GAIA STELLAR CHEMICAL ABUNDANCES AND GALACTIC ARCHAEOLOGY

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ABSTRACT

The chemical information derived from the Gaia data will be crucial for tagging stars in the Galaxy and thus for disentangling the Galactic history. The derivation of detailed chemical abundances using the Gaia tools (RVS, Astrometry, MBP) is examined exploring its impact on Galactic evolutionary models. We look into the difficulties for obtaining an accurate diagnostic of the Galactic chemical history, like NLTE effects, chromospheric activity and the consequences of the element diffusion in stellar interiors. Finally, we point out some open questions on the Galactic evolution that Gaia abundances can precisely help to answer.

Key words: Gaia; Radial Velocity Spectrometer; Galaxy: evolution, formation; Stars: abundances.

1. INTRODUCTION

The extraction of the chemical abundance information from the Gaia/RVS data is a crucial task for Gaia's contribution to Galactic archeology. The identification of present-day components of the Galaxy with elements of the original protocloud can help us to unveil the detailed sequence of events which led to the Milky Way. In particular, individual stars carry information about the birth site at the time of their formation. Gaia will provide a rich data set of stellar properties, for a vast catalogue of stars that will offer, for the first time, the possibility of listing the survived inhomogeneities after the dissipative process occurred at an early stage of Galactic history. On one hand, three-dimensional kinematic measurements will enable the identification of stars with Galactic halo component, thin disc, thick disc, retrograde motion stars, highly elliptical orbits, etc. On the other hand, thanks to the resolution of the Gaia Radial Velocity Spectrograph (RVS), it will be possible to derive individual chemical abundances of elements stored within stellar atmospheres. Abundances are one of the keys to associate large samples of stars with a time and a site of formation mainly because of their intimate link with Galactic star formation history. In the following, we will look into the process of stellar chemical abundance determinations with Gaia. First, the chemical information stored on RVS data is reviewed in Section 2. The extraction of the information using abundance synthesis techniques, together with its possible limitations is treated in Section 3. A particular mention to non-local thermodynamic equilibrium is included. In Section 4, the difficulties in the data interpretation are discussed and, finally, Section 5 analyses the contribution of Gaia chemical data to Galactic studies of formation and evolution. This review is focused on late-type stars, which will have a central role on the Gaia impact to Galactic evolution models.

2. GALACTIC ARCHEOLOGY AND RVS ABUNDANCE DATA

Thanks to the RVS spectral resolution, R=11 500, several element lines, depending on stellar spectral type and signal to noise ratio, can be identified. As illustrated in Figure 1, the most relevant features in the RVS wavelength range are the ionized calcium triplet lines, together with the hydrogen Paschen lines. Many lines of iron and iron peak elements can be also found. Moreover, besides of calcium, other alpha-elements like silicon, sulfur, magnesium and titanium have features in the RVS range. One s-process element, zirconium, has one measurable line in the appropriate conditions of signal to noise and atmospheric parameters. Finally, molecular lines, like the TiO and CN lines, are detectable for the coolest stars.

In addition to the chemical information stored on the different lines of the RVS spectra, the dependence of spectral features on stellar atmospheric parameters can help to derive the effective temperature, gravity, global metallicity and microturbulent velocity of the stars we are dealing with (see Recio-Blanco et al. 2005).

The relevance of determining individual chemical abundances to our knowledge of Galactic formation and evolution can be better understood if we take into account the different origins of these elements. The complex interactions between stars and the interstellar medium (ISM), that lead the galactic chemical evolution, are one of the keys to unveil the Milky Way history. Stars inject energy, recycled gas and nuclear reaction products enriching the interstellar medium from which other generation of stars form later. On the other hand, nuclear products may be lost from the ISM by galactic winds or diluted by inflow of relatively unprocessed material.

