The Abundance of Elements in Cool Stars, as Determined from High-Resolution, 1-5 µm Spectroscopy

N. Ryde, B. Gustafsson, K. Eriksson, and R. Wahlin

Department of Astronomy and Space Physics, Uppsala University, Sweden

Abstract. We review the field of abundance determinations of elements in cool stars, with special interest paid to determinations based on analyses of high-resolution, 1 – 5 µm spectra. We discuss the current status, problems, and challenges of exploring high-resolution, near-infrared spectra. In particular, advantages and drawbacks are pointed out. A few examples of current, chemical-abundance determinations are highlighted and, finally, we discuss the development and future prospects of the field.

1 Introduction

When P. Connes in the years 1966-67 constructed and set up his prototype Fourier Transform Spectrometer (FTS) for infrared studies at Observatory de Hautes Provence, his main objective was not to study stars. In his review on "Astronomical Fourier Spectroscopy" [6] he writes "The spectra of a few bright stars were also recorded on a spare-time basis." Most of the observing time was instead devoted to planetary studies. The stellar spectra obtained were described by Spinrad et al. [43]. Among the results described is a first determination of the isotopic ratio $^{12}$C/$^{13}$C for Betelgeuse. Later Maillard [29] obtained the isotopic ratios $^{12}$C/$^{13}$C, $^{16}$O/$^{17}$O and $^{16}$O/$^{18}$O for Alpha Her from infrared CO lines with a new FTS at Observatoire de Hautes Provence, and in collaboration with Flaud and Camy-Peret [9], he made the first estimate of the H$_2$O abundance in R Cas. In a report on the status of infrared FTS spectroscopy, Maillard [30] presented a table of all astronomical FTS:s in Europe and USA at that time, and the astronomical objects observed. It is interesting, but not unexpected, that the favorite stellar sources were bright infrared sources like M stars, carbon stars, miras, with very complex molecular spectra. This work also stimulated work in molecular spectroscopy in order to interpret the wealth of data further. Also with the Fourier-transform spectrometers used at McDonald Observatory and Kitt Peak National Observatory (KPNO), early studies were devoted to isotopic ratios, notably of carbon and oxygen isotopes [3,8,21]. Another area of intense study of stars was the exploration of the dynamics of mira atmospheres by Hinkle and collaborators. An early attempt to derive abundances of elements (C, N, and O) by high-resolution, infrared spectroscopy was made for Betelgeuse by Lambert et al. [26] in 1984, soon followed by the determination of C, N, and O abundances and $^{12}$C/$^{13}$C ratios for 30 Galactic carbon stars by Lambert et al. [27] in 1986. By then, high-resolution spectroscopy in the infrared and the analysis of the
spectra produced had matured to become central tools for studying cool-star atmospheres, and not least for measuring chemical abundances. (For a more detailed account, see, for example, Gustafsson [12].) A great step forward was next taken with the development of cryogenic echelle spectrometers such as the Phoenix spectrometer at KPNO and later at Gemini Observatory, which made it possible to reach much fainter stars [34].

The art of determining chemical abundances in cool stars thus benefits strongly from the realization of sensitive spectrographs capable of providing high-resolution, near-infrared spectra, such as the Phoenix and the CRIRES spectrographs. In this review we will examine why abundances of elements in cool stars are of interest, why we need high-resolution spectroscopy, and discuss the advantages and drawbacks of high-resolution, 1-5 \( \mu \)m spectroscopy. The status of model atmospheres needed in the analyses based on spectral synthesis will also be reviewed briefly. By cool stars we mean K and M dwarfs, and M, C, and S giants, i.e. red giants including AGB stars. By high-resolution spectra, we will denote spectra dispersed by a resolving power, \( R \), greater than 50,000.

2 Why do we need chemical abundances in cool stars?

Accurate abundances\(^1\) of atoms, their isotopes, and molecules in cool-star atmospheres are necessary for the understanding of the stars themselves, the interpretation of their spectra in terms of fundamental stellar parameters, the exploration of their interior nuclear reactions and mixing processes, and of the structure of their outer layers and the driving mechanisms of their winds. Also, accurate abundance patterns in cool stars are required for the understanding of late stellar evolution. In order to put constraints on evolutionary models, the details of, for example, the processes taking place during the transition phases from the Asymptotic Giant Branch (AGB) to the Planetary Nebula phases as reflected in changing surface abundances, can and should be investigated observationally. Also, stellar evolution for different initial conditions can be probed by measuring chemical abundances.

