Prospects of Stellar Abundance Studies from Near-IR Spectra Observed with the E-ELT

N. Ryde* ⋆

Received 30 May 2005, accepted 11 Nov 2005
Published online later

Key words stars: abundances, infrared: stars, instrumentation: spectrographs, telescopes

In 2006 ESO Council authorized a Phase B study of a European AO-telescope with a 42 m segmented primary with a 5-mirror design, the E-ELT. Several reports and working groups have already presented science cases for an E-ELT, specifically exploiting the new capabilities of such a large telescope. One of the aims of the design has been to find a balance in the performances between an E-ELT and the James Webb Space Telescope, JWST. Apart from the larger photon-collecting area, the strengths of the former is the higher attainable spatial and spectral resolutions. The E-ELT AO system will have an optimal performance in the near-IR, which makes it specially advantageous. High-resolution spectroscopy in the near-infrared has, however, not been discussed much. This paper aims at filling that gap, by specifically discussing spectroscopy of stellar (mainly red giant), photospheric abundances. Based on studies in the literature of stellar abundances, at the needed medium to high spectral resolutions in the near-infrared (0.8 – 2.4 μm), I will try to extrapolate published results to the performance of the E-ELT and explore what could be done at the E-ELT in this field. A discussion on what instrument characteristics that would be needed for stellar abundance analyses in the near-IR will be given.

1 Introduction

The objective for P. Connes when he in 1967 set up his Fourier Transform Spectrometer (FTS) for astronomical, near-IR spectroscopy, was the investigation of planets (Connes 1970). However, a few stars were observed and among the first stellar results was a measurement of the 12C/13C ratio for Betelgeuse (Spinrad et al. 1971). In the seventies and eighties, most high-resolution IR studies of stars were devoted to studying bright IR stars, such as the dynamics in mira stars and isotopic ratios in M giants, carbon stars, and mira stars, see e.g. Maillard (1978), all with FTSs. An early investigation of abundances of elements in stars (C, N, and O) was done by Lambert et al. (1984) for Betelgeuse. Later, the CNO elements and the isotopic ratio of carbon were determined for 30 Galactic carbon stars by Lambert et al. (1986). A large step forward in order to study abundances in fainter stars too, was taken with the development of cryogenic echelle spectrometers.

Spectroscopic studies of abundances in red stars benefit from being performed in the near-infrared at medium or preferably at high spectral resolution. As we will see, a large range of questions can be investigated, from the formation and evolution of the Milky Way and the Magellanic Clouds, to stellar structure and the evolution of stars of very different metallicities. But also the difficult task of observing and modelling the coolest dwarf stars, the M, L, and T dwarfs and brown dwarfs can now be done with high-resolution, near-infrared spectrometers. The detailed study of AGB stars and their winds can be best analysed in the near-IR where most of their flux is emitted. High-resolution is needed to disentangle the molecular spectra, which contain much information about the star. Cool M dwarfs have a large amount of lines in their spectra and the continuum is difficult to define. For such a case, a very high resolution (R > 60,000) is really needed. The only way to analyses these type of spectra is by calculating detailed synthetic spectra.

With a medium-to-high spectral resolution spectrometer for the near-IR on E-ELT, we will be able to expand our views and study other galaxies in detail, their chemical evolution and different structures. We will be able to start addressing detailed questions on the formation and evolution of other galaxies and start comparing different galaxies of various kinds. The investigation will provide unique empirical pieces of evidence for the fundamental, and not understood question of how galaxies form and evolve. Furthermore, fundamental questions concerning nucleosynthesis and yields from stars can be investigated by spectroscopically exploring stars in different environments. The stellar structures and the evolution of red giants of different metallicities can be studied. Fainter objects, such as cool dwarf stars and brown dwarfs, will be surveyed opening up this field. Metal-poor stars that need spectra with a high signal-to-noise (SNR) will be studied in detail and in larger numbers, investigating the large C- and N-bearing molecular

* e-mail: ryde@astro.lu.se

1 AGB stars - the Asymptotic Giant Branch Stars - are bright red giants on their second ascent on the giant branch
contents in these stars. Hence, the E-ELT era will provide many exiting scientific questions to address.

Thus, studying stellar abundances is of interest for many reasons. For example, assembling abundances of a variety of elements from an ensemble of stars ranging over different metallicities in galaxies or a component of a galaxy, will determine abundance trends and spatial composition gradients. This will eventually provide us with information on metallicity distributions, the star-formation rates, initial-mass functions, and the distribution of populations within the systems. Furthermore, the ages of the populations, time-scales of the enrichment of the systems and the merger history of the galaxy structures can be investigated. All this will place constraints on how the systems formed and evolved, whether merger events dominated or whether the systems evolved slowly without interactions.

Traditionally, abundance analyses of stellar populations have been done in the UV/optical wavelength regions preferably using high-resolution, cross-dispersed, echelle spectrometers observing main-sequence stars and giants, especially F, G, and K stars. Red giants are very luminous stars and are therefore useful as probes for studies in regions such as the Galactic bulge or external galaxies, which may not be readily accessed by observing dwarfs or sub-giants. It should also be noted that red giants are responsible for most of the light in other galaxies. For instance, with the E-ELT stellar abundance investigations of giants as far away as in the most distant galaxies in the Local Group will be possible. Late-type giants are brightest in the near-IR with a sharp decline in flux towards the blue, implying that near-infrared spectroscopy would be more suitable for a detailed determination of abundances of these stars. A further advantage when it comes to the E-ELT, is the performance of its adaptive optics (AO) system which will be optimal in the near-IR. This means that higher spatial resolutions will be achievable than in the optical and shorter observing times are required compared to not using AO. Thus, an analysis of red-giant stars in the near-infrared would be rewarding. Fortunately, sensitive medium and high-resolution spectroscopy has become possible in the near-IR due to the development of IR detector technology. The art of determining chemical abundances in cool stars in the near-IR has benefited strongly from the realization of sensitive, cryogenic echelle spectrographs capable of providing high-resolution, near-infrared spectra, such as the Phoenix (Hinkle et al. 1998, started operation in the late 90:s at KPNO and later at Gemini South Observatory).

Late-type dwarfs are useful probes of the chemo-dynamic evolution of stellar populations, since they span a range in age, and their surface abundances reflect the composition of the gas clouds from which they were once formed and as such trace the star-formation history and enrichment of the interstellar medium. This is encoded in the stellar elemental abundances. Late-type giants have evolved from the low-mass stars, the most common stars in galaxies. They too span a range of ages and the warmer ones should have mostly unaffected surface compositions, with the exception of C and N, which can not be assumed to be pre-stellar. C+N is, however, assumed to be conserved for stars on their first ascent up the giant branch. AGB stars are more complicated and their surface abundances are affected by internal processes. 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. Age determinations are, however, difficult and a problem. This review will emphasize on the use of stellar abundances studies of red giants, due to their brightness.

2 Studies of element abundances based on near-IR spectroscopy of late-type stars

Near-IR spectroscopy fits well into the emerging realization that the near-IR is a preferred wavelength region for many science cases for the E-ELT. There is an emphasis on the near-IR not only due to other science drivers, but also since the high spatial resolution of the E-ELT will first be realized in the IR, with the Adaptive Optics (AO) system having an optimal performance there. For example, Olsen et al. (2006) show the promise of ground-based AO systems by using the NIRI camera on the Gemini North telescope to retrieve colour-magnitude diagrams of resolved stars in the crowded regions in the bulge and disk of M31, the nearest massive spiral galaxy in the Local Group of galaxies. Based on H and K band observations they could retrieve star-formation histories for these populations and could show that there does not seem to be an age difference between them. Most stellar population work is confusion-limited rather than sky-background or photon-limited, which means that we need the high spatial resolution achievable in the near-IR. For example, in the K band the diffraction limit will be less than 0.015” for a 42-meter telescope, which means that it will be possible to resolve stars lying 1/20 pc apart in projected distance in the Andromeda galaxy, cf. Table 2.

2 The CODEX spectrograph (Pasquini et al. 2006) studied for the E-ELT will address this need. It is planned for the $\lambda = 0.4 - 0.8 \mu m$ range (ESO-SC-430[2007]).

3 A red supergiant of an effective temperature of 3600 K like Betelgeuse has a maximum flux, $F_{\lambda}$, around 700 – 1000 nm and the red giant R Dor (T$_{eff} = 3000 K$) shines strongest in the range of 1 – 1.5 $\mu m$.

4 The J, H, and K bands are the most effective regions, whereas the L and M bands in the thermal infrared have a large telluric background brightness to overcome. However, the fundamental band of CO at 4.6 $\mu m$ might still be of interest.
2.1 The virtues of exploring stellar abundances by near-infrared spectroscopy

There is a number of advantages of observing stellar abundances of late-type stars in the near-infrared wavelength region. Below a few aspects are mentioned and highlighted. For instance, the near-IR is preferred for studies of dust-obscured regions since IR radiation penetrates gas and dust much better than optical radiation. The galactic bulge is an example of a region which is hidden behind massive amounts of gas and dust. The bulge is the last major component of the Milky Way which is still essentially unexplored, mostly due to this fact. Furthermore, cool stars can have a fair amount of molecular lines and might have messy optical spectra. Near-IR absorption spectra are less crowded with lines and fewer lines are blended, compared to wavelength regions in the optical spectral window. It is thus easier to find portions of the spectrum which can be used to define a continuum, which is so very important in an abundance analysis. This reduces the uncertainties significantly and makes the exploration easier and more accurate (Ryde et al. 2005). Especially, the study of mira stars and carbon stars benefits largely when going to the near-IR. In fact, also the number of atomic and ionic lines is much smaller in the near-IR than in the ultraviolet. 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. However, it should be realized that there are enough of suitable metallic lines in the infrared for many purposes, especially from the diagnostically important α elements (such as Mg, Si, Ca, S, and Ti).