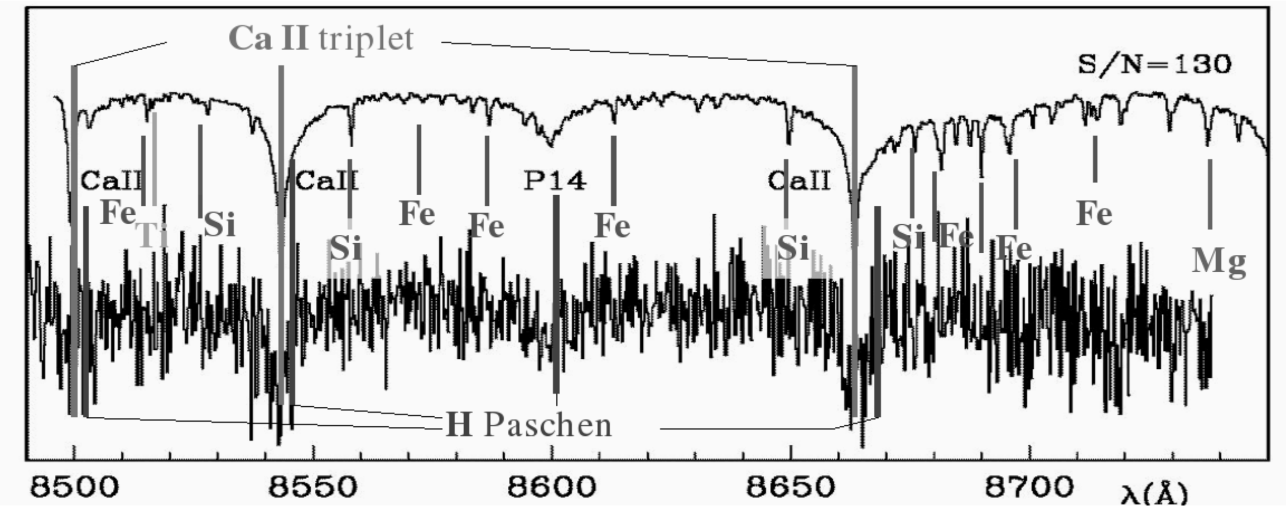

Figure 1. Example of line identifications for one F3 III star, with different signal to noise ratios, in the RVS wavelength range and R=11 500.

The effects of different sorts of stars on the ISM depend on their initial mass and on whether they are effectively single stars or interacting binaries. The elements with measurable lines in the RVS lambda range come from different stellar sources. Massive stars, with initial mass above about 10 solar masses, have short lives and they emit partially burned material in the form of stellar winds. Those that are not too massive eventually explode as Type II (or related Types Ib and Ic) supernovae ejecting elements up to the iron group, including alpha-elements, and a sprinkling of heavier elements. Intermediate mass stars, between 1 and 10 solar masses, undergo complicated mixing processes and mass loss in the advanced stages of their evolution, culminating in the ejection of a planetary nebula while the core becomes a white dwarf. Such stars are important sources of fresh carbon, nitrogen and heavy elements formed by the slow neutron capture (s-) process. On the other hand, some interacting binaries, believed to be the progenitors of Type Ia supernovae, are important contributors to iron-group elements in the Galaxy.

As a result of the variety of sources, with differing lifetimes, from which the measurable elements come from, the chemical abundance ratios of some species to another provide an indication of the star formation history time scale and details of the chemical enrichment for one specific population.

One clear example of this approach, applicable through the RVS data, is the [α/Fe] ratio. As mentioned before, α-elements are mostly ejected by Type II supernovae (SNe II) from massive stars with short lifetimes. They come from the hydrostatic burning phase within the pre-supernova star and, therefore, α yields would not highly depend on the mass cut or details of the fall-back explosion mechanisms. On the contrary, iron is mostly produced by Type Ia supernovae, occurring in binary systems after much longer times. As a consequence, stars with high [α/Fe] ratios should be formed shortly after the interstellar medium has been enriched by SNe II, while low [α/Fe] values should indicate that the star was born after the later SNe Ia contribution. It is worth noticing, however, that the timescale for changes in [α/Fe] depends not only on the star formation history, but also on the initial mass function, the SNe Ia timescale and timescales for mixing the SNe Ia and SNe II products back into the interstellar medium (see, among others, Matteucci, 2001). Nevertheless, the [α/Fe] ratio can reveal time gaps or spatial gradients in the star formation history and is, therefore, one precious information to extract from Gaia/RVS spectra (see also Nissen 2005).

Finally, the contribution of a specific type of star will be possible to estimate via the corresponding element abundances, as those of CNO cycle products and s-process elements for the case of intermediate mass stars.