Furthermore, theoretically calculated yields of elements in different evolutionary phases of stars are needed in Galactic evolution models, but are, in several cases, still very uncertain. Direct measurements of yields in these phases, such as the AGB phase and the Planetary Nebulae phase, are therefore essential (cf. [13]). The AGB stars are thought to be the main contributors of the s-elements (e.g. Sr, Y, Tc, Ce, and Hg) and significant contributors of \( {^{19}}F \) and \( {^{12}}C \) [17]. A systematic observational study of how these yields vary with initial stellar composition and mass is an important programme, far from completion.

Moreover, K and M dwarfs and sub-giants are also useful as probes of the chemo-dynamic evolution of the Milky Way system, since their surface abundances reflect the composition of the gas clouds in which they were once formed. Also K and M giants are used as valuable probes, e.g. in regions which may

\(^1\) For some elements and purposes, for example in studies of Galactic chemical evolution, relative abundances need to be determined at an accuracy of 0.1 dex or better
not be readily accessed with dwarfs or sub-giants such as the Galactic Bulge or external galaxies such as the dwarf spheroidals. If chemical abundances in giants could be measured as accurately as for solar-type stars, and be understood theoretically, e.g. in terms of the modifications of the initial stellar abundances by the individual stars, their value as probes would be even greater. To a considerable degree, such further understanding relies on more systematic abundance measurements. Clearly, abundance studies of elements in cool stars are of high scientific value.

3 The virtue of high-resolution spectroscopy

Since cool stars have crowded spectra due to the presence of molecules, high-resolution spectrographs, such as CRIRES, are needed in order to disentangle the spectral information. The cooler the star the more crowded the spectrum. For example, for a typical cool, oxygen-rich red-giant of $T_{\text{eff}} = 3000$ K, and $\log g = 0.0$, the general flux distribution follows the $\text{H}_\alpha$ and $\text{H}_\beta$ continuous opacities leading to a maximum continuum level at approximately 1.6 $\mu$m. However, molecular lines determine the detailed flux distribution of the star. Whereas the atomic absorption does not play a large role anywhere in the spectrum except in the extreme blue end, TiO and VO totally dominate in the optical region and water vapour, OH, CO, and SiO dominate the near-infrared region. For a corresponding cool, carbon-rich red giant, the infrared spectrum is dominated by CN, CO (which dominate the M-band), CH, C$_2$, and the polyatomic molecules C$_3$, C$_2$H$_2$, and HCN, the latter two apparent in the Johnson L band. It is clear that in order to model spectra which are so dominated by molecules, even for high-resolution spectroscopy, spectral synthesis is a prime tool for analysis.

A further merit of high-resolution spectroscopy is the match between the resolution and the intrinsic widths of stellar spectral lines. Lines formed in a stellar atmosphere have an inherent line width of the order of $2 - 5$ km s$^{-1}$. In these crowded spectra, a resolution of approximately $R \sim 100 000$ is often needed to obtain full information from the spectra about line strengths. High spectral-resolution also makes it possible to detect and decompose line blending, large-scale motions, and acquire more precise knowledge on, for example, ‘turbulence’ and magnetic-field strengths.

4 Advantages of an abundance analysis at 1 – 5 $\mu$m

There are a number of advantages of studying chemical abundances in cool stars at near-infrared wavelengths. Here, we will mention a few.

A general reason for studying cool stars at 1 – 5 $\mu$m is their brightness at these wavelengths. A red giant of $T_{\text{eff}} = 3000$ K, and $\log g = 0.0$ has its largest flux output around 1 – 2 $\mu$m, i.e. in the Johnson J and H bands. Red giants are also bolometrically luminous. (Actually, a majority of all stars that can be seen, even optically, on a dark night are red giants.)
Furthermore, at infrared wavelengths the opacity of interstellar or circumstellar dust is less than in the optical domain. Thus, owing to the fact that infrared radiation can penetrate through optical dust-obscuration, stars also in dusty environs of the Universe, for instance star-forming regions, or stars in the Galactic Bulge with a large column density of dust in the line-of-sight, can readily be observed.

