calculated from a standard, spherically symmetric model photosphere, without any surrounding layers. This contradiction to the predicted spectrum from the, at low resolution convincing, MOLsphere –model, shows the importance of developing superior detection techniques.

Further, since the photons detected by our instruments, and more precisely in our case the photons with a wave length of approximately 12 µm, are sent out at $\tau_{12\mu m} = 1$, it is of interest to know how the relative molecular pressure change with optical depth for photons in the wave length interval of 12 µm, according to classical models. As can be seen in fig 5 a-d the curve representing the concentration of water meets a narrow, critical interval where the concentration drastically decreases. This critical interval where the concentration suddenly starts to decrease is close to $\tau_{12\mu m} = 1$, not only for certain effective temperature and surface gravity but for all $3200K \leq T_{eff} \leq 5000K$ and log g = 1, 2 and 3. Interestingly, they entire shape of the water concentration curve looks more or less the same for all values of the parameters of T_{eff} and log g. The main difference is a shift in positive direction of the y-direction for lower effective temperature or higher surface gravity. How the shift in concentration for different parameters behaves is presented in fig 6. Together with the curve of water concentration, CO and OH can be seen to display similar behavior and faces a critical value for the optical depth where the molecules dissolves at about the same depth. Related to this interval of dissolve, lies an interval of increasing rate of creation for molecules such as CN and CH. A complete picture of how the classical model predicts the creation and dissolve of the atmospheric atoms and molecules are presented in fig 7.

Looking at fig 5 a-d, one can see that at optical depths lower than ≈1, the H_2O – concentration holds an almost constant value. In the high resolution spectroscopic observation of µ – Cephei (Ryde et al. 2006), the presented solution to explain the behavior of the strong water absorption in the 12 µm bands was a cool model photosphere, representing cool outer layers, gave a good fit with the observational data. This could be a hint of how a possible correction of the classical model photospheres shall be made. However, this explanation failed in reproducing the observed lines in emission at 6 µm.




Concentrations for Teff=4000.0K and log G = 1
log Pmol/Pg
log Tau1200
CO
OH
CH
H2O
CN
-2
-4
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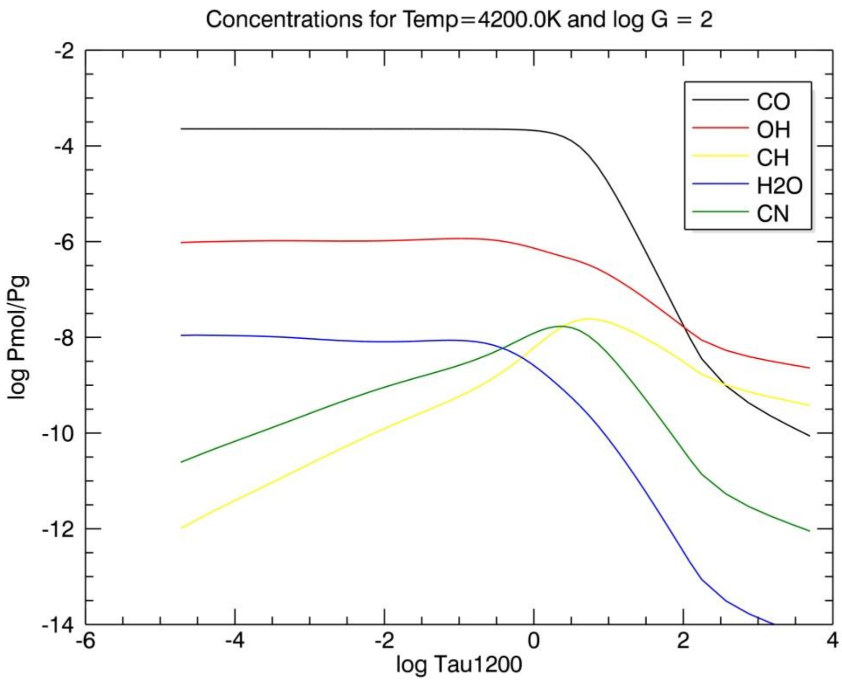
-4
-2
0
2
4


Concentrations for Temp=4200.0K and log G = 2
log Pmol/Pg
log Tau1200
CO
OH
CH
H2O
CN
-2
-4
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-2
0
2
4