3. EXTRACTION OF THE CHEMICAL INFORMATION FROM THE GAIA/RVS SPECTRA

The basic idea of the chemical abundance synthesis is to calculate a spectrum, in the appropriate wavelength range, by solving the equation of radiative transfer through a stellar atmosphere, which is finally compared to the observed one. Accurate abundance analysis is therefore an elaborate physical and numerical exercise involving several steps. First of all, a model atmosphere has to be chosen, given a set of stellar parameters, suitable for the analyzed star. In addition, spectral line data, such as the central wavelength, excitation potential, oscillator strength, damping, etc have to be compiled for each of the atomic and molecular lines. The population of atoms, ions or molecules in a given energy level has to be derived, together with the corresponding absorption and emission coefficients. The equation of radiative transfer is then integrated as a function of the assumed abundances to produce the synthetic spectrum.

In this section, we will briefly described the above men-

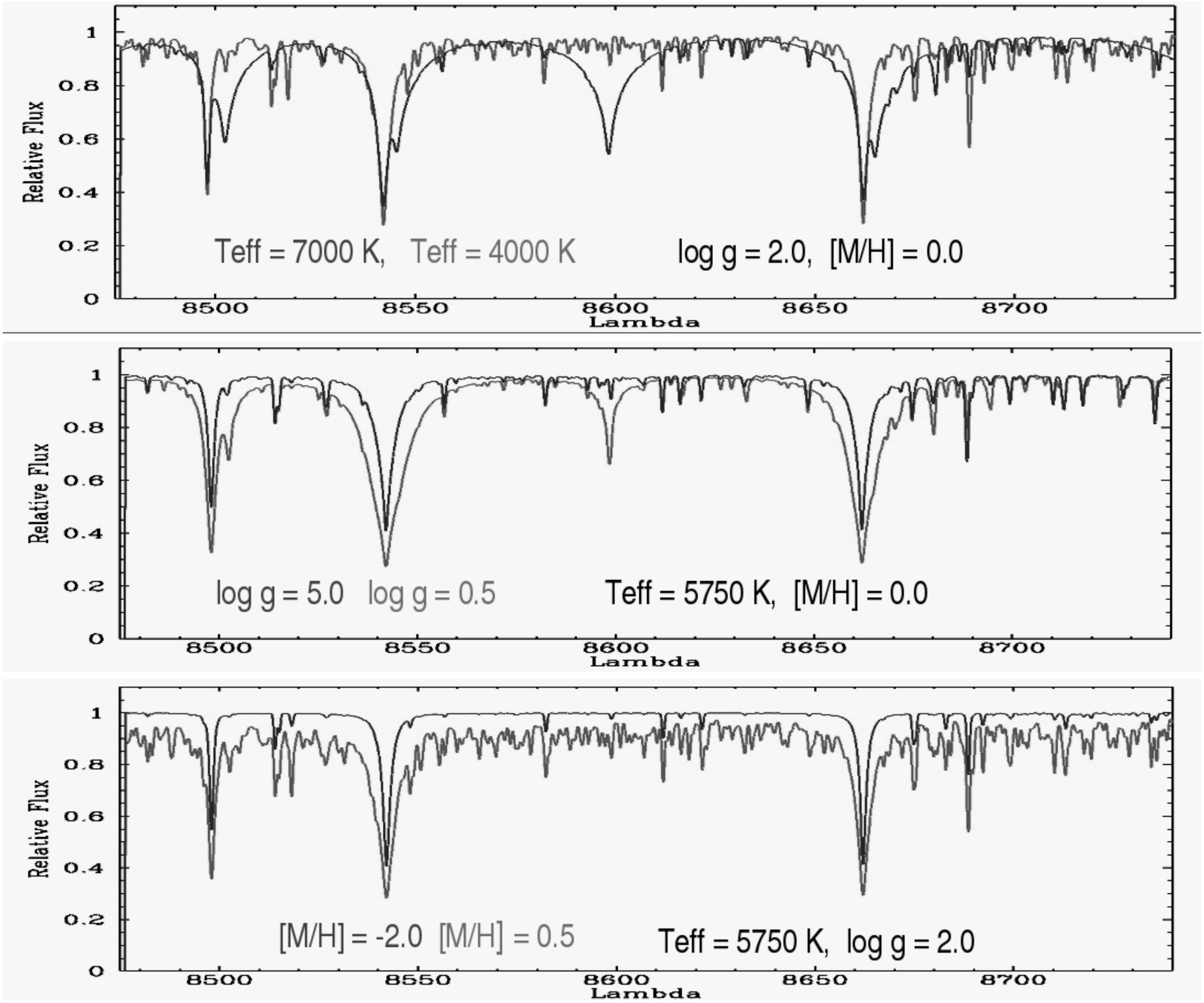

Figure 2. Continuum-normalized synthetic spectra, with the RVS spectral resolution, showing the variation of spectral features in the RVS region by changing the effective temperature (upper panel) the surface gravity (middle panel) and the global metallicity (lower panel).

tioned points of the abundance synthesis process, for the specific case of the Gaia/RVS data, taking into account the possible limitations and problems in the Gaia chemical information derived from them.

3.1. Atmospheric Parameters and Model Atmospheres

The first thing to do is to deduce the stellar effective temperature, surface gravity and global metallicity in order to select the appropriate atmospheric model for the star under analysis. One possible approach to this is the derivation from the Gaia photometric and astrometric data. This information, complementary to the spectroscopic one, will be crucial for the classification of the stars observed by RVS and will benefit from the wider wavelength range covered by the photometric bands. For details about the photometric derivation of atmospheric parameters we refer to the contributions presented by the photometric and classification working groups (Jordi & Høg 2005, Bailer-Jones 2005).