Molecular lines are ubiquitous in the IR which implies the possibility to more reliable abundances. Note, however, that the abundance of molecules are often quite temperature sensitive. Obviously, it is an advantage to have many lines of different strengths from the same molecule to minimize measuring uncertainties and systematic effects. Furthermore, several diagnostics for the same element might exist. For instance, in order to determine the carbon abundance it is possible to measure lines from CH, CO, C$_2$, and CI. The near-IR also has the virtue that only that region offers all indicators necessary for an accurate determination of the important C-N-O molecular and atomic equilibria in the atmospheres of cool stars, through the simultaneous observation of many clean CO, CN and OH lines. A further advantage is the fact that in the 1-5 µm domain, lines from most molecules are often pure vibration-rotational lines. The forest of molecular lines is also cleaner in the sense that several electronic systems less often overlap severely compared to in the ultraviolet. Since the transitions within the vibration-rotational bands occur within the electronic ground-state, the assumption of Local Thermodynamic Equilibrium (LTE) in the analysis of the molecules is probably valid (Hinkle & Lambert 1975). The assumption of LTE simplifies the analysis considerably and should make it more accurate.

Measurements of isotopic abundances of carbon, nitrogen, and oxygen are of great interest, for example, for the study of nucleosynthetic processes in stars 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 molecules of different isotopic mass leads to unequal rotational constants, affecting the wavelengths of rotational and vibration-rotational lines of the molecules.) For example, the isotopic shift between the $^{12}$CO($v = 1 - 3$) and $^{13}$CO($v = 1 - 3$) band heads at 2.4 µm is as much as 0.05 µm.

Several diagnostic lines of elements are stronger in the near-IR beyond approximately 0.8 µm. For instance, the carbon abundances in disk stars can be investigated from the lines at 710 nm (Tomkin et al. 1995) but a better diagnostic is the forbidden line at 872.7 nm (Bensby & Feltzing 2006; Gustafsson et al. 1999). For halo stars these diagnostics are, however, too weak. Instead, the lines at 920 nm are much more useful. Also, when it comes to the origin of sulphur in the halo, earlier lines at 869.4 nm (for instance, Israeli & Rebolo 2001; Takada-Hidai et al. 2002) have been used at large telescopes, but the lines at 920 nm are approximately 10 times as strong (Caffau et al. 2005; Korn & Ryde 2005; Nissen et al. 2004; Ryde & Lambert 2004, 2005) and should therefore be used. The latter provide more accurate sulphur abundances and are also detectable at 3 meter class telescopes provided these have high-resolution spectrometers capable of detecting light up to 1 µm. Recently, also sulphur lines beyond 1 µm have been analysed, such as the [Si] line at 1082 nm (Ryde 2006), and the lines at 1047 nm (Nissen et al. 2007). These new lines are providing new insight into the origin of sulphur. The near-IR is preferred for a number of other elements too, e.g. the diagnostics of HF, $^{13}$C, and Na are superior in the IR.

The opacity in a cool, stellar atmosphere has its minimum at 1.6 µm which implies that the continuum is formed deepest in the atmosphere (where the physical state is relatively well known) at these wavelengths. Furthermore, the intensity is less sensitive to temperature variations in the IR. Just as for black-body radiation ($B_\nu(T)$), $\delta B_\nu(T)/\delta T$ is small in the Rayleigh-Jeans regime, which means that the effects of uncertainties of, for instance, $T_{eff}$ or surface in-homogeneities on line strengths may be smaller in the IR (Ryde et al. 2005).

2.2 Drawbacks of near-IR spectroscopy for abundance determinations

The near-IR spectral region has not been used much previously for abundance analyses of stars. The optical wavelength region is much more studied. For instance, there are larger data bases of well-determined and well-studied optical spectral lines to use. Also, the use of optical spectra and
photometry to determine the stellar parameters \((T_{\text{eff}}, \log g, \text{metallicity}, \text{and microturbulence})\) are better developed in the optical regime. However, as near-IR spectroscopy gets more commonly used and more work is done, these drawbacks will be alleviated. A few further drawbacks in doing an abundance analysis in the IR compared to the optical are discussed here.

There is a large need for identifications, measured atomic wavelengths, and strengths (gf values) of atomic lines in the near-IR. The inventory of useful spectral lines has not been done, and for the many lines which could potentially be very useful, line data (such as accurate wavelengths and transition probabilities which are needed) are not known accurately enough or at all (see the review by Johansson 2005). Many lines from high-excitation levels in neutral and singly ionized atoms in the first half of the periodic table are present in the near-IR, which is actually also true for resonance lines of rare-earth elements.

Accurate wavelengths are possible to measure for all permitted lines, thanks to Fourier Transform Spectrometers (FTS) working in the near-IR. Absolute gf values can be obtained by combining experimental lifetimes and branching fractions (Johansson 2005). Note that for a relative abundance analysis, astrophysical gf values can also be used. Very little experimental data for line strengths exists today. Theoretical data only exist for some lines. For example, theoretical line strengths for hydrogenic transitions are very accurate (Johansson 2005). For neutral elements, the hydrogenic \(n = 4 \rightarrow n = 5\) transitions lie blue-wards of Br\(\alpha\) at 4.05 \(\mu\)m, and for singly ionized atoms these transitions lie close to 1 \(\mu\)m. The \(4f \rightarrow 5g\) transitions are the most hydrogenic ones. Such transitions are seen in the solar spectrum for C, Na, Mg, Al, Si, Fe, Cr, and Ni (Geller 1992). For the alkali atoms (\(3p \rightarrow 4s\) in Na and \(4s \rightarrow 4p\) in K) and alkaline earth elements (MgI and CaI), measurements of absolute gf values should be possible (Johansson 2005). This is also true for Iron-Group elements (3d shell) which have hundreds of lines in the near-IR due to their complex atomic structures. For the Rare-Earth elements (4f shell) it should also be possible to measure absolute gf values, but it will be difficult (Johansson 2005). These are the elements (e.g. Ceti) with resonance lines in the near-IR. For the P-shell elements (e.g. the important C, N, O, Si, and S elements) it will be very difficult to measure lifetimes and branching ratios, and therefore one will need to rely on theoretical data or astrophysical gf values, with the uncertainties that come with these.

A further specific difficulty for an abundance analysis in the near-IR of IR bright stars is that several of the interesting ones have dust surrounding them. This dust radiates thermally in the \(2-10\ \mu\)m region, making an abundance analysis very difficult if the amount of dust emission is not known. Low-resolution spectra or a Spectral Energy Distribution is needed to estimate the dust contribution to the continuum level. Also circumstellar molecular layers seen in some cool giants (see for example Tsuji 2003) can distort the classical picture. Line profiles and line centers should be carefully studied in these cases.

Finally, the most efficient near-IR, high-resolution spectrometers today are single order echelle spectrometers. The wavelength coverage is relatively small leading to a limited amount of spectral lines to be analyzed in a given amount of telescope time. A cross-dispersed spectrometer is needed to make near-IR abundance studies more efficient.

### 2.3 The need for high spectral resolution

For the purpose of this paper, I define high spectral resolution as \(20,000 \lesssim R = \lambda/\Delta\lambda \lesssim 60,000\), and \(R \gtrsim 60,000\) very high resolution. Furthermore, we consider \(5,000 \lesssim R \lesssim 20,000\) to be medium spectral resolution. The lower limit is arbitrary but indicates a reasonable lower limit for studying abundance indicators in stars. Thus the spectral resolutions covered by the JWST are considered ‘low resolution’. From medium resolution spectra, a metallicity indicator of a star can be retrieved from measuring the strength of the near-IR Ca\(\text{II}\) triplet at \(8600\ \mu\)m (see for instance, Battaglia et al. 2006; Tolstoy et al. 2001, and references therein). Furthermore, molecular bands can be observed at medium resolution and especially isotopic ratios can be retrieved (cf. Recio-Blanco & de Laverny 2007, Shetrone 2003). However, intrinsically, the line-broadening mechanisms (thermal, collision, and micro- and macroturbulent broadening) in a stellar atmosphere range from a few to tens of km s\(^{-1}\) in velocity space. This corresponds to a broadening of \(\Delta\lambda \sim \lambda/20,000\) or \(\lambda/150,000\), which means that in order to resolve lines from the stellar atmosphere we would need spectral resolutions of \(R = \lambda/\Delta\lambda \sim 20,000 - 150,000\). Typical spectral resolutions for accurate stellar abundance work is \(R > 40,000\), which is necessary for an accurate analysis of stellar spectra (see, for instance, Ryde et al. 2005). Note, that for interstellar spectroscopy a very high spectral resolution is crucial.