The fact that the opacity in a cool, stellar atmosphere has its minimum at 1.6 \(\mu\)m implies that the depth of formation of the continuum is largest at 1.6 \(\mu\)m. Weak, infrared atomic lines in the H band are therefore mostly formed deep in the atmosphere where the physical state is relatively well known. This is a definite advantage. Moreover, in the Rayleigh-Jeans regime, the intensity is less sensitive to temperature variations; just as for black-body radiation \((B_\nu(T)), \delta B_\nu(T)/\delta T\) is small in the Rayleigh-Jeans regime. This means that the effects of, for example, effective-temperature uncertainties or surface inhomogeneities on line strengths may be smaller in the infrared. As an example, we can compare iron abundances derived from a given, weak spectral-line from neutral iron in two cases: In the first case the iron abundance is derived from a combination of 50% of a giant-star model-atmosphere with an effective temperature of \(T_{\text{eff}} = 3000\) K and 50% of a \(T_{\text{eff}} = 4000\) K atmosphere, thus simulating an inhomogeneous atmosphere with two temperature components. In the second case the abundance is derived from a homogeneous model with the same total flux as the two-component model, i.e. an atmosphere with a \(T_{\text{eff}} = 3600\) K. If the weak Fe line is situated at 2 \(\mu\)m then the derived abundance would only be approximately 0.05 dex higher from the two-component model than from the homogeneous model for high-excitation lines. For the low-excitation lines we get almost no effect. If, on the other hand, the weak line were situated in the optical wavelength region, say at 500 nm, the effect would be larger, up to 0.2 dex, and now for the low-excitation lines. For the high-excitation lines the effect is smaller and even reversed.

A further advantage is that in the 1−5 \(\mu\)m domain, lines from most molecules are often pure vibration-rotational lines. However, this is not the case for CN and C\(_2\). The forest of molecular lines is also cleaner in the sense that several electronic systems less often overlap severely compared to the ultraviolet. Since the transitions occur within the electronic ground-state, the assumption of Local Thermodynamic Equilibrium (LTE) in the analysis of the molecules is probably valid [20]. For the warmer of the cool stars, an additional advantage of analyzing the near-infrared compared with the optical wavelength region, is that it is easier to find portions of the spectrum which can be used to define a continuum. In fact, also the number of atomic and ionic lines is much smaller than in the ultraviolet, reflecting the sparser term diagrams for the lower, most-populated states of the atoms. This is, however, also a general drawback of the infrared spectral region - the number of useful atomic and ionic lines is relatively limited in practice.

Lines from molecular species (with a host of lines in the 1−5 \(\mu\)m region) are beneficial in the sense that their identification is relatively easy due to an (often) regular multiplicity of lines. For complex molecules, however, the easy
The abundances of elements in Cool Stars

The abundances of elements in Cool Stars

identification is true only if there exists a theoretical line list of that specific molecule which is sufficiently accurate (see for example the discussion on the identification of water vapour in Arcturus [38]). The ladder of different vibration-rotational transitions, with varying line strengths, is also suitable for a semi-empirical modelling of an atmosphere, since the different lines together sample a large range of atmospheric, optical depths.

Measurements of isotopic abundances of carbon, nitrogen, and oxygen are of great interest, for example, for the study of nucleosynthesis and stellar evolution. The infrared wavelength region is ideal for studying isotopic abundances, chiefly since the isotopic shifts are larger for molecules than for atoms, and molecular lines are ubiquitous in the infrared. (The mass difference of two isotopic molecules leads to unequal rotational constants, affecting the wavelengths of rotational and vibration-rotational lines of the isotopic molecules.) For example, the isotopic shift between the $^{12}$CO($v = 1 - 3$) and $^{13}$CO($v = 1 - 3$) band heads at 2.4 $\mu$m is as much as 0.05 $\mu$m.

A further benefit of working with molecules is that for an element which can form many different molecules, such as carbon, nitrogen and oxygen, several diagnostics can be utilized for the determination of the abundance of that element.

Finally, the formation and destruction of molecules can be very sensitive to the temperature structure in the atmosphere. Thus, for certain cases the molecular lines may probe the upper-most atmosphere just because they exist only there. This is of diagnostic value for the study of atmospheric surface layers, but is a drawback in abundance analyses which one would wish to be as insensitive as possible to the uncertainties in the atmospheric structures.