A second possible approach is the spectroscopic derivation of the stellar parameters, which relys on the dependences of spectral lines on effective temperature, surface gravity and global metallicity. Figure 2 presents three couples of continuum-normalized synthetic spectra showing the variation of spectral features in the RVS region by changing the temperature (upper panel) the gravity (middle panel) and the global metallicity (lower panel). It is important to point out, on the other hand, that one important characteristic of the above mentioned dependences is non-linearity.

At the Observatoire de la Côte d'Azur, we are presently developing an automatic procedure that uses the minimum distance technique, combined with the objective analysis, to compare one observed spectrum of unknown atmospheric parameters and abundances to a multi-dimensional grid of synthetic spectra. The distance from the observed spectrum to each spectra of the grid is treated as an exponential weight to perform a mean of the individual parameters, with a weight$=\exp(-dn)$. The optimal value of n depends on the signal to noise of the object spectra, being higher for lower S/N. The n parameter is for the moment optimized to give the best mean error over all the grid of parameters. Details of this method are described by Recio-Blanco et al. (2005). This procedure is also applicable, and will be specifically developed, to derive chemical abundances for individual elements.

Summing up, there are two possible and complementary ways to determine stellar atmospheric parameters prior to the selection of an atmospheric model. These two approaches are illustrated in Figure 3. The possibility to combine photometric, astrometric and spectroscopic data, one of the main characteristics of the Gaia mission, will be crucial to accurately deduce the information about stellar atmospheres, necessary to the individual chemical abundance measurements.

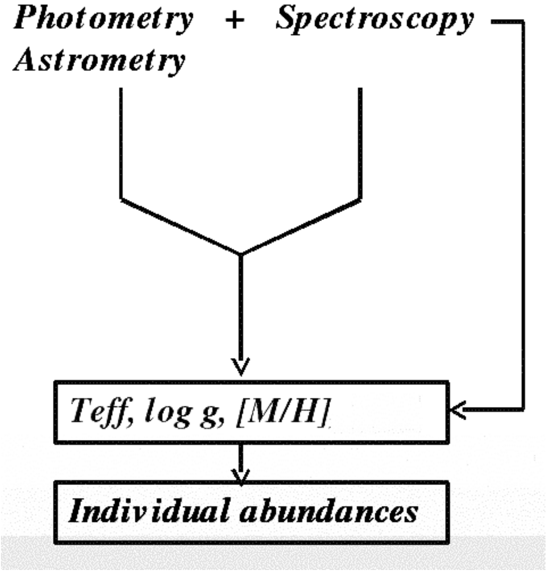

Figure 3. The complementary approaches, photometry plus astrometry on one hand, and spectroscopy on the other hand, to derive the stellar atmospheric parameters necessary for the individual chemical abundance measurements.