High, and very-high resolution spectroscopy in the near-IR have several advantages (see, for instance, Black 2005) which should be taken into account in the practical trade-offs. For example, there will be an increased usefulness of the near-IR wavelength region, since only by matching the resolution to the widths of the telluric features, can these be corrected for properly. Also, it will enable the study of weak and narrow lines. Observations will be more sensitive to weak lines, which is advantageous at abundance analyses since their strengths are more sensitive to the abundances and less sensitive to other circumstances such as atmospheric motions and other line-broadening mechanisms. Generally, it is obvious that more information can be retrieved concerning line shifts and broadening, when working at very high spectral resolution. Furthermore, the ubiquitous molecules that exist in the near-IR can be studied in detail at high spectral resolution only, resolving rotational and vibrational bands. As always, when going towards higher degree of detail we will certainly also discover new features not realized before. For example, going towards
very high resolution \((R = 80,000)\), mid-infrared spectra of warm, red super-giants for the first time \cite{Ryde2006a,Ryde2002,Ryde2003,Ryde2006b}. Unexpected spectral features were discovered in these well-studied stars. The features, due to photospheric water vapor, were previously overlooked since earlier observations were made at lower spectral resolution. The unexpected discovery of photospheric water vapor pointed to a lack of understanding of the outer parts of the atmospheres of red supergiants.

### 2.4 The status of the modeling of stellar atmospheres

In order to determine elemental abundances in stars, a model of the stellar atmosphere is needed. Subsequently a synthetic spectrum is computed. A discussion on the how realistic these steps are for cool stars is given in \cite{Ryde2005}. It should be noted that the largest systematic uncertainties and problems in abundance analyses are mostly within the modeling of the stellar atmospheres and the calculation of synthetic spectra.

Several ingredients in the modeling procedure have uncertainties. First, there are uncertainties in the input parameters to the stellar atmosphere modeling \((T_{\text{eff}}, \log g, \text{metallicity, mass or radius and microturbulence})\). Second, in the modeling itself, several assumptions may be wrong or the physics may be wrongly described. The physical structures of the atmospheres depend on the accuracy of the opacities used. For cool giants, opacity from water vapor is uncertain. The situation is even more severe in model atmospheres of carbon stars, where the lack of accurate molecular opacities of \(C_2H_2, CH_4, C_2H, \) and \(C_3H\) hampers the modeling efforts. Other effects like sphericity of giants and supergiants \cite{Plez1992}, non-LTE effects \cite{Short2003}, inhomogeneities in the atmospheres \cite{Asplund2000} all have to be taken into account to a certain level of realism.

Furthermore, the dynamic behavior of the atmosphere of supergiants \cite{Collet2007,Freytag2003}, and mira stars \cite{Bowen1988,Hofner1997,Hofner2003} has to be taken into account, both in the spatial structure of the atmosphere and its temporal evolution. For some stars the structures depart markedly from the static structure calculated by static models. For M dwarfs \((\text{and cooler})\) and mira stars, dust plays an important role in driving a stellar wind and shaping the model structure. There can be an intricate interplay between radiation and dust in the outer parts of the atmospheres, which has to be modelled \cite{Hofner1997}. Finally, magnetic fields on, for example, cool dwarfs could affect their structures, both vertically and horizontally, and should therefore be modelled. Also, magnetically-sensitive lines in the IR are affected by magnetic fields through the Zeeman effect.

Still only one-dimensional \((1D)\), LTE models, treating convection crudely, exist as a standard for abundance analyses of red giants and dwarfs. Diagnostic tests of their validity are needed, and the development of 3-D, non-LTE models is needed to estimate systematic errors in studies using standard models. An example of an unexpected discovery, which was made since the outer structure of the stellar atmosphere was not correctly described, was the existence of atmospheric water-vapor in Arcturus, a star assumed to be too warm to have water in its atmosphere \cite{Ryde2002,Ryde2003}. This discovery was based on water-vapor lines in the mid-IR. Furthermore, \cite{Tsuji2003,Tsuji1997} present empirical evidence of a molecular-forming region \((\text{MOLsphere})\) close to the photosphere of several M giants, which is neither expected theoretically. Clearly, caution has to be taken, and we can obviously not trust current models in all cases.

For the calculation of synthetic spectra, line identifications, accurate wavelengths, transitions probabilities, statistical weights, excitation energies, together with line-broadening parameters, partition functions, and dissociation energies \((\text{for molecules})\) are needed. The accuracy of the calculation depends on these input data and on the validity of the assumed approximations of the physics. For the IR, more data is still needed, both for atoms and a large number of molecules \cite{Ryde2005}. If a spectral line in study can not be assumed to be formed in Local Thermodynamic Equilibrium, a full statistical-equilibrium calculation for the entire atom is needed. One problem for such calculations is that the needed data for collisional transitions is uncertain or non-existent, which could leading to uncertain results.

### 3 Examples of published studies

The refereed literature on chemical abundance analyses of cool stars based on medium and high-resolution spectroscopy at \(0.8 - 2.4 \mu m\) shows that this is clearly an emerging field. We can expect the field to generate much more scientific return in the future, especially in the E-ELT era. Thanks to the realization of high-resolution, infrared \((1 - 5 \mu m)\) spectrometers such as the CRIRES \(^6\) spectrometer \cite{Kaufl2006,Moorwood2005} on the VLT, this field will grow rapidly in the near future too.

An example of abundance analyses of cool stars at high spectral resolution is the work by \cite{Nissen2007} who discuss the chemical evolution of sulphur, based on part on CRIRES data, but chiefly on the near-IR lines at 8694 and 9213 – 38 Å observed with the UVES spectrograph. Sulphur is of interest since it is not depleted on dust, which means that sulphur is a good probe of chemical enrichment and star-formation histories at cosmological distances \cite{Nissen2004}. In a number of projects on different telescopes, near-IR lines are now being used to increase the number of diagnostics available \cite{Caffau2005,Korn2005,Nissen2007,Ryde2006,Ryde2005a}. Another example is an ongoing CRIRES project \cite{Ryde2008,Ryde2009b}, the goal of which is to reveal the secrets of the Galactic bulge and to answer the questions how it was formed and how it evolved, benefiting

\(^6\) CRIRES is the last of the first generation of VLT instruments. It is more sensitive and provides a wider wavelength range than any other corresponding spectrometer available.
from the dust penetration properties of IR light (Cardelli et al. 1989). Currently spectra of mainly bright giant stars in low-obscured regions are reachable (Fig. 1), but in the E-ELT era the bulge will be exploitable in larger detail and in more regions. Note, however, that recently microlensed bulge dwarfs have also been targeted (Bensby et al. 2009). Meléndez et al. (1989) observed seven K and M giants in the bulge and determined C, N, O, Ti, Na, and Fe abundances from H and K spectra recorded with Phoenix. The C and N abundances show signatures of CN cycling and this implies that the oxygen abundance has not been altered during the stars’ lifetime. In general, the CNO abundances as well as the isotopic abundances of C and O in giants in the K band are useful as probes of mixing processes in red giants and are valuable in testing evolutionary models. Predicted values are still not consistent with observed values, which may imply that extra mixing is needed in the models. Livia Origlia and co-workers (e.g., Origlia et al. 2002, 2008) have written a number of papers on abundance studies of red giants, both in the field and in open and globular clusters in the Galactic bulge, based on NIRSPEC spectra, which are at lower resolution. Furthermore, Rich et al. (2007) presented the first detailed abundance analysis of 17 M giants of the inner bulge, also based on NIRSPEC spectra. The study by McSaveney et al. (2007) is a further example. They determine abundances in luminous, intermediate-mass AGB stars in the Magellanic Clouds with the Phoenix spectrometer. Their result is the first confirmation of a large production of primary nitrogen in these stars. Similarly, Wahlin et al. (2005, 2006) used both high-resolution Phoenix spectra and medium-resolution ISAAC spectra to determine the CNO abundances, and the $^{12}$C/$^{13}$C ratio for carbon stars in the dwarf galaxies surrounding the Milky Way of different metallicities. Even though observations in the near-IR are already being performed of the close satellite galaxies of the Milky Way, with the E-ELT many more galaxies will be targeted. The optical high-resolution spectrograph UVES has been used extensively for the determin-

7 The NIRSPEC spectrometer (McLean et al. 1998) is one of the Keck II telescope’s most used spectrometers (McLean 2005). It is a cross-dispersed echelle spectrometer, working at $0.96 - 5.5 \mu m$ at resolutions of $R = 2000 - 37,000$. It has a high-resolution mode ($R \sim 20,000 - 30,000$) which has been used in studies on spectral features and stellar abundances in, for example, brown dwarfs and red giants and dwarfs.

8 ISAAC is the medium-resolution, near-IR spectrograph. It is able to reach $R = 10,000$, and it covers a larger wavelength range than CRIRES.