5 Drawbacks of an abundance analysis at 1 – 5 $\mu$m

There are obviously also some disadvantages in using the infrared to study abundances in cool stars, but none of these is generally severe. Many cool stars form dust in their outer atmospheres, in a few cases so much that the dust obscures the star. The main spectral contribution of the dust is, however, an additional spectrally broad, thermal emission on top of the stellar spectrum. The maximum of this emission lies at 3 to 12 $\mu$m, depending on the temperature of the dust, which is typically a few hundred to a thousand Kelvin. This extra emission complicates the spectral analysis. Also, the telluric atmosphere, with its ubiquitous water-vapour lines and its thermal emission beyond 2 microns hampers the analysis, as does the thermal emission from the telescope.

Moreover, as was mentioned above, there are much fewer atomic and ionic lines in the infrared region. The ones present often originate from highly excited levels in atoms, which also complicates an interpretation. Furthermore, many lines are not properly identified and/or lack known oscillator strengths, which are needed in an abundance analysis. A further drawback for a molecular abundance analysis in this wavelength region is the lack of clear and well studied signatures from several molecules, such as TiO and ZrO beyond the J band.
Finally, even though significant advances have been made in the technology for recording near-infrared light, existing spectrometers are still much less effective than optical ones, one of the main reasons being the present lack of cross-dispersion.

Thus, to summarize, the advantages of chemical-abundance analyses of cool-star atmospheres in the infrared are considerable and numerous. The disadvantages are few, and some of these will even be possible to surmount in the near future.

6 The status of high-resolution abundance analyses at $1 - 5 \mu m$

In order to analyze stellar spectra, a model atmosphere must be calculated. Subsequently, a synthetic spectrum is computed by solving the radiative transfer through this model atmosphere. How realistic are cool, stellar model-atmospheres and synthetic spectra? Here, only a short account will be given. For more detailed discussions, see, for example [15] or [14].

6.1 The status of stellar atmospheres

The answer to the question on how well model atmospheres reflect reality, has two components. First, the input parameters have to be well determined. A star’s fundamental parameters are its effective temperature, $T_{\text{eff}}$, surface gravity, $\log(g)$, metallicity, and mass (or radius). Second, the physical description of the star’s light-forming atmosphere has to be relevant, i.e. all important physics has to be included at a sufficiently high level of realism.

Concerning the stellar parameters, in general, the determination of a star’s effective temperature, $T_{\text{eff}}$, is satisfactory also for cool stars based on their angular diameters (for nearby giants and supergiants) and on the InfraRed Flux Method (IRFM). The assessment of a star’s $\log(g)$ is very difficult, with uncertainties of the order of $\pm 0.3$ dex or even more for cool giants. However, the surface gravities of stars in the Magellanic Clouds and in the Dwarf Spheroidals in the Local Group can be assigned more readily because of their relatively well-known distances. The astrometric GAIA mission will contribute to the solution of this problem by providing parallaxes to a host of stars in the Galaxy. The determination of the overall-metallicities of cool stars may be difficult due to the forest of molecular lines and few pure atomic lines. The determination of masses is even more involved. However, since measurements of diameters of nearby giants are possible by means of interferometry, a mass can in principle be calculated from this diameter and the spectroscopic surface gravity of the star. Thus, although several severe difficulties do exist in the determination of a cool star’s fundamental parameters, these difficulties are not insurmountable in principle.

Concerning the model atmospheres, several ingredients are important. The physical structure of a model depends on accurate opacities. For cool stars these
The abundances of elements in Cool Stars are dominated by lines from diatomic and small, polyatomic molecules. Today, the observed line-blocking in M giants and dwarfs is well reproduced by models (see, for example, [2]). However, the water opacity is still in need of improvement (see, for instance, [25], [24], and [37]). The modelling of carbon stars is still hampered by the lack of reliable opacity data of some polyatomic molecules, such as C$_2$H$_2$, CH$_4$, C$_2$H, and C$_3$H. Important work on carbon-star opacities is being performed by several groups, see, for example, [18] and [4].

For bright giants and supergiants, which have atmospheres with large geometric extensions, the sphericity affects the radiative transfer and therefore the physical structure. For these stars, codes for calculating models taking the spherical nature of a star into account, do exist and should be used in the analysis (see, for example, [36] and [19] and others). Non-static (i.e. dynamic) models for red giants, Asymptotic Giant Branch stars, and red supergiants are still under development, but have already yielded several important qualitative results. Dynamic models are crucial for the understanding of these types of stars, as they are physically much more realistic and their structures depart markedly from static models. Advances are being made both concerning pulsation models (even including dust formation) which primarily concentrate on temporal variations of, for instance, mira variables (see, i.a., [5], [10], [22], and [23]) and hydrodynamic 3D models which allow for the formation of spatial inhomogeneities due to convection (c.f. [11], [28], and others). These are very important frontiers to be explored in order to proceed with detailed spectroscopy of red giants in general.