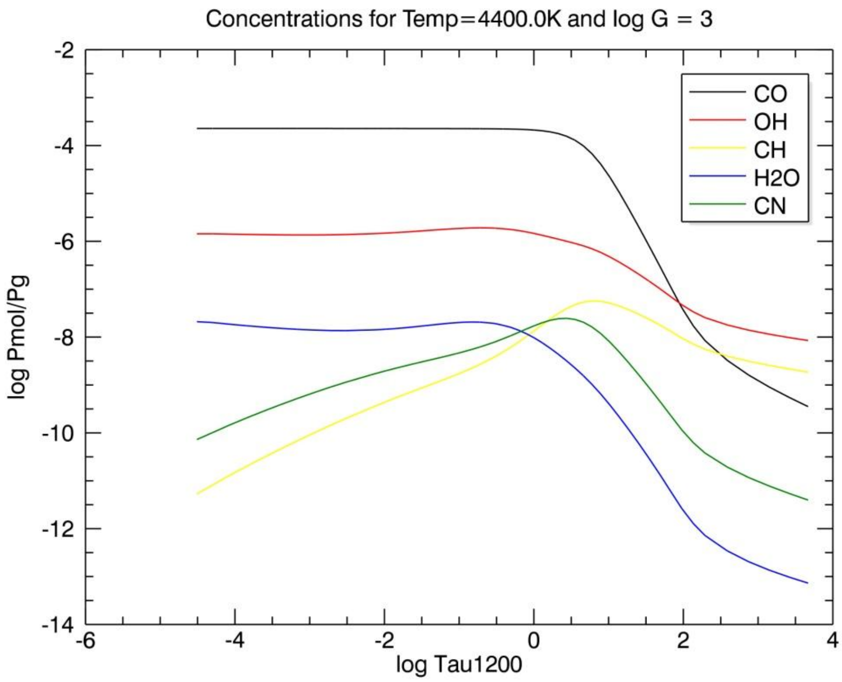

Fig5 a-d) In the plot a-d, relative gas pressure of the five most interesting molecules is presented as functions of $\log \tau_{1200}$. One can see that the shape of the water molecule pressure keeps more or less constant with temperature and surface gravity and is only shifted in the y-direction. Furthermore, for $\log \tau_{1200} > 0$ the relative gas pressure is almost constant. (The optical depth, τ, has in these plots the unfortunate denotation of 1200 but should be interpret as of 12 µm.)

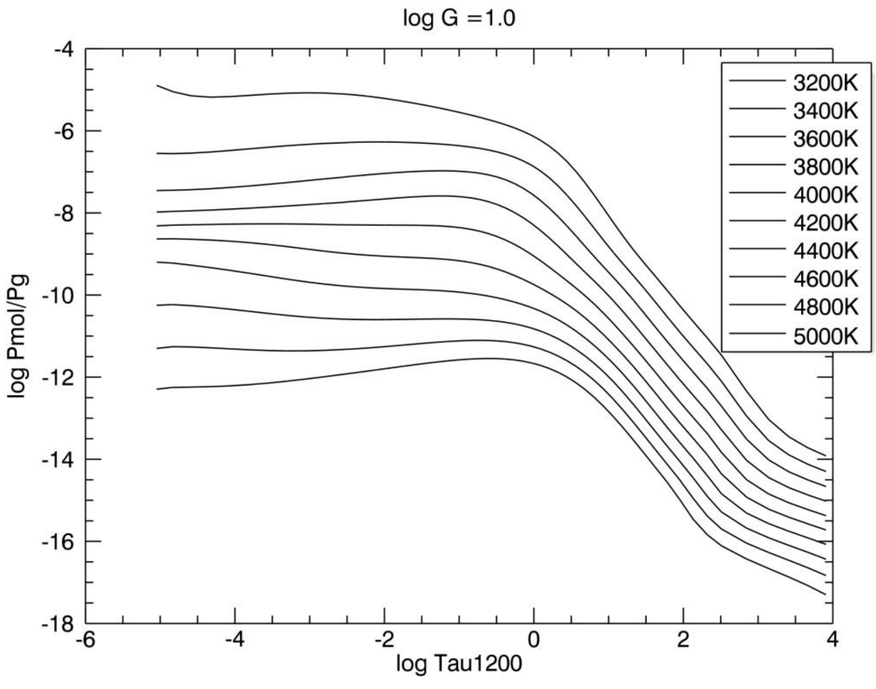

Fig 6) This is a collected plot of the plots in fig 5 but with all water curves corresponding to temperatures 3200-5000K in the same figure. Here it is even more obvious that not must happens with the shape of the curves