9 UVES has a wavelength coverage in the red up to approximately 1 $\mu m$. The FLAMES spectrograph is a multi-object spectrograph capable of medium and high spectral resolution. In the GIRAFF configuration, 130
nation of stellar abundances of galactic and extra-galactic stellar populations, the latter being a key science case of the E-ELT and which can be address by infrared spectra of longer wavelengths too. For example, Kaufer et al. (2004) determine the first [Fe/H] and [α/Fe] abundance ratios in the Dwarf Irregular Galaxy Sextans A, by observing three A type supergiants. They find a near solar [α/Fe], which is consistent with a slow chemical enrichment in these systems. Several investigations of dwarf spheroidal (dSph) galaxies surrounding the Milky Way have been performed, for example, by Tolstoy et al. (2003) and Shetrone et al. (2003) using UVES, and Shetrone et al. (2001) using HIRES at slightly lower resolution at KECK I. Especially by the DART team (Dwarf Irregular Galaxy Sextans A, by observing three SPEC spectra, and find, as expected, that T dwarfs later than M2.5 to T6) in a survey of brown dwarfs. They discuss the relative behavior of spectral features through the sequence of stars and brown dwarfs. Del Burgo et al. (2009) determine physical parameters of T dwarfs based on NIRSPEC spectra, and find, as expected, that T dwarfs later than T5 have dust free atmospheres due to dust sedimentation.

As a final example, McLean et al. (2007) present a sequence of NIRSPEC spectra in the J band of 16 M, L, and T dwarfs (M2.5 to T6) in a survey of brown dwarfs. They discuss the relative behavior of spectral features through the sequence of stars and brown dwarfs. Del Burgo et al. (2009) determine physical parameters of T dwarfs based on NIRSPEC spectra, and find, as expected, that T dwarfs later than T5 have dust free atmospheres due to dust sedimentation.

4 Exploring stellar abundances based on near-IR observations at the E-ELT

4.1 Science drivers

Science drivers are important science cases that are used to derive the requirements for the E-ELT telescope and its instruments. A reference science driver for the E-ELT is the imaging (photometry) and spectroscopy of resolved stellar populations (SWG report 2006), which aims at answering the fundamental question of the origin and evolution of galaxies. This field represents one of the most outstanding scientific challenges in modern astronomy and will dominate galactic astrophysics for decades to come (see e.g. Bland-Hawthorn & Freeman, 2006 and Renzini, 2006). As yet there is no detailed understanding of galactic structure and evolution that is physically consistent, even for the closest galaxies (in the Local Group). For example, the number of faint galaxies is below that theoretically predicted (the missing satellite problem or cosmological substructure problem). Furthermore, environmental effects have been difficult to constrain, as also the relative importance of internal dynamic processes in undisturbed galaxies (Kormendy & Kennicutt 2004). Indeed, it is not clear how the Milky Way fits into the currently emerging cosmological model in detail. Stars are being formed today but at low rates. But the questions are when did the stars in central bulges of spiral galaxies form? Did they form early on or later through merger-induced star formation? Obviously, we have to learn more about the assembly sequence of the major components of galaxies and the role of internal versus external processes in building galaxies. The way forward is to collect more empirical facts from observations in order to constrain theoretical models. One way to elucidate such questions is to study the detailed chemical abundances of stars in large numbers of stars in various populations and fields of galaxies (see for example Silk & Wyse, 1993). This can be done by medium and high resolution stellar spectroscopy.

Hence, the study of resolved stellar populations of galaxies in order to understand the origin and evolution of galaxies, and the formation of stars, is one of three highlighted science cases for the E-ELT (SWG report 2006). The spatial resolution of an ELT will allow an exploration of individual stars even in galaxies beyond the 42 galaxies in the Local Group. Stars in several galaxies in the Virgo Cluster (18 Mpc) should be observable by photometry providing first-order ages and metallicities (Evans et al. 2006; SWG report 2006; Tolstoy 2006) and stars in galaxies of the Local Group (within approximately 1 Mpc) should be attainable spectroscopically, cf. Section 4.2. All projects on ELT-sized telescope concepts today have the formation and evolution of galaxies as one of a few key science drivers. Among the six science cases for the GMT, we find ‘ Stellar Populations and Chemical Evolution’ and ‘the Evolution of Galaxies’, and the TMT pushes it as one of its drivers and highlights it as one of the most ambitious scientific goals of the next decade. Furthermore, for the JWST the ‘Assemblies
of Galaxies’ is one of four science drivers. This field is also one of four targeted for the long-term strategic planning of European Astrophysics as expressed in the Science Vision of Astronet.

4.2 The spectrographic performance of an E-ELT.

A general consideration in the planning of the E-ELT and its instrumentation, is the balance sought in performance and complementarity to ALMA and especially to the planned JWST. The goal is to create synergy effects similar to those with the VLT/HST combination, with follow-up observations. The area in the parameter space that the E-ELT occupies by itself compared to JWST is the better achievable spatial resolution, the larger collecting power, and the possibility to carry out medium and high resolution spectroscopy. The difference in telescope sizes of JWST (6 meters) and the E-ELT (42 m), means that not only will the spatial resolution of the E-ELT at the diffraction limit be a factor of 7 better, but the E-ELT will also collect 50 times more photons per second (corresponding to more than 4 magnitudes).

The JWST wins on the ability to detect weak sources due to its higher sensitivity and the lower background in space. The spectrometers planned (which are not restricted to telluric windows) for the JWST will all have spectral resolution of less than $R = 2700$. The E-ELT has no principle restrictions on the resolution for spectroscopic studies.

The detailed exploration of stellar abundances requires spectroscopy at high resolution ($R = \lambda/\Delta\lambda \geq 40,000$). More photons are needed in spectroscopy than for imaging and photometry, which means that it will not be possible to observe as faint stars as by photometry. To estimate a relevant limiting magnitude for spectroscopy (see Table 1), we have estimated the faintest magnitude of a star with which it is possible to achieve a signal-to-noise ratio (SNR) per resolution element of approximately 50 for an observation with an exposure time of 3 hours. This limit is of course arbitrary and, depending on the science that is to be done, the SNR may need to be higher. However, with a 42 m telescope, observing at a high spectral resolution of $R = 50,000$, and using laser tomography AO, $I \sim 19.0$, and $J = H = K \sim 19.5$ is attainable. This calculation is based on the E-ELT Exposure Time Calculator in Spectroscopy Mode Version 2.14. Thus, based on the magnitudes in Table 2, Turn-Off (TO) stars in the Galactic bulge (but hardly in the Large Magellanic Cloud), red giants in open and globular clusters, in the Galactic bulge, and in dwarf spheroidal galaxies surrounding the Milky Way (marginally in M31) should be within reach for an abundance analysis in the K band, even in dense fields. Also, red giants at the Tip of the Red Giant Branch (TRGB) and supergiants will be marginally observable out to the Sculptor Group, a group of galaxies that contains several large spiral galaxies.

### Table 1 Limiting magnitude estimates based on the ETC of the E-ELT, version 2.14. For the given resolution the approximate magnitudes are given for an observation with an exposure time of 3 hours achieving a SNR~ 15 per resolution element for the $R = 50,000$ mode and SNR~ 15 per resolution element for the $R = 5,000$ mode.

| Resolution | $I$ | $J$ | $H$ | $K$ |
|------------|-----|-----|-----|-----|
| $R = 50,000$ | 19  | 19.5| 19.5| 19.5|
| $R = 5,000$  | 23.5| 24  | 24  | 24  |

Furthermore, the high spatial resolution of a 42 m telescope will be crucial for crowded star fields, such as the nuclei of Local Group galaxies such as the Andromeda galaxy. However, in order to explore large elliptical galaxies it is necessary to observe Cen A or galaxies in the Leo group (Tolstoy, SWG report 2006). They are still too far away to make it possible to study stellar abundances in detail in elliptical galaxies at high spectral resolution.

A measurement of the rough metallicity of a system can be obtained at lower resolution ($R = 5000 - 8000$) by observing the near-IR Ca II triplet at 0.86 μm (see for example Tolstoy et al. 2001). Also, isotopic ratios derived from molecular bands can be determined from lower resolution spectra (Shetrone 2003). Thus, lowering the resolution to $R \approx 5,000$ implies reaching, for example, $K = 23$ at a SNR per resolution element of 15 after 3 hours, see Table 1. This means that red giant stars in all galaxies in the Local Group can be analysed, and marginally in the galaxies in the Sculptor group. Furthermore, TO stars in some of the dwarf galaxies surrounding the Milky Way can be analysed. TRGB stars will be possible to analyse out to M81/82 and even out to Cen A.

4.3 Examples of scientific questions to be addressed

There are, in principle, three different types of possible applications at the E-ELT for determining stellar element abundances (Ryde et al. 2005). First, one could study fainter objects than before, for example, reaching for dimmer, nearby dwarfs or stars in external galaxies. 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 depend on the possibility of the E-ELT to acquire high S/N and high-resolution spectra across wide regions of the spectrum.

---

11 RGB stars have large ranges in bolometric magnitude depending on their position on the giant branches. Observing red giants higher up on the branch will make it possible to reach red giants in M31.

12 For instance Battaglia et al. (2006) require a SNR per resolution element of larger than 10 for an accurate measurement, and Bosler et al. (2007) measure calcium abundances from the Ca II triplet in spectra of SNR per pixel greater than 10.