Another important aspect when discussing the computation of the model structure of the atmospheres of cool stars, is the validity of the assumption of LTE and molecular equilibrium. The assumption of LTE could lead to erroneous inferences. Hauschildt and collaborators (see, for example, [40]) are working on codes with which to compute atmospheric structures, assuming statistical equilibrium instead of LTE to calculate both line and continuum radiative transfer as well as the gaseous state.

For a large fraction of cool stars, especially evolved AGB stars and M dwarfs and cooler, dust plays an integral role in driving winds, where appropriate, and shaping the model structure, for example, by back scattering. Furthermore, in M dwarfs dust may, for instance, be in a suspension, heating the line-forming regions [45] or, for even cooler dwarfs, fall to deeper stellar layers. The study of the process of dust formation and the effect of the dust on these stars is a field attracting increasing attention (see, for example, [39], [41], [10], and [19]). The examination of K and M dwarfs in this respect is of importance, since they are interesting as probes of Galactic evolution; they are common and often relatively old, thereby sampling the state of the Milky Way in earlier phases of its evolution.

Also, magnetic activity on dwarfs should be given some attention. Magnetic fields could affect the structures of stars, both vertically and horizontally, and certainly affect the spectra in the infrared through the Zeeman effect. This sensitivity also opens up another significant aspect of high-resolution, infrared spectroscopy: to measure and map the magnetic fields on late-type stars, for example,
by Doppler imaging (cf. Piskunov's contribution in the present proceedings). Ultimately, this will also lead to better models of stellar atmospheres and synthetic spectra for abundance analyses, not least for cool dwarfs which are known to have overall atmospheres and fluxes considerably affected at activity regions on the stellar surface.

To summarize, all the above-mentioned aspects should, where appropriate, be taken into account when modelling an atmosphere of a cool star. For instance, the analysis of atmospheres of M dwarfs needs models superior to the classical ones. These atmospheres are not well understood due to the presence of a host of molecular lines, the inhomogeneity and magnetic fields of their atmospheres, and the presence of dust in their photospheres. Their spectra may also be affected by an optically thin, H$\textsubscript{2}$ convection zone [45]. Today, only one-dimensional, LTE models, treating convection through the mixing-length approximation, exist as a standard for abundance analyses of red giants and dwarfs. Diagnostic tests of such models are, therefore, very important. Realistic 3-D, non-LTE models are needed for many investigations, in particular to estimate systematic errors in studies based on standard models.

6.2 The status of synthetic spectra at 1–5 µm

We now turn to the second question on how good we can expect synthetic spectra at 1–5 µm to be. Generally it is possible to synthesize spectra at a relatively high accuracy. The accuracy of the synthetic spectra depends on the input data and the validity of the assumed approximations of the physics. Given a model atmosphere, in order to calculate a synthetic spectrum in LTE, atomic and molecular line-data are required: wavelengths, identifications, excitation energies, transition probabilities and statistical weights, line-broadening parameters, as well as partition functions and dissociation energies for the molecules. For the computation of an atmospheric structure it is necessary to have global absorption data as complete as possible, but these individual data need not be very accurate. For a calculation of a synthetic spectrum, on the other hand, the accuracy is especially important for data directly affecting the spectral diagnostics to be calculated. For synthetic spectra in the infrared, more and better data are definitely needed both for atoms and a large number of molecules. It should also be noted that for pressure broadening of molecular lines, especially in dwarfs, available evidence indicates that Unsöld's classical prescription (which is used in current calculations) is only correct to about one order of magnitude (as for atoms; Barklem, 2003, private communication). In general, astrophysicists should gratefully acknowledge the important, difficult, and tedious work performed by atomic and molecular physicists!

If LTE is not assumed, a full, computationally demanding, statistical-equilibrium calculation is required, needing (as yet, uncertain or non-existent) collisional and radiative transition data for all 'important' transitions for the modelled atoms, ions, and/or molecules. Simultaneously, the radiation field throughout the photosphere has to be calculated. For certain cases, a non-LTE descrip-
The abundances of elements in Cool Stars

formation of the line formation may be crucial. Unfortunately, however, we do not know as yet for which spectral diagnostics this is so.