representing the relative gas pressure of water when raising the temperature. First curv, representing the highest relative gas pressure corresponds to 3200K and the curve of lowest relative gas pressure corresponds to 5000K.

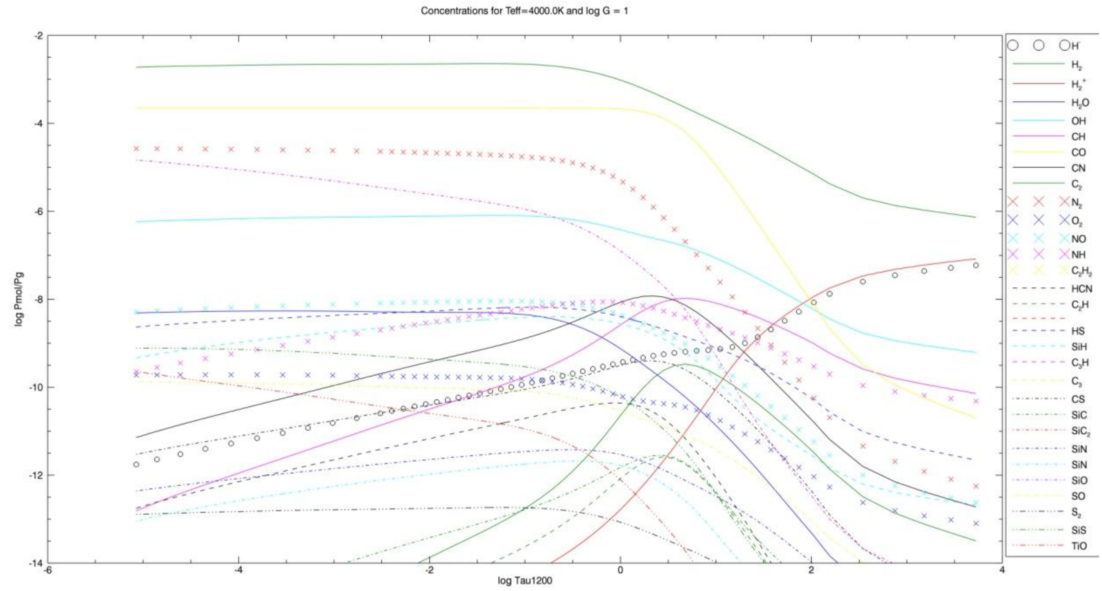

Fig 7) Here is every atmospheric element's behavior, according to the MARCS-models, presented.

Discussion

When running the synthetic spectra we observed how the lines had different critical values where they disappear for different values of the surface gravity. This fact only is not too fascinating since this fits well with our predictions; a stronger gravitational effects can manage to control a gas of higher temperature. Although, what has to be taken into account is that these three critical values are calculated from theoretical predictions. What will affect the corresponding lines and thus the critical values of where the weakest lines are detectable in a real observation is the fact that a real observation is always contaminated with noise and signal distortion. Other factors may indeed also affect the observation, resulting in a lower detected signal than what is actually sent out from the atmosphere. All these possible factors, and most importantly the noise contamination, will affect the critical value of where the lines disappear and thus are undetectable to an even lower value for the temperature. It is important to analyze every factor before an observation but looking only at what the model tells us, we have these three presented critical values of an effective temperature of 4000K, 4200K and 4400K for log g = 1, 2, 3, respectively.

Furthermore, looking at the line's behavior at lower temperatures, one notices that the lower the effective temperature gets, more and more will the lines overlap and the spectra will be crowded of overlapped lines and a completely hidden continuum-line. This will also affect how useful a recorded spectrum will be to analyze and one starts to understand that there might be a lower limit of where the effective temperature become too low to be useful. Obviously, this lower limit will, due to the same principle as to the upper limit, also depend on surface gravity. Considering these two limits, one can draw the conclusion that there indeed exist certain stars that fits better than other when testing classical MARC-model photospheres, depending on their effective temperature and surface gravity.