But, what about model atmospheres by themselves? Current more generally used plane-parallel treatment is an approximation of three-dimensional hydrodynamic models, which give a more physically founded prediction of velocity fields and its role in the formation of the line profiles. 3D hydrodynamic models are already giving important improvements to our knowledge of solar abundances (cf. Asplund et al. 1999) and will hopefully substitute plane-parallel models by the time the Gaia data arrives.

3.2. Spectral Line Data.

A validation of the spectral line data for all the lines in the RVS wavelength range is necessary prior to the beginning of the Gaia mission. This can be done through a comparison of synthetic spectra to a set of spectra of well known stars, spanning a wide range of stellar parameters. In particular, there is an important effort to be done in atomic physics in order to provide reliable physical properties of the lines that will be used in the chemical abundance determinations.

3.3. Non-Local Thermodynamical Equilibrium Effects.

As already pointed out by many spectroscopists, the use of non-local thermodynamical equilibrium (NLTE) codes to compute synthetic spectra is required to estimate carefully the fundamental parameters of stars like the surface gravity of B type or of metal poor late-type stars. NLTE line formation is also important for accurately deriving the abundances of chemical elements. In the Gaia wavelength range, for late-type stars, the number of elements for which the abundances can be derived is mainly limited to Fe and some alpha elements: Ca, Mg, Si and Ti. It has been demonstrated that Fe, Ca and Mg suffer from NLTE departures on both the statistical equilibrium and on the ionization equilibrium, although their extent for the transitions corresponding to the RVS lines is still not well established. These elements altogether contribute to the success or not of the ability of the minimum distance technique to derive the three fundamental parameters (T_{eff}, log g, [M/H]), and in that context the most important element is the calcium because its three lines are strong and carry an important amount of information. What happens with the derived solution when departure from LTE is strong compared to the solution given by photometry and astrometry? To pinpoint it we have explored departures from LTE of the CaII triplet in the atmospheres of some stars well representing the halo and the disc of the Galaxy. A more exploratory work will be done in the future. The present developed atom of CaII is a multi-level atom with 51 levels plus the continuum of CaIII and 321 line transitions. This is a complete representation of CaII which could be used for late- or early-type stars. The multilevel transfer code MULTI developed by Carlsson (1986) has been used to compute the statistical equilibrium for five well studied stars and for a test subdwarf halo star.

The obtained results are presented in Table 1 in the form of the ratio of NLTE to LTE equivalent widths of the CaII triplet lines. The two first columns are for two solar models, one from the Kurucz grid and the other one, the VAL3C, corresponding to an empirical model including a chromospheric temperature increase based on the quiet Sun. As we can see, both solar models differ strongly in their results. This is well known since the work done by Linsky and collaborators on the CaII lines (see for example Linsky & Ayres 1973). They extensively demonstrated that H&K and the triplet lines have their core formed in the chromospheres where the source function

Table 1. Departures from LTE (ratio of NLTE to LTE equivalent widths) for the three CaII lines in the RVS wavelength range, for the Sun (Kurucz model and model Val3D including chromosphere), Procyon (F5 V metal rich), HD122563 (F8 IV metal poor), HD140283 (G IV metal poor), Arcturus (K1.5 III) and one hypothetical metal poor dwarf star with effective temperature equal to 6000 K.

λ	Sun (Val3C)	Sun (Kur)	Procyon	HD122563	HD140283	Arcturus	Teff=6000, logg=4.5, [M/H]=-3.0
8498	1.240	1.019	1.040	1.255	1.178	1.022	1.041
8542	1.154	1.011	1.022	1.179	1.110	1.029	1.032
8662	1.175	1.013	1.025	1.211	1.164	1.027	1.036

decouples completely from the Planck function. Then the lines are formed under conditions of NLTE resulting in strong different profiles when compared with the non chromospheric solar Kurucz model. As shown in Table 1, NLTE predictions vary strongly from giant to dwarf stars and solar or metal poor stars. The dependence of the CaII profiles on the input atmospheric parameters, Ne, T, velocity field is hard to establish. One cannot ignore NLTE effects, because in many cases NLTE equivalent width corrections are strong (cf. Table 1) and can mimic a temperature effect or an abundance effect which are able to give a false solution of the atmospheric parameters with the minimum distance technique. To a lesser extent, other lines of Fe, Si,... should also be treated in NLTE. The second important point is that stellar chromospheric activity can make the core of the lines of CaII triplet useless for any study of abundances or minimum distances. An important by-product of the Gaia survey would be to provide a statistically significant compilation on the stellar chromospheric activity among all spectral and luminosity classes, but also with respect to PopI and PopII stars.