7 Some recent examples from the literature

As of today, there exist some tens of articles in the literature on chemical abundance analyses of cool stars based on high-resolution spectroscopy at $1 - 5 \mu m$. Here, only a few recent examples will be high-lighted. It is clearly an emerging field, which can be expected to generate much more scientific information in the near future, in particular thanks to the realization of high-resolution, infrared spectrometers such as CRIRES.

Several interesting studies have been published based on high-resolution spectra observed with the Phoenix spectrometer mounted on the Gemini South telescope. For instance, Cuhna et al. [7] measured the abundance of fluorine based on lines from the HF molecule for a sample of red giants in the Large Magellanic Cloud and the Galactic globular cluster $\omega$ Cen. Based on these observations, performed at $2.3 \mu m$ at $R = 50,000$, they conclude that Asymptotic Giant Branch stars do not seem to be the chief contributor to fluorine, after all. Wolf-Rayet stars could be important players in this context. We note that the Wolf-Rayet stars have been suggested to be a major contributor also for carbon, again even more significant than the AGB stars [16].

A further example of abundance determinations using the Phoenix spectrometer is the work by Smith et al. [42]. They determined abundances of $^{12}$C, $^{13}$C, $^{14}$N, $^{16}$O, Na, Sc, Ti, and Fe in 12 red giants also in the Large Magellanic Cloud at $R = 50,000$. The abundance pattern found shows evidence of material characteristic of the first dredge-up, i.e. mixed material processed by the CN cycle.

Examples of abundance determinations using both Phoenix (then mounted on the Kitt Peak 2.1 m telescope) and the high-resolution NIRSPEC spectrometer (mounted on a Keck telescope) are the oxygen studies by Meléndez et al. [31,32]. Oxygen abundances for metal-poor Galactic stars were determined from vibration-rotational OH lines at a resolution of $R = 40,000 - 50,000$. A constant, relative oxygen abundance, independent of metallicity [Fe/H], was found to follow the other $\alpha$-elements: $[O/Fe] = 0.4$ for $-2 < [Fe/H] < -1$. This investigation supports the idea that oxygen is synthesized in Supernovae Type II.

Origila et al. [33] determined chemical abundances for four giants in old, metal-rich globular clusters in the Galactic Bulge using NIRSPEC at a (medium) resolution of $R = 25,000$. This is an example of utilizing the fact that infrared light can more easily penetrate dust. They found a metallicity of $[Fe/H] = -0.3 \pm 0.2$, an oxygen abundance of $[O/H] = 0.3 \pm 0.1$, and an $\alpha$-element enhancement of $[\alpha/Fe] = 0.3 \pm 0.2$ for giants in two different globular clusters. The composition found in the globular-cluster giants is similar to the one found in field stars in the Bulge. This seems to support the idea that these clusters were formed early, with a rapid enrichment.

Pilachowski et al. [35] observed four giants in the globular cluster M3 using NIRSPEC at medium resolution ($R = 25,000$) and Phoenix to determine C-
isotopes. They find typical $^{12}$C/$^{13}$C values for three of the globular cluster giants, but a higher value for a Li-rich giant, giving support to the idea that a Li-burning shell may be the cause of the existence of Li-rich giants in globular clusters.

Aoki & Tsuji [1] analyse FTS spectra of K and M giants, observed at KPNO ($R \sim 100\,000$) in the H, K, and L Johnson bands, to determine nitrogen abundances from CN and NH lines. They discuss the abundance trends with respect to spectral type and conclude that extra mixing and additional CN-processing after the 1st dredge-up is required for the observed giants.

Finally, Viti et al. [44] presented a metallicity determination of the M dwarf CM Draconis by measuring CO first overtone lines ($v = 0 - 2$ and $1 - 3$) using CGS4 at UKIRT at a (medium) resolution of $R = 10\,000$. The CO bands were modelled and are found, as expected, to vary with metallicity and to be a powerful diagnostic tool for analyzing M dwarfs. The CO vibration-rotational lines give a metallicity of $[\text{Fe/H}] = -1$ for CM Dra.

8 Future prospects for high-resolution, near-infrared spectroscopy of element abundances in cool stars

There are now, in principle, three different types of possible applications of the recent developments of 1 – 5 $\mu$m spectroscopy for determining stellar element abundances. First, one could study fainter objects than before, for example, reaching for dimmer, nearby dwarfs or stars in external galaxies. Second, one could study more objects, performing systematic studies of populations or performing surveys of complete samples, e.g. within a certain volume. Third, one could strive towards higher accuracy in the observations or the analyses, in order to support the element-abundance analyses, with details about observed atmospheric velocity-fields or magnetic fields.