The grayed rhombus in fig 8 below corresponds to the area of stars that are well suited for testing the MARC-models. Again, this rhombus of stars are found when not including any kind of noise or other negative effects, and if one would include this, the shape of the rhombus would correspond to a narrower interval of effective temperatures and thus become thinner in size.

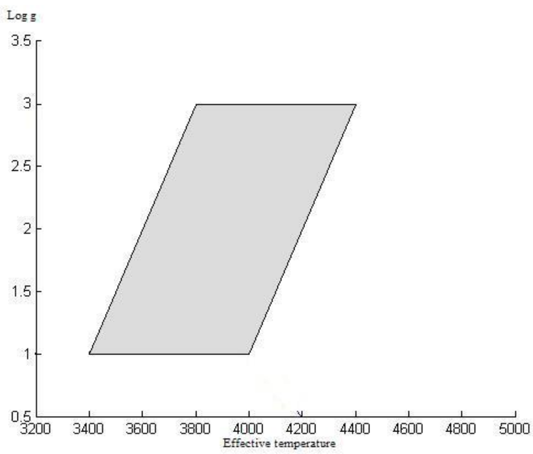

Fig 8) When empirically testing the MARC-model atmosphere, one needs to know which stars are suitable or not for observation. Within the grayed area lie the values of the surface gravity and effective temperate that such suitable stars should possess, when not considering a non-contaminated sample.

Considering fig 3, one noticed that the relative gas pressure of water vapor was, on a logarithmic scale, linearly dependent on the effective temperature. There was in other words, nothing drastic that occurred within some certain temperature interval, and the relative gas pressure behaves according to the MARC-models nice and easy. This is of course not what has been observed, since strong absorption lines of water have been confirmed in as hot as early K stars. These hot K stars can have an effective temperature of up to 5000K, of which in the synthetic spectra of the MARC-models show absolutiely no water lines, not even in theoretically perfect circumstances. It is certain that the atmospheric particle concentrations must be changed, the question is how and why.

In Ryde et al. 2006, they managed to reproduce the spectrum and Planck curve obtained from µ Cephei in the 12 µm region with good precision by changing the effective temperature by some 100 K. This could be dangerous if there indeed would have shown a drastic increase or decrease in the relative gas pressure within some interval of the effective temperature, but since the curves in fig 3 behaves as pleasing as they do, this small correction should not be too drastic of an explanation.

In the MOLsphere scenario, which has a drastic increase in water concentration at a distance, for the case of µ Cephei, of 2 stellar radii, the new molecular envelope is simply added to this classical photosphere. As mentioned, it works reasonably well for low resolution spectra in the 6 µm region but when analyzing observations made in higher resolution in the 12 µm region, this concept of a molecular envelope struggles with great contradictions. This contradiction relies on the fact that if there indeed is water observed in emission in the 6µm region, it immediately implies that the lines in the 12 µm region too must be in emission. Since the data of the 12 µm region are recorded of such high quality, showing distinct absorption, it is much more motivated to question the interpretation of the 6 µm detections. The reason to why the 12 µm detection disproves a possible MOLsphere scenario relies on Planck's theory of black body radiation, as explained below and described in Ryde et al 2006.

Consider the intensity distribution curve of a star corresponding to its effective temperature, it will, as explained in the theory section, behave similar to a Planck curve of a black bode with same temperature. As the theory tells us, the intensity will have a peak of maximum intensity for a certain wavelength and then have a intensity decrease as for the longer wavelength. Following the created photons of~ 6µm from their region of birth, on their path of propagation through the atmosphere, they will most probable face some matter particle and become extinct. However, not only will the atmospheric matter work as photon annihilators; it will create and radiate new photons and the net flow of photons relates to the source function. One can often assume that the source function for a certain region works as the corresponding Planck curve for the regional temperature. Therefore, whether the net flow of photons is positive or negative, in other words whether the absorption is less or greater than the emission, depends on if the source function is greater than the intensity of the inner radiation.