4. CHEMICAL DATA INTERPRETATION

Looking at details of stars populating a HR diagram reveals the diversity of nature. There are several groups of Chemically Particular stars (CP) of spectral types, mainly from early F through B types characterized by intense magnetic field, slow or rapid rotation, showing variability and for many of them the surface abundances depart from the solar mixture by many orders of magnitude. Characterizing the Galaxy evolution needs to concentrate on stars less affected by peculiarities, hence by tradition late F to K stars are used. *A priori* for a single star, surface abundances are those of the local ISM of the Galaxy at the epoch of its formation. It means that no physical processes are at work or having small influences on the atmospheres of the star like the gravitational settlement or levitation by radiation or mixing with internal layers enriched by fresh nucleosynthesis material. The radiative diffusion model suggested by Michaud (1970, 1976) can explain qualitatively the abundance pattern in CP stellar atmospheres under the hypothesis that stellar atmospheres are quiet, e.g., no rotation inducing turbulence mixing and no magnetic field. Therefore, they become chemically differentiated via the microscopic migration of elements undergoing influences of gravitational acceleration and radiation pressure. The characteristic time of pure diffusion is given by the approximate formula:

$$\tau \simeq KM_{cz}/(MT_{cz}^{3/2})$$

where M$_{cz}$ and T$_{cz}$ are the mass of the convective zone and the temperature at the base of the convective zone, respectively. A solar-type star with a large convective zone does not suffer important diffusion, -0.04 dex of abundance changes for heavy elements in the atmosphere of the Sun after 4.6 Gyr of evolution. For the F star Procyon, that mechanism is very active because the convective zone becomes shallow and the temperature at the base of the convective zone is lower compared to the Sun. Radiative forces are necessary to help Procyon to keep heavy elements in its atmosphere at the age of the star, see Kervella et al. (2004). Some evolution of the surface abundances with different stellar masses and then different effective temperature in a single dwarf stellar population like the Hyades (age of 570 Myr) have been done by Morel & Thévenin (2002). They were able to reproduce the chemical abundances measured by Varenne & Monier (1999). Surface abundance discrepancies of 0.4 dex between a F0 type and a G0 type star of that open cluster are found, all stars being supposed to have had the same surface chemical abundances at age zero. Here we would like to force the attention to spectroscopists that to interpret a large amount of stellar chemical abundances could be hazardous before cleaning of that diffusion effect. The same problem could exist in all stars for which the convective zone is very small like PopII stars (see also Lebreton 2005).

We have computed with the CESAM code (Morel 1997) a set of models with diffusion controlled by the radiative diffusivity (Morel & Thévenin 2002) in order to reproduce surface abundances of stars belonging to the globular cluster NGC 6397. We varied the mass from 0.7 to 0.85 M$_\odot$ that covers the main sequence before the turnoff to the RGB. Figure 4 shows the variation of the surface abundances along the isochrones for two different ages of the cluster (11 and 13 Gyr, the rectangle corresponds to the measure abundances in that cluster for stars at the turnoff around T$_{\rm eff}$ $=$ 6150 K). We adopted for the computation an initial abundance of the cluster (at zero age) of [Fe/H] $= -1.65$ with enhanced alpha elements giving a mixture Z $=$ 5.689 $\times$ 10^{-4} or [Z/X] = -1.515, in order to reproduce the measure abundances (Thévenin et al. 2001) at the age of the cluster which is supposed to be around 13 Gyr. These computations reveal an important discrepancy between the abundances at the turnoff and the original one (cf. Figure 4) that could be measurable