13 M82 is the nearest starburst galaxy with ongoing star formation in a Super Star Cluster (SSC), cf. Evans et al. (2006).

14 In principle, nearly 4 magnitudes fainter, only considering the size of the telescope.
spectral regions. Second, one could study more objects in a given time, performing systematic studies of populations or performing surveys of complete samples, e.g. within a certain volume. The usefulness of surveys will be considerable as they will presumably give further clues concerning the role of red giants in stellar evolution and nucleosynthesis. Third, one could strive towards higher accuracy in the observations or the analyses, in order to achieve a better element-abundance analyses, with details about observed atmospheric velocity-fields or magnetic fields.

Examples of specific questions to address, by exploring near-IR spectra at high spectral resolution, are given herein in random order. The E-ELT will be able to address these questions for many more and fainter stars in new environments and other galaxies. A large variety of new populations will be investigated and intercompared.

### 4.3.1 Chemical evolution of galaxies and the study of stellar populations

The quantity of metals in stellar systems and in the Universe as a whole grows with time. The relative distribution of the abundances of different chemical elements and their different growths with time, provide information on the star-formation rate and initial-mass function of the systems but also on internal processes in stars and their explosions, and on processes in stellar evolution. This is possible since different elements are synthesized by different processes and in stars of different masses. Thus, chemical evolution of galaxies and the study of stellar populations can be investigated in detail for a large range of galaxies of different types and morphology. Models can best be tested with detailed abundances of an ensemble of stars. In general, the precise element compositions (e.g. C, N, O, Mg, and Ca) and kinematics can be determined, sampling different stages of the chemical enrichment of a stellar system. The metallicity distributions and the distribution of populations within stellar systems can be determined. Stars with unaltered surface compositions can be used as probes of the parent cloud from which they were formed and as such trace the star-formation history and enrichment of the interstellar medium. This is encoded in the stellar elemental abundances. The life times of the stars used in this context are long, comparable to the age of the universe, and can therefore measure the star-formation rate and metallicity at different times.

In general, studying abundances of elements in stars in a population is important for the following reasons. First, the \( \alpha \) elements (Mg, Si, S, Ca, and Ti) are important tracers of the star-formation rate (SFR) of the stellar system or population being studied. The SFR can be determined from the functional behaviour of the \([\alpha/Fe]\) ratio as a function of metallicity. A faster enrichment due to a high SFR will keep the curve at a high value also for high metallicities. Precise elemental abundances are required from many lines. This is only possible at high spectral resolution. The behaviour of the different \( \alpha \) elements can also be investigated for different stellar systems. Second, the initial-mass function (IMF) of a stellar system or population can be determined from the over-abundance of \( \alpha \) elements relative to the scaled solar value. A shallower IMF will increase the number \( \alpha \)-element producing stars thus raising the over abundance. Third, the

### Table 2 Distances, distance moduli, spatial resolutions, and magnitudes of red giants and turn-off stars in galaxies and galaxy components relevant for high-resolution, near-IR spectroscopy with the E-ELT.

| Object                   | Approx. distance [Mpc] | \( (m-M)_0 \) | \( \Theta(1 \, \text{pc}) \) | \( I_{\text{TRGB}} \) | \( K_{\text{TRGB}} \) | \( K_{\text{RBR}} \) | \( K_{\text{TO}} \) |
|--------------------------|------------------------|--------------|-----------------|------------------|------------------|-----------------|-----------------|
| Galactic bulge           | 0.008                  | 14.4\(^b\)  | 26\(^a\)        | 10.5             | 8                | 12              | 17.5            |
| LMC                      | 0.05                   | 18.5\(^e\)  | 4\(^e\)         | 14.5             | 12               | 16              | 21.5            |
| SMC                      | 0.06                   | 18.9\(^e\)  | 3.5\(^e\)       | 15               | 12.5             | 16.5            | 22              |
| Sculptor Dwarf Galaxy    | 0.09                   | 19.7\(^d\)  | 4\(^d\)         | 15.5             | 13               | 17              | 22.5            |
| Fornax Dwarf Galaxy      | 0.14                   | 20.7\(^e\)  | 1.5\(^e\)       | 16.5             | 14               | 18              | 23.5            |
| Leo I Dwarf Galaxy       | 0.25                   | 22.0\(^f\)  | 0.8\(^f\)       | 18               | 15.5             | 19.5            | 25              |
| M31                      | 0.7                    | 24.3        | 0.3\(^f\)       | 20.5             | 18               | 22              |
| Local Group              | ~ 1.0                  | 25.0        | 0.2\(^f\)       | 21               | 18.5             | 22.5            |
| Sculptor Group           | 2.5                    | 26.5        | 0.1\(^f\)       | 22.5             | 20               | 24              |
| M81/82                   | ~ 3.5                  | 27.8        | 0.06\(^f\)      | 24               | 21.5             | 25.5            |
| Cen A                    | ~ 3.5                  | 28.5        | 0.04\(^f\)      | 24.5             | 22               |
| Virgo Cluster            | 18                     | 30.9        | 0.014\(^f\)     | 24.5             |

\(^a\) TRGB (tip of the RGB) and AGB: \( M_V \sim -2.5, M_I \sim -4.0 \) and \( M_K \sim -6.5 \); RGB stars: \( M_V \sim -0.5 \) and \( M_K \sim -2.5 \); oldest turnover stars, TO: \( M_V \sim +4.5 \) and \( M_K \sim +3.0 \) (Arnold et al. 2001; ELT SWG 2006).

\(^b\) Nishiyama et al. (2006)

\(^c\) Keller & Wood (2006)

\(^d\) Kaluzny et al. (1995)

\(^e\) Gullieuszik et al. (2007)

\(^f\) Bellazzini et al. (2004)
CNO abundances are important for many reasons. Oxygen is particularly important since accurate O abundances and O/Fe ratios in an ensemble of stars will also set strong constraints on the star formation history of a stellar population. The OH lines at 1.55 μm are very useful (see, for example, Meléndez et al. 2001). The determination of carbon abundances is needed for O determinations, since CO molecules bind much O in cool stars. Optical estimates of the C abundances are highly uncertain (in most cases only upper limits), whereas the CO and OH lines at 1.55 and 2.33 μm will together easily provide C and O abundances. C is also interesting in itself. The precise site for the formation of C is still being debated (Carigi et al. 2005). In order to determine the carbon abundance it is possible to measure lines from CH, CO, C₂, and CI. The near-IR also has the virtue that only that region offers all indicators necessary for an accurate determination of the important C-N-O molecular and atomic equilibria in the atmospheres of cool stars, through the simultaneous observation of many clean CO, CN and OH lines. Finally, numerous CN lines in the H band will make it possible to determine much more accurate nitrogen abundances than from optical lines. The C+N abundances reflect the original composition of the star better than the two individual elements. The C/N ratio will also map the degree of mixing in the stars as a function of metallicity and luminosity.

Examples of more specific questions that can be tackled are, first, the dynamic evolution of the Milky Way that will be better understood by exploring the fine-structure of abundance patterns of different stellar populations (Gustafsson 1999). Studies at high accuracy of Galactic halo and thick disk stars will provide clues to early galaxy evolution. Hypotheses of the enrichment of large galaxies compared to dwarf galaxies and the enrichment of the intergalactic medium by outflows caused by stellar winds from stars and supernova explosions in dwarf galaxies can be tested. The chemical enrichment in low-mass galaxies seems to be an episodic process, whereas it is more smooth in larger galaxies. But when were the first stars formed? How many periods of large star-formation have there been? We know that there was a period of enhanced star formation at intermediate redshifts (2 < z < 4). Was this the first and dominating episode of star formation in the Universe? Studies of elemental abundances will be able to shed light on this sort of questions. The chemical evolution of galaxies will depend on the location and environment in which the stars are embedded. It seems that chemical evolution is a local process, implying that we need to investigate the chemical evolution of many more systems, such as the dwarf spheroidal galaxies and M31. Second, a comprehensive study of the components of the Milky Way, based on a solid statistical foundation, with a large sample of stars observed, will be of fundamental importance of the study of the formation and evolution of galaxies in general. A study of the relations of the thin and thick disks, and especially the least studied component, the highly obscured Galactic bulge, would be of major interest: are the disk and bulge separated components? Are bulges in general associated with the inner disks or reflect the last major merger? If disks grew later after a merger-formation of a bulge then small disks should be younger than bulges surrounded by large disks. In this picture there should be strong similarities between bulges and ellipticals. Ellipticals can be seen as bulges that have not had time (or are in a dense environment) to form a disk surrounding them. Therefore, a study of the Milky Way bulge, the closest bulge that we can investigate in detail and which near-IR spectrometers on the E-ELT will readily reach, is of great interest in connection with and complementary to the exploration of stellar populations in the elliptical galaxies also attainable with the E-ELT. Third, studying the properties of the halos, and the thick and thin disks and bulges of nearby galaxies would give empirical evidence of the formation of these structures. Disentangling the heating mechanisms, whether internal or external, which heat up the thick disks will be possible by studying stellar abundances in disk galaxies (Arnold et al. 2001).