The limiting factors in these various approaches will be different. In the first case for dwarfs, the modelling of atmospheres and spectra, plagued by complex molecular absorption and dust as well as diffusion, surface activity etc., will most probably limit the accuracy of the abundances much more than the spectral data as such. For distant giants in the Local Group galaxies, the analyses will be relatively straightforward as long as the stars seem similar to stars known already from the Galaxy or the Magellanic clouds. When chemical abundances, or other spectral characteristics, seem different or exotic – in many respects the most interesting case – the accuracy in the atmospheric parameters derived will, however, probably be relatively low, in particular as long as high S/N and high-resolution spectra cannot be acquired across wide spectral regions. For the second case, the usefulness of surveys will be considerable as they will presumably further illuminate the multitude of different types of AGB stars, and of different degrees of activity on red dwarfs. They may thus give further clues concerning the role of these giants in stellar evolution and nucleosynthesis, and regarding the evolution of stellar magnetic fields and their dynamos. The great use of surveys of chemical abundances in dwarfs and giants in the spectral interval F - K, e.g. for studies of Galactic chemical evolution, will however probably not be
correspondingly important for studies in the infrared region of M and carbon stars, due to the individuality of these latter stars, essentially reflecting the marked effects caused by molecules and dust, which in turn depend on differences in element abundances, in particular that of the C, N, and O elements. Also, the difficulty in determining abundances of elements in dusty, heavily line-blanketed and inhomogeneous atmospheres, will most probably limit the efforts. As regards the third application, the more detailed study of the underlying atmospheric physics is no doubt a very significant aspect of the new spectroscopic possibilities. First after establishing a more profound understanding of the physics of cool-star atmospheres, shall we see further important developments in abundance determinations of elements beyond the mere empirical inter- or extrapolation from more nearby or bright stars. For example, in order to understand the real news, or to be able to distinguish it at all, we need to look deeper at what determines the phenomena we see, and thought we understood.

The future of chemical-abundance determinations in cool stars seems thus more interesting than easily predictable. No doubt, however, with CRIRES and similar spectrometers at large and intermediate-size telescopes, in combination with more realistic models of cool stars, we may in the end look forward to reliable abundance determinations in a variety of fundamentally interesting objects in the future. As a major side effect, or perhaps as the most rewarding part of the effort, we will learn a lot more about the physics of cool stars, the interesting interplay between stellar nuclear reactions, pulsations and travelling shocks, magnetic fields, convection, mass loss, dust formation and non-equilibrium radiation fields. CRIRES will be important in bringing our understanding of stars closer to physical reality.

Acknowledgments We are grateful to Dr. Jean-Pierre Maillard for valuable help.