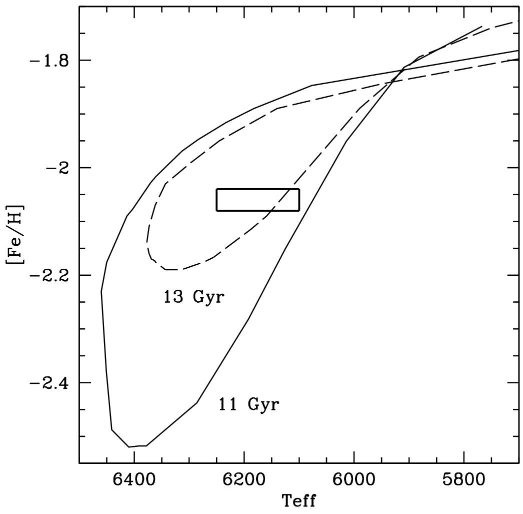

Figure 4. CESAM code models with diffusion controlled by the radiative diffusivity (Morel & Thévenin 2002) for stars belonging to the globular cluster NGC 6397. The rectangle corresponds to the measure abundances in that cluster for stars at the turnoff around $T_{\rm eff} = 6150$ *K.*

in giant stars. LTE abundances at the turnoff are around -2.25 dex (Thévenin et al. 2001) for iron whereas the LTE abundances in giants are found to be ranging from -2.0 to -1.7 dex (Gratton et al. 2001, Thévenin 1998). The measured discrepancy between the turnoff and giant stars seems to be $\approx$0.3 dex with large error bars. More studies, theoretical and observational, are needed before concluding the validity of actual modelling of the surface abundances with diffusion and radiative forces in balance. On the other hand, 3D hydrodynamic models of metal poor giants could also partially explain such discrepancies (Collet et al. 2004) and should be taken into account.

5. CONCLUSIONS: INPUTS FOR GALACTIC MODELS

Models of disc Galaxy formation and evolution, which are already able to make predictions about stellar populations, will find in the Gaia/RVS chemical data a precious source of information. Several efforts have already been done in order to have large homogeneous chemical compilations of stars in our Galaxy and its satellites. Large data chemical surveys are presently stimulated by the multi-fiber facilities of ground-based spectrographs. However, Gaia will provide an enormous quantitative jump, providing a wide area systematic survey, high statistics, no biases and combined detailed chemical and dynamical information. It is therefore crucial to get prepared to exploit to the maximum the richness of the Gaia data set. The important objective of quantifying and analising Galaxy populations requires the improvement of our present knowledge about stellar atmospheric models, spectral line data, chromospheric activity, local thermodynamic equilibrium departures, element diffusion, stellar rotation, etc. All these effects could blur our interpretation of the RVS data in terms of Galactic chemical evolution and it is therefore of great importance to take them into account, being conscious of the significant goal they will help us to achieve.

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REFERENCES

Asplund, M.; Nordlund, A.; Trampedach, R.; Stein, R. F.,1999, A&A, 346L, 17

Bailer-Jones, C.A.L., 2005, ESA SP-576, this volume

Carlsson M., 1986, Uppsala Astron. Obs. report 33.

Collet R. et al., 2004, proceedings of the ESO/Arcetri workshop on *Chemical abundances and mixing in stars in the Milky Way and its satellites*.

Gratton R.G. et al. , 2001, A&A, 369, 87

Kervella, P., Thévenin, F., Morel, P., Berthomieu, G., Bordé, P., Provost, J., 2004, A&A 413, 251

Jordi, C., Høg, E., 2005, ESA SP-576, this volume

Lebreton, Y., 2005, ESA SP-576, this volume

Linsky J. L., Ayres, T., 1973, ApJ 180, 473

Matteucci F., 2001, The chemical evolution of the Galaxy, Kluwer

Michaud G., 1970, ApJ 160, 641

Michaud G., Charland Y., Vauclair S., Vauclair G., 1976, ApJ 210, 447

Morel P., 1997, A&AS 124, 597

Morel, P., Thévenin, F., 2002, A&A 390, 611

Nissen, P.E., 2005, ESA SP-576, this volume

Recio-Blanco, A., et al., 2005, ESA SP-576, this volume

Thévenin, F., 1998, CDS, Cat3193

Thévenin, F., Charbonnel, C., de Freitas Pacheco, J. A.et al., 2001, A&A 373, 905

Varenne, O., Monier, R, 1999, A&A, 351, 247