4.3.2 Nucleosynthesis of different elements

The detailed nucleosynthesis of different elements can be investigated by studying specific resolved lines of these elements. Metals are formed in the nuclei of stars and in the end phases of stars’ lives, in AGB stars and in supernova (SNe) explosions. They are later expelled into the Interstellar Medium (ISM), and used in the formation of a new generation of stars. The yields from different types of stars are uncertain but are needed in the chemical evolution models. Accurate abundance studies of field stars and of stars in dwIrr galaxies will provide knowledge of the role of different production sites for different nuclei (Gustafsson 1999). Also, the role of SNe and hypernova in low-metallicity regions can be investigated. An example is the investigations of the origin of fluorine which is still being debated and can be investigated in the near-IR for a large sample of stars with the E-ELT. Meynet & Arnould (2000) proposed that the WR winds are significant sources of F. Thus, measurements of F, as well as C, provide a test of the WR wind models. The only F criteria are IR lines from the HF molecule. The vib-rot line at 2.34 μm is suitable for this purpose. Furthermore, stellar evolution and structure can be studied by looking at the change of specific elements, such as C, N, and O but also the s-elements (Y, Zr, Ba, La, Sr, Ce,...) in an evolutionary sequence of stars of different parameters and in different galaxies. AGB stars are luminous and red, thus favoring near-IR spectroscopy. With the E-ELT they can be studied in all Local Group galaxies.

4.3.3 Red giants, miras, and carbon stars

Investigations of red giants, miras, and carbon stars is challenging but important from an stellar evolution point-of-view. The understanding of their evolution, their structures and atmospheres are of interest. A majority of all stars will

© 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

www.an-journal.org
go through the Asymptotic Giant Branch phase, a stage that is not well understood, but very important, not the least as regards the mass return they are responsible for through their massive mass-losses. Furthermore, we do not understand the AGB stars’ evolution with increasing bolometric luminosity. Investigations of AGB stars in different populations in different Local Group galaxies would be needed. Today, we can barely reach carbon stars for an abundance analysis in the Magellanic Clouds (Wahlin et al. 2005). The Milky Way seem to have a mixed population of carbon stars. These stars have very complicated spectra with a large amount of molecular lines and bands, which means that near-IR observations are necessary in order to analyze them. Dust-enshrouded carbon stars can also be studied much easier in the near-IR.

Red giants are important as probes for studies of the chemical evolution of galaxies since they are bright. Therefore, the abundances and their variation with their evolution is important to understand. For example, their internal mixing processes can be studied in more detail. The carbon and oxygen isotopic ratios and the nitrogen abundances (e.g. from CN and NH lines) are crucial indicators of the evolutionary phase of red giants and of the efficiency of their interior mixing processes. For instance, the low ratio observed for some red giants, such as the bulge-like star Arcturus, is still not understood. Investigations of red giants (and carbon stars) in more galaxies of different characteristics will add to the investigations on the mixing processes in these stars. Also the mass-loss process from red giants is important to study, since it is not understood from first principles and plays an important role in the lives of these stars and the expulsion of newly synthesized elements into the ISM.

4.3.4 The coolest dwarfs

Large surveys of the coolest dwarf stars (such as the M, L, T, and brown dwarfs) can be done, which is important for the analysis and modeling of these stars. Spectral features of CO in the near-IR is a powerful diagnostic tool to analyze M dwarfs.

4.3.5 Extremely metal-poor stars

The systematic study of extremely metal-poor stars [Fe/H]<−3, providing information on the first steps of chemical enrichment and of early star-formation of the first stars, will be possible with the E-ELT. It may also give insights into the signatures of individual Supernova Type II explosions and thereby constraints on their yields, which are still very uncertain. The very first stars can be searched for in the Galactic bulge where they are expected to be, representing the earliest phases of the formation of the Milky-way or even the protogalaxy. Also, due to the high spatial resolution of an E-ELT in the near-IR, the study can extend to other Local Group galaxies. Since the lines of extremely metal-poor stars are very weak, very high S/N ratios are needed, a feature the E-ELT also will be able to deliver.

4.3.6 Zeeman splitting

Due to the sensitivity of certain infrared lines to magnetic fields through the Zeeman effect, studies of stellar magnetic field should be possible. High signal-to-noise ratios are needed. The ratio of the wavelength separation of the Zeeman splitting (ΔλB ∼ gλB) and the non-magnetic Doppler width (ΔλD ∼ λ), is given by ΔλB/ΔλD ∼ gλB (Ryde et al. 2004; Ryde & Richter 2004). Since the ratio grows linearly with wavelength, it is easier to detect Zeeman split lines in the infrared compared to the optical.

5 Options and Requirements on ELT instrumentation for stellar abundance work

In order to discuss the requirements for near-infrared, medium and high-resolution spectrometer concepts for the E-ELT, a few key projects are proposed here. First, the exploration of the elemental abundances in the atmospheres of red giants, subgiants, or even TO stars in the Galactic bulge. A survey of abundances of bulge stars will determine how the bulge was formed and give crucial insights into galaxy formation and evolution in general. TO stars will be reached. However, subgiants and red giants are spectroscopically more interesting in the near-IR. Second, the study of the TRGBs in M81/82 and Cen A. The Tip of the Red Giant Branch (TRGB) will be reached in these galaxies at low spectral resolution. The TRGB in galaxies in the Virgo Cluster will, however, be difficult. A survey of the diagnostically important Cati Triplet in these galaxies would give metallicities of stars in a range of galaxy types. This is one of the main science drivers of ELTs in general. Third, the investigation of the First Stars, that is, extremely metal-poor stars in our and other galaxies. These can be observed by the E-ELT at very high SNR in order to detect very weak lines. Fourth, the exploration of the Galactic Chemical Evolution in M31 and in other galaxies of the Local Group in the same way that has been done for the Milky Way (Bensby & Feltzing 2006; Reddy et al. 2006). Different components of the galaxies, such as the thick and thin disks and the halo, can be explored. Previous work on our galaxy has changed our view of it profoundly. We also believe that other galaxies may look different. In Table 3, the specifications of important parameters are shown for the different key projects.

5.1 Requirements for a medium- to high-resolution spectrometer for the E-ELT

Thus the requirements for a medium- to high-resolution spectrometer for the E-ELT based on the scientific questions outlined above are provided below.

- A high spatial resolution is needed for crowded fields in the Galactic bulge and in Local Group galaxies. This is achieved with a 42 m telescope with adaptive optics. As noted earlier, in the K band the diffraction limit will be less...
than 0.015′′ for the E-ELT, implying that stars lying 0.05 pc apart in projected distance in M31 will be resolved, cf. Table[2]. Likewise, stars lying 1 pc apart on the sky in galaxies in the Virgo cluster will be resolved. In a typical galaxy field the mean projected distance between stars is estimated to 0.1 pc for dense stellar fields like the Galactic bulge and 1 pc for red giants in galaxy fields. This would imply approximately 500 stars/arcminute for the Galactic bulge. However, a check with a few 2MASS fields of the bulge shows an order of magnitude lower spatial density of identified stars. 2MASS has a magnitude limit of $K \sim 14$ which means that one can assume that it has detected most bulge red giants (the reddening is 1/10 [Cardelli et al. 1989] of what it is in the visual, implying that $A_{\text{visual}}(K) < 3$). This factor of ten is therefore used to estimate the density of red giants in M31, where the E-ELT will only detect red giants. The same factor, although it ought to be higher, is also used for an estimate of an upper limit of the surface density of red giants in Cen A.

- The **spectral range** of interest for high spectral resolution spectroscopy which is not covered by the CODEX concept for the optical region [Pasquini et al. 2006], is 0.8 – 5.0 μm. At least the J, H, and K bands will provide a necessary wavelength region, for instance enabling the determination of α elements and the CNO abundances. See Table[4] to see examples of which lines are available in the different bands.

- Exploring stellar abundances in detail requires a high **spectral resolution**. Stellar spectral lines are typically a few km s$^{-1}$ broad, which means that in order to resolve them an $R \sim 100,000$ is needed. This will minimise blends. However, depending on the stars investigated a lower resolution might still be appropriate, but a resolution of at least $R > 40,000$ is desirable.

- The two high-resolution instruments existing today at 8-10 meter telescopes are the Phoenix [Hinkle et al. 2003] and CRIRES [Käufl et al. 2006; Moorwood 2005] spectroimeters. These are single order instruments, which hampers their efficiency. A **full coverage** of a band in one or a few exposures would increase the efficiency and scientific return with a large amount. Thus, a cross-dispersed spectrometer would be required and would increase the instantaneous wavelength coverage up to 20 times compared to that of CRIRES. A full wavelength coverage would be a new feature for high-resolution spectrometers working in the near-IR.