References
1. W. Aoki, T. Tsuji: Astron. Astrophys. 328, 175 (1997)
2. R. Alvarez, B. Plez: Astron. Astrophys. 330, 1109 (1998)
3. T. G. Barnes, K. H. Hinkle, D. L. Lambert & R. Beer: Astrophysical Journal 213, 71 (1977)
4. A. Borysow, J. P. Champion, U. G. Jørgensen, C. Wenger: In the ASP Conference proceedings of the ‘Stellar Atmosphere Modeling’ workshop, I. Hubeny, D. Mihalas, and K. Werner (eds.) 288, 352 (2003)
5. G. H. Bowen: Astrophysical Journal 329, 299 (1988)
6. P. Connes: ARA&A 8, 209 (1970)
7. K. Cunha, V. V. Smith, D. L. Lambert, K. H. Hinkle: Astronomical Journal 126, 1305 (2003)
8. J. F. Dominy, K. H. Hinkle, D. L. Lambert, D. N. B. Hall, S. T. Ridgway: Astronomical Journal 223, 949 (1978)
9. J. M. Flaud, C. Camy-Peret, J. P. Maillard: In the proceedings of ‘Les Molécules simples au Laboratoire et en Astrophysique’, 21st International Colloquium on Astrophysics of Liege, p. 246 (1980)
10. A. J. Fleischer, A. Gauger, E. Sedlmayr: Astron. Astrophys. 266, 321 (1992)
11. B. Freytag: Highlights of Astronomy 12, 298 (2002)
12. B. Gustafsson: ARA&A 27, 701 (1989)
13. B. Gustafsson: In the proceedings of ‘Future of Astro-nuclear Physics’, Jorissen et al. (eds.), in press (2004)
14. B. Gustafsson, S. Höfnér: In ‘Asymptotic Giant Branch stars’, H. J. Hабинг, and H. Olofsson, (eds.) p. 149 (2004)
15. B. Gustafsson, U. G. Jørgensen: Astron. Astrophy. Review 6, 19 (1994)
16. B. Gustafsson, T. Karlsson, E. Olsson, B. Edvardsson, N. Ryde: Astron. Astrophys. 342, 426 (1999)
17. B. Gustafsson, N. Ryde: In the proceedings of ‘the Carbon Star Phenomenon’, IAU Symposium 177, 481 (2000)
18. G. J. Harris, O. L. Polynsky, J. Tennyson: Astrophysical Journal 578, 657 (2002)
19. P. H. Hauschildt, E. Baron, F. Allard: Astrophysical Journal 483, 390 (1997)
20. K. H. Hinkle, D. L. Lambert: MNRAS 170, 447 (1975)
21. K. H. Hinkle, D. L. Lambert, R. L. Snell: Astrophysical Journal 210, 684 (1976)
22. S. Höfnér, E. A. Dorfi: Astron. Astrophys. 319, 648 (1997)
23. S. Höfnér, R. Gautschy-Loidl, B. Aringer, U. G. Jørgensen: Astron. Astrophys. 399, 589 (2003)
24. H. R. A. Jones, Y. Pavlenko, S. Viti, J. Tennyson: MNRAS 330, 675 (2002)
25. U. G. Jørgensen, P. Jensen, G. O. Sørensen, B. Aringer: Astron. Astrophys. 372, 249 (2001)
26. D. L. Lambert, J. A. Brown, K. H. Hinkle, H. R. Johnson: Astrophysical Journal 284, 223 (1984)
27. D. L. Lambert, B. Gustafsson, K. Eriksson, K. H. Hinkle: Astrophysical Journal Supp. Ser. 62, 373 (1986)
28. H.-G. Ludvig, B. Freytag, S. Höfnér, F. Allard, P. H. Hauschildt: In the proceedings of ‘Stars as Suns: Activity, Evolution and Planets’, IAU Symposium 219, 41 (2003)
29. J. P. Maillard: In the proceedings of Joint Discussion on Infrared Stellar Spectroscopy, IAU General Assembly 1973, G. Contopoulos (ed.), p. 313 (1974)
30. J. P. Maillard: In the proceedings of the 4th International Colloquium on Astrophysics (High resolution spectrometry), M. Hack (ed.). p.108 (1978)
31. J. Meléndez, B. Barbay: Astrophysical Journal 575, 474 (2002)
32. J. Meléndez, B. Barbay, F. Spite: Astrophysical Journal 556, 858 (2001)
33. L. Origlia, R. M. Rich, S. Castro: Astronomical Journal 123, 1559 (2002)
34. C. Pilachowski, H. Dekker, K. H. Hinkle, et al.: PASP 107, 983 (1995)
35. C. Pilachowski, C. Sneden, E. Freeland, J. Casperson: Astronomical Journal 125, 794 (2003)
36. B. Plez, J. M. Brett, À. Nordlund: Astron. Astrophys. 256, 551 (1992)
37. N. Ryde, K. Eriksson: Astron. Astrophys. 386, 874 (2002)
38. N. Ryde, D. L. Lambert, M. J. Richter, J. H. Lacy: Astrophysical Journal 580, 447 (2002)
39. C. Sandin, S. Höfnér: Astron. Astrophys. 398, 253 (2003)
40. C. I. Short, P. H. Hauschildt: Astrophysical Journal 596, 501 (2003)
41. Y. J. W. Simis, V. Icke, C. Dominik: Astron. Astrophys. 371, 205 (2001)
42. V. V. Smith, K. H. Hinkle, K. Cunha, et al.: Astronomical Journal 124, 3241 (2002)
43. H. Spinrad, L. D. Kaplan, P. Connes, et al.: In the proceedings of the Conference on Late Type Stars, KPNO Contribution 554, 59 (1970)
44. S. Viti, H. R. A. Jones, P. Maxted, J. Tennyson: MNRAS 329, 290 (2002)
45. R. Wehrse: In the proceedings of the 10th workshop on Nuclear Astrophysics, W. Hillebrandt and E. Müller (eds.) MPA P12, 79 (2002)