Adding a MOLsphere on a classical model photosphere, which corresponds to a certain temperature, will have a characteristic intensity distribution according to its Planck curve. Since the temperature is cool compared to the rest of the star, the peak will be shifted to lower wavelength than the curve-peak of the star, and the MOLsphere curve must thus, in order to explain the emission at the 6 µm region, lie above the corresponding 6µm intensity of the star. This immediately implies that it also lies above the star's curve at longer wave lengths thus also at 12 µm. However, what we measure is not the intensity itself but the received flux. The above discussion is although still relevant because the flux is directly related to the intensity, according to

$$F = \int I \cos\theta \, d\Omega$$

The only difference is that the intensity is simply integrated over the area of the object so consequently, if the intensity from the MOLsphere is greater than from inside, it still implies that the flux at 12 µm must be greater than radiated from inside, and should therefore show up in emission. This fact, based on simple but fundamental physics is what should rule out the possibility of a MOLsphere for many stars. This suggests that the MOLsphere model, if it is a real component for certain stars should not be some general phenomenon.

Furthermore, as fig 5 shows, the relative gas pressure as a function of τ_{12000} shows a drastic decrease within the interval of approximately $0.1 \leq \tau_{12000} \leq 2$.For $\tau_{12000} < 0.1$, the gas pressure keeps a more or less constant value for certain effective temperature and log g and changing input value of either effective temperature or log g will not have any significant effect on the gas pressure's curve structure more than just shifting it in y-direction, as shown in fig 6. The fact that $\tau_{12000} < 0.1$ more or less keeps a constant value is interesting since a change in temperature for a certain value of τ_{12000}, which could be due to non-local thermodynamic equilibrium, would indeed change the curve to a more non-constant value and could have interesting effects on a spectrum.

Conclusions

At this present time, a scenario of a new, general atmospheric component in red (super)giant stars of spectral class K-M, referred to as a MOLsphere, which was originally created to explain the recently found behavior of water in atmospheres of stars within the spectral class range of K-M , is rather unlikely. This conclusion is based on the presentation of high resolution data from observations detecting distinct and strong absorptions lines of water vapor in the region of 12 µm, when the MOLsphere predicts the lines to be, not only weaker but in emission.

The MOLsphere model should however not be disregarded since it still manages to explain low resolution spectra for certain stars with certain accuracy. Not only does it fit well with low resolution spectrum for e.g. µ Cephei, it has also being indications coming from interferometry that there exist many masering water clouds around red supergiant stars such as VY Cma and S Per. The very long array has also revealed the presence of some new unknown component over the classical chromosphere.

However, the observed spectra in the 12 µm have been reproduced with desirable accuracy by changing the effective temperature. The relative gas pressures expected by the MARC-models, shows that there is no drastic change in the gas pressure when changing effective temperature and this is certainly motivates this way of reproducing the 12 µm spectra.

Furthermore, before experimentally testing the predictions of the MARC-models, one should indeed calculate the corresponding rhombus to fig 8 of which stars may be suitable for observation when noise has been included, as well as when the degree of overlap for the specific observation becomes too much and ruins the spectrum. When planning an observation of this kind, there is no room for chances, and one should therefore consider a temperature interval for certain surface gravities carefully. The conclusion from this is therefore that the presented grayed rhombus in fig 8 is only an ideal rhombus predicted from theoretically perfect circumstances and should only be considered as a boundary of which cannot be exceeded.

It is of great importance to continue the research of how the atmospheres of K-M stars actually behave since there is absolutely no doubt that the present models are lacking. It is also a positive fact that the theoretical research are based on more than one idea since it helps every research team to be stay open minded and not get too assure of their own view. Despite the fact that the MOLsphere scenario has started to face great resistance, one cannot argue with the newly found masering water clouds on the above presented stars, and even though the right answer may not be the MOLspheres presented so far, the origin of these masering clouds could be found continuing the MOLsphere research.

The other base of research, regarding an explanation based on smaller changes in our classical models, is from above presented arguments indeed motivated since it has presented good explanations. Further arguments to the importance to continue the research is of course to find the missing pieces and form a new theory that could be considered as a general answer to the atmospheric problems of K-M red (super)giant stars.

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Fig 1: *http://upload.wikimedia.org/wikipedia/commons/1/19/Black_body.svg*