### Table 3

| Subgiants in the Galactic bulge | TRGB stars in M81/82 and Cen A | First stars | Galactic Chemical Evolution in M31 |
|---------------------------------|---------------------------------|-------------|-----------------------------------|
| Angular resolution              | $\leq 2''$                      | $\leq 0.04''$ | $\leq 3''$                       | $\leq 0.3''$ |
| Spectral range                  | $0.8 - 2.5 \mu m$              | $0.8 - 2.5 \mu m$ | $0.8 - 2.5 \mu m$ | $0.8 - 2.5 \mu m$ |
| Spectral resolution             | $R > 60,000$                   | $R > 5,000$ | $R > 60,000$ | $R > 60,000$ |
| SNR                             | high                           | low         | very high                        | high         |
| Spectral coverage               | full                           | parts       | full                             | full         |
| in one exposure                 |                                |             |                                  |              |
| Spatial density$^a$             | $\sim 500$ stars/('')$^2$      | $\sim 50$ stars/('')$^2$ | N/A                              | $\sim 1$ star/('')$^2$ |

$^a$ The numbers for the spatial density of stars given in the Table are based on the assumption that the stars are evenly spaced in projected distance and the mean projected distance between stars is estimated to 0.1 pc for dense stellar fields like the Galactic bulge and 1 pc for red giants in galaxy fields.

### Table 4

| Band | Spectral diagnostics |
|------|----------------------|
| J band (1.0 – 1.3 μm) | CN, Na, Al, Mn, Si, Ti, Fe, Mg, Sr, etc. |
| H band (1.5 – 1.8 μm) | CO ($\Delta v = 3$), OH, Mg, Al, Si, etc. |
| K band (2.0 – 2.4 μm) | CO ($\Delta v = 2$), Na, Ca, Si, Al, Mg, Ti, etc. |
| L band (3.3 – 4.2 μm) | OH, SiO($\Delta v = 2$), Mg, Ca, etc. |
| M band (4.5 – 5.5 μm) | CO($\Delta v = 1$), SiO($\Delta v = 2$), AI, etc. |

- In order to reach beyond the galaxies of the Local Group, i.e. to probe galaxies of a wider range of morphological types, by high-resolution spectroscopy, a **multi-object spectrometer** would make observing more efficient and make it possible at all. If a large number (10-50) of red giants could be observed at once, then long exposures could be justified, allowing us to start probing stars in galaxies beyond the Local Group. Another way to proceed is to co-add observations of a large number of stars to the same type, which would require a multi-fiber system.

- An image slicer would increase the amount of light that is recorded by the spectrograph from the AO image on the narrow (high-resolution) slit. A fiber-fed spectrograph would also solve this problem.

### 5.2 Current E-ELT instrument studies

In the Phase B study of the E-ELT there are 8 detailed instrument and two post-focal AO studies currently well under way, and performed by institutes or consortia of institutes
6 Conclusions

In spite of the emerging character of near-IR spectroscopy and, for instance, the lack of spectroscopic data, the near-IR is a wavelength region where much scientific progress can be made, also concerning the determination of stellar abundances. It is preferred over the optical region in conjunction with crowded fields since the diffraction limit of a large telescope will be achieved in the near-IR first, and in conjunction with dust-obscured regions in the Universe, due to the lower opacity of gas and dust in the near-IR. Red giants, the probes that will enable us to study stellar abundances in detail in all Local Group galaxies, are brightest in the near-IR and their spectra show several advantages, thus making the analyses more accurate. Furthermore, the important C, N, and O abundances are more accurately determined in the near-IR, as are isotopic ratios from molecular lines. However, the advantage of the near-IR depends on the sensitivity of the IR detector arrays compared with the optical CCDs. Also the possibility of a larger wavelength coverage gives the optical an advantage, if the near-IR spectrometers are not cross-dispersed. Depending on the project, the near-IR would be complementary to the optical region.

For a detailed abundance analysis a high spectral resolution is needed. Blends and uncertainties can only be minimized by observing at high resolution. Especially red giants, late M-stars, and carbon stars can have messy spectra that can only be disentangled by analyzing the intrinsic spectrum of the stars, i.e. a stellar spectrum that is not degraded by an instrumental profile that is much broader than the intrinsic widths of the stellar features. However, some questions can be addressed at medium resolution too, such as observing the metallicity indicator (Ca II Triplet) and molecular bands.

The SIMPLE spectrometer concept, being studied for the E-ELT, will provide a high spectral resolution in the near-IR, which would allow a detailed abundance analysis of stars in stellar populations at large distances. The EAGLE (Cuby et al. 2008) and HARMONI (Tecza et al. 2009) spectrometer concepts will satisfy the needs at medium spectral resolution and the CODEX (Pasquini et al. 2006) plans the needs for a high spectral resolution spectrometer working in the optical (λ = 0.4 – 0.8 µm range (ESO/STC-430 2007)).

No doubt, with high-resolution spectrometers in the near-IR at extremely large telescopes, in combination with more realistic models of cool stars, we may eventually look forward to uncovering the detailed secrets of stellar populations and stellar evolution in galaxies in the Local Group but also 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 traveling shocks, magnetic fields, convection, mass loss, dust formation and non-equilibrium radiation fields.

Acknowledgements. This work was initiated while the author was a visitor to the E-ELT Instrumentation Department at the ESO.
Garching headquarters in 2007 and 2008. The author wishes to thank Sandro D’Odorico for giving him the opportunity to write this paper and for reading and giving valuable comments improving the manuscript. The author also wishes to thank Bengt Gustafsson and Suzie Ramsay for carefully reading the manuscript.

References

Arnold, L., Bacon, R., Davies, R., et al.: 2001, in www.astro-opticon.org/lps /leiden_gal.ps
Asplund, M., Nordlund, Å., Trampedach, R., Allende Prieto, C., and Stein, R. F.: 2000, A&A 359, 729
Battaglia, G., Irwin, M., Tolstoy, E., et al.: 2008, MNRAS 383, 183
Battaglia, G., Tolstoy, E., Helmi, A., et al.: 2006, A&A 459, 423
Bellazzini, M., Gennari, N., Ferraro, F. R., & Sollima, A.: 2004, MNRAS 354, 708
Bensby, T. & Feltzing, S.: 2006, MNRAS 367, 1181
Bensby, T., Feltzing, S., Johnson, J. A., et al.: 2009, ArXiv 0911.5076
Black, J. H.: 2005, in H. U. Kaufl, R. Siebenmorgen, & A. F. Moorwood (eds.), High Resolution Infrared Spectroscopy in Astronomy, p. 3
Bland-Hawthorn, J. & Freeman, K. C.: 2006, Memorie della Societa Astronomica Italiana 77, 1095
Bosler, T. L., Smecker-Hane, T. A., & Stetson, P. B.: 2007, MNRAS 378, 318
Bowen, G. H.: 1988, ApJ 329, 299
Caffau, E., Bonifacio, P., Faraggiana, R., et al.: 2005, A&A 441, 533
Cardelli, J. A., Clayton, G. C., & Mathis, J. S.: 1989, ApJ 345, 245
Carigi, L., Peimbert, M., Esteban, C., & García-Rojas, J.: 2005, ApJ 623, 213
Collet, R., Asplund, M., & Trampedach, R.: 2007, A&A 469, 687
Connes, P.: 1970, ARA&A 8, 209
Crampton, D., Simard, L., & Silva, D.: 2009, in A. Moorwood (ed.), Science with the VLT in the ELT Era, p. 279
Cuby, J.-G., Morris, S., Bryson, I., et al.: 2008, in I. S. McLean & M. M. Casali (eds.), Ground-based and Airborne Instrumentation for Astronomy II., Vol. 7014 of Proc. SPIE, p. 70141K
Cunha, K. & Smith, V.: 1999, A&A 342, 426
Gustafsson, B., Karlsson, T., Olsson, E., & Ryde, N.: 1999, A&A 319, 648
Gustafsson, B., Gauschter-Loidl, R., Aringer, B., & Jorgensen, U. G.: 2003, A&A 399, 589
Israelian, G. & Rebolo, R.: 2001, ApJ 557, L43
Johansson, S.: 2005, in H. U. Käufl, R. Siebenmorgen, & A. Moorwood (eds.), High Resolution Infrared Spectroscopy in Astronomy, p. 62
Kalluzny, J., Kubiak, M., Szymanski, M., et al.: 1995, A&AS 112, 407
Kashikawa, N., Aoki, K., Asai, R., et al.: 2002, PASJ 54, 819
Kauer, A., Venn, K. A., Tolstoy, E., Pinte, C., & Kuridzicki, R.-P.: 2004, AJ 127, 2723
Kaufer, A., Amico, P., Ballester, P., et al.: 2006, The Messenger 126, 32
Keller, S. C. & Wood, P. R.: 2006, ApJ 642, 834
Kobayashi, N., Tokunaga, A. T., Terada, H., et al.: 2000, in M. Iye & A. F. Moorwood (eds.), Optical and IR Telescope Instrumentation & Detectors, Vol. 4008 of Proc. SPIE, p. 1056
Kormendy, J. & Kennicutt, Jr., R. C.: 2004, ARA&A 42, 603
Korn, A. J. & Ryde, N.: 2005, A&A 443, 1025
Lambert, D. L., Brown, J. A., Hinkle, K. H., & Johnson, H. R.: 1984, ApJ 284, 223
Lambert, D. L., Gustafsson, B., Eriksson, K., & Hinkle, K. H.: 1986, ApJSS 62, 373
Letarte, B., Hill, V., Jablonka, P., et al.: 2006, A&A 453, 547
Letarte, B., Hill, V., & Tolstoy, E.: 2007, in EAS Publications Series, Vol. 24 of Engineering and Science, p. 33
Maillard, J. P.: 1978, in M. Hack (ed.), High resolution spectroscopy, p. 108
McLean, I. S.: 2005, in H. U. Käufl, R. Siebenmorgen, & A. F. Moorwood (eds.), High Resolution Infrared Spectroscopy in ESO/STC-430, 5 April 2007
Evans, C., Atad, E., Hastings, P., et al.: 2006a, in EC FP6: E-ELT Design Study: Momsi, a multi-object, multi-field spectrometer & imager for the E-ELT, Vol. ELT-TR-EUKA-11200-0002
Evans, C., Cunningham, C., Atad-Ettedgui, E., et al.: 2006b, in I. S. McLean & M. Iye (eds.), Ground-based and Airborne Instrumentation for Astronomy, Vol. 6269 of Proc. SPIE, p. 62692V
Freytag, B. & Höfner, S.: 2003, Astronomische Nachrichten Supplement 324, 173
Geller, M.: 1992, in Key to Identification of Solar Features, NASA Ref. Publ. 1224, vol III (Washington, DC)
Gullieuszik, M., Held, E. V., Rizzi, L., et al.: 2007, A&A 467, 1025
Hinkle, K., Wallace, L., & Livingston, W. C.: 1995, Infrared atlas of the Arcanus spectrum, 0.9-5.3 microns, San Francisco, Calif.: Astronomical Society of the Pacific, 1995.
Hinkle, K. H., Blum, R. D., Joyce, R. R., et al.: 2003, in P. Guhathakurta (ed.), Discoveries and Research Prospects from 6- to 10-Meter-Class Telescopes II., Vol. 4834 of Proc. SPIE, p. 353
Hinkle, K. H., Cuberly, R. W., Gaughan, N. A., et al.: 1998, SPIE 3354, 810
Hinkle, K. H. & Lambert, D. L.: 1975, MNRAS 170, 447
Höfner, S. & Dorfi, E. A.: 1997, A&A 319, 648
Höfner, S., Gautschy Loidl, R., Aringer, B., & Jorgensen, U. G.: 2003, A&A 399, 589
Keller, S. C. & Wood, P. R.: 2006, ApJ 642, 834
Kobayashi, N., Tokunaga, A. T., Terada, H., et al.: 2000, in M. Iye & A. F. Moorwood (eds.), Optical and IR Telescope Instrumentation & Detectors, Vol. 4008 of Proc. SPIE, p. 1056
Kormendy, J. K. & Kennicutt, Jr., R. C.: 2004, ARA&A 42, 603
Korn, A. J. & Ryde, N.: 2005, A&A 443, 1025
Lambert, D. L., Brown, J. A., Hinkle, K. H., & Johnson, H. R.: 1984, ApJ 284, 223
Lambert, D. L., Gustafsson, B., Eriksson, K., & Hinkle, K. H.: 1986, ApJSS 62, 373
Letarte, B., Hill, V., Jablonka, P., et al.: 2006, A&A 453, 547
Letarte, B., Hill, V., & Tolstoy, E.: 2007, in EAS Publications Series, Vol. 24 of Engineering and Science, p. 33
Maillard, J. P.: 1978, in M. Hack (ed.), High resolution spectrometry, p. 108
observations (Spring 2009). It will be able to observe from the UV planned for the period 2008-2012.

A resolution of IR (scope’s near-IR Spectrograph (Elias et al. 2006) works in the near-infrared resolution of 12,000 and in the near-IR arm (1000-2500 nm) it will achieve a spectral range of 0.96-5.6 μm and, finally, FOCAS (Kashikawa et al. 2002) and HDS (Noguchi et al. 1998) also at Subaru covers a spectral range to 1 μm at up to R = 7500 and 100,000, respectively. The Giant Magellan Telescope (GMT) consortium has identified a few instrument concepts which are candidates for the set of generation instruments to be developed. Relevant for stellar spectroscopy in the near-IR is the GMTNIRS: the GMT near-IR High-Resolution Spectrometer. It is planned to work at 1 - 5 μm, and provide spectra at a resolution of R ∼ 50, 000 – 120, 000.

First-decade’ instruments, relevant for stellar spectroscopy, which are planned to be operational within the first decade of the TMT’s life-time are, (in order of decreasing spectral resolution), first the very relevant spectrometer NIRES, which is a near-infrared Echelle Spectrograph. It will be a diffraction-limited spectrometer for the 1 - 2.4 μm region providing high-resolution spectra of R = 20, 000 – 100, 000. Second, HROS, the High-Resolution Optical Spectrometer, will work up to at least 1 μm (with the goal of reaching up to 1.3 μm) at a resolution of 50, 000 < R < 90, 000. Finally, IRMOS, the Infrared Multi-Object Spectrograph, will work in the near-infrared (0.8 - 2.5 μm) at a resolution of R = 2, 000 – 10, 000 with multiple Integral Field Units (IFU) to access a S’ field.

The Giant Magellan Telescope (GMT) consortium has identified a few instrument concepts which are candidates for the set of generation instruments to be developed. Relevant for stellar spectroscopy in the near-IR is the GMTNIRS: the GMT near-IR High-Resolution Spectrometer. It is planned to work at 1 - 5 μm, and provide spectra at a resolution of R ∼ 50, 000 – 120, 000.

MRS/HRS) which provide R = 30,000-120,000 up to 1100 nm (Tull 1998) and R = 5,000-10,000 up to 1800 nm (Ramsey et al. 2003), respectively. The HIRES spectrometer (Vogt et al. 1994) at KECK I has a red configuration working up to 1 μm with resolutions of R = 25, 000 – 85, 000. GNIRS, the Gemini South telescope’s near-IR Spectrograph (Elias et al. 2006) works in the near-IR (1 - 5.5 μm) at a resolution up to R = 18, 000. IRCS, the Subaru telescope’s medium resolution echelle spectrometer (Kobayashi et al. 2000) covers the spectral region of 0.8-5.6 μm, and, finally, FOCAS (Kashikawa et al. 2002) and HDS (Noguchi et al. 1998) also at Subaru covers a spectral range to 1 μm at up to R = 7500 and 100,000, respectively.

There also exist instrumentation plans for existing 8-10 meter class telescopes. The VLT 2nd generation instruments are planned for the period 2008-2012. Xshooter has recently been commissioned and was highly oversubscribed in the first call for observations (Spring 2009). It will be able to observe from the UV to the K-band in one observation at medium resolution (D’Odorico et al. 2006). In the visual-red arm (550-1000 nm) it will achieve a spectral resolution of 12,000 and in the near-IR arm (1000-2500 nm) it will have a R ∼ 7500 for a 0.6” slit. Limiting AB magnitudes, for a 1 hour exposure and S/N=10 per resolution element, are R = 21.2, J = 20.5, H = 20.8, and K′ = 19.3. The KMOS instrument will work from 1000-2500 nm and have R = 3400 – 3800, i.e. low resolution. At GEMINI the plans for the HNRS, a near-infrared high-resolution spectrometer, are unclear. It was chosen in 2003 for further review, but was not endorsed as it is at the Aspen meeting in 2005. Finally, at the Large Binocular Telescope, LBT, the Pepsi spectrometer will be able to achieve resolutions of R = 40, 000 – 300, 000 up to 1050 nm and the near-IR spectrometer, LUCIFER, will achieve resolutions up to R = 40, 000.

Apart from the E-ELT there are two other ELT concepts under study today. One of them is the Thirty Meter Telescope, TMT, which is being planned as a collaboration between USA, Canada and Japan (and is the result of the merging of the earlier CELT, GSMT, and VLOT ELT efforts). It will have a 30m, highly segmented primary mirror consisting of 738 individual 1.2-meter mirrors, and is scheduled for first-light in 2018. The other ELT concept is the Giant Magellan Telescope, GMT, which is an USA, Australian and Korean initiative to build an ELT. It will consist of 7 individual 8m primary mirror segments having a resolving power corresponding to a 24.5 meter telescope, and a light collecting power corresponding to a 21.2 meter telescope. It too has a scheduled completion date of 2018.

TMT instrument plans (Crampton et al. 2009) are divided into ‘early-light’ and ‘first-decade’ instruments. Three early-light instruments, which are planned to be operational from the start, have been chosen (Hickson 2006). These are, first, the IR imaging spectrometer, IRIS, performing diffraction-limited spectroscopy with slits or multiple employable IFU in the 0.8 - 2.5 μm region at a resolution of R = 4, 000. This resolution is marginally what we have defined as medium resolution. One of three science cases for this spectrometer is the study of stellar populations in galaxies out to the Virgo Cluster. Second, the IR multi-slit spectrometer, IRMS which is a clone of MOSFIRE for KECK (0.9 - 2.5 μm, Rmax = 5, 000 with full coverage.). Third, the wide-field optical spectrometer, WFOS, which is a multi-object spectrometer mainly for the region up to 1.1 μm, but it once had the goal of reaching 1.6 μm. The spectral resolution planned for is R ≤ 5, 000. The goal is still to achieve R ≲ 7, 500.

In passing it can be noted that for the JWST (scheduled to be launched in 2013) the most relevant spectrometer planned is the NIRSPEC spectrometer which works at low resolution (Rmax = 3000).