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STELLAR PHYSICS WITH GAIA

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Abstract. Gaia will provide a three-dimensional map of our Galaxy, with unprecedented positional and radial velocity measurements for about one per cent of the Galactic stellar population. Combined with astrophysical information derived from spectroscopy and photometry for each star, this will lead to a detailed understanding of the formation, and dynamical and chemical evolution of our Galaxy. Other scientific products include extra-solar planets, minor bodies in the solar system, or distant quasars. The contribution of Gaia to stellar physics is less publicized, although very significant. I show here a number of illustrative examples. For example, we will have access to very precise HR diagrams with very large sample of stars allowing extensive tests of fine effects in stellar evolution. Accurate parameters (esp. luminosities, and masses) will allow the independent determination of surface gravities, the characterization of non-LTE effects, and the derivation of more accurate chemical abundances. We will be able to quantify transport processes in various populations of stars, and shed new light on abundance anomalies. In addition, the preparation of Gaia induces a very large effort devoted to homogenize the stellar parameters of a great number of reference stars, and the development of performant tools designed to automatically extract parameters from tremendous amounts of spectra.

Keywords:

1 Introduction

Gaia's main goal is to provide high-precision astrometric data (positions, parallaxes, and proper motions) for one billion objects in the sky. These data, together with multi-epoch photometric and spectroscopic data will allow us to reconstruct the formation history, structure, and evolution of the Galaxy. Many other exciting breakthroughs will also result from this tremendous data set of unprecedented accuracy, in the fields of, e.g., exoplanets, fundamental physics, solar system science, dark matter, the cosmological distance scale (Perryman et al. 2001). In the study of the Galaxy, stars are used as markers of the kinematics, and chemistry. The purpose of this paper is to show that stars will be studied by Gaia as targets per se. We will gain insight into various aspects of stellar physics, thanks to the knowledge of many accurate distances, luminosities, radii, and masses. In addition the preparation of the Gaia mission generates an enormous amount of efforts aimed at a better understanding of stars, and at the development of extremely performant tools for the analysis of stellar observations. I will illustrate these two points through selected examples in the following.

2 What will Gaia provide for stellar physics studies?

Gaia aims at measuring parallaxes of one billion stars with an accuracy better than 300 micro-arcsec, for a complete magnitude limited sample down to V=20. The accuracy will be 20 mas (milli-arcsec) for 26 million stars down to V=15. As an illustration this translates to 2% errors for Sun-like stars at 1 kpc, 5% errors for red giants out to 2.5 kpc, and M-L dwarfs distances with 3% errors within 100 pc. In total, distances will be known to better than 1% for 11 million stars, and to better than 10% for 150 million stars. Proper motions should be 50% more accurate than parallaxes. The RVS (radial velocity spectrometer) will collect radial velocities down to V=16, with an accuracy of 1 to 10 km/s. Details about all these numbers can be found in Turon et al. (2012), and at `http://www.rssd.esa.int`. This unprecedented data set will allow the determination of accurate luminosities for a very large sample of stars. Luminosity (L) is the most commonly missing parameter

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in Galactic star studies. Luminosities combined with effective temperatures ($T_{\rm eff}$) derived from photometry or spectroscopy will give radii (R). With precise masses (M) from the numerous binaries, this will lead to surface gravities (g) independently of ill-controlled hypotheses, as is the case when they are spectroscopically derived, due to NLTE effects. An aspect not to underestimate is the possibility to increase the scientific return using Gaia data in synergy with asteroseimology data that provide strong constraint on other combinations of stellar parameters such as the mean density, M/R^3 or the state of evolution. The multiple epochs of observation (80 per object on average) will allow the study of stellar variability, and of rare types of stars in short evolutionary stages. It is estimated that about 18 million variables will be observed and characterized (Eyer & Cuypers 2000).

3 Examples in the field of stellar evolution

One field that will greatly benefit from Gaia results is stellar structure and evolution. Modeling stellar evolution requires the inclusion of the the most up-to-date physics, e.g., equation of state, nuclear reaction rates, opacities, atomic diffusion, atmosphere models. Special difficulties are encountered for cool, dense stars, late stages of evolution, and of course when very accurate modeling is demanded by very high-quality observations, as in the case of the Sun (Lebreton 2005, 2008). Atmospheres are a particularly critical ingredient as they constitute the boundary condition of the stellar interior, they provide the transformation from theoretical (L, $T_{\rm eff}$) to observed quantities like magnitudes, colors, and bolometric corrections. Finally, the stellar parameters $T_{\rm eff}, \log g$, chemical composition, are mostly derived from spectroscopic or photometric observations using calculated spectra from model atmospheres. Despite great recent progress (opacities, 3D hydrodynamical models, NLTE calculations), there are still relatively large systematic errors for, e.g., cool giants, hot stars, very metal-poor stars.

3.1 Isochrones: calculations and observations

Stellar evolution models provide stellar parameters like $L(t), R(t), T_{\rm eff}(t), Z(t)$, that must be confronted to quantities derived from observations, in order to estimate ages, masses, helium content, or metallicities. One widely used, and in principle straightforward way to derive a star's age, mass and initial metal content is to compute isochrones for a distribution of initial masses and just place the star in the magnitude-$T_{\rm eff}$ diagram. This is not as easy as it seems, nor unambiguous. Isochrones overlap on the main sequence, around the turn-off, and on the red giant branch (RGB). But even outside these domains, there is a need for very precise, and accurate L, $T_{\rm eff}$, and metallicity determinations (Jørgensen & Lindegren 2005). Gaia will dramatically increase the precision of luminosity determinations through better distance measurements, and indirectly also the precision of stellar parameter determinations (see section 4), thus allowing better age determinations (Lebreton & Montalbán 2009). Nevertheless, only the combination with asteroseismology will allow to lift degeneracies in the HR diagram (Lebreton 2011; Gilliland et al. 2011).

3.2 Validation of stellar evolution models

Before these models can be used on a large scale they must be validated using well observed, well constrained systems, of which the Sun, and the α Cen binary are among the few that can be used nowadays.

The case of the Sun is much debated, with the most recent atmospheric abundance determinations (Asplund et al. 2005; Grevesse et al. 2010) leading to discordance of the observed and predicted sound speed profile, and of the depth of the lower boundary of the convection zone. The progress we anticipate Gaia will induce in our understanding of stellar structure on one hand, and of line formation and NLTE effects on the other hand will certainly impact the work on the Sun.

The basic parameters of the α Cen system are known within very small error bars. For the A and B components the masses are $M_A = 1.105 \pm 0.007, M_B = 0.934 \pm 0.006\ M_\odot$ (Pourbaix et al. 2002), and the interferometrically derived radii are $R_A = 1.224 \pm 0.003, R_B = 0.863 \pm 0.005\ R_\odot$ (Kervella et al. 2003), resulting in surface gravities $\log g_A = 4.307 \pm 0.005, \log g_B = 4.538 \pm 0.008$ (in c.g.s. units). Porto de Mello et al. (2008) recently published a very careful spectroscopic study of the system leading to $T_{\rm eff\,A} = 5824 \pm 26$ K, and $T_{\rm eff\,B} = 5223 \pm 62$ K. At least for α Cen B, this is not compatible with the hotter $T_{\rm eff\,B}$ derived from the very well known luminosity and radius. The fit of isochrones on the system's data leads to different ages for the components. The most probable explanation put forward by Porto de Mello et al. (2008) is that the estimated temperature of the B component is too low. In addition a review of all abundance determinations for this system show a very large scatter (up to 0.4 dex for Ti). To impose a consistent solution for all parameters of this system brings a strong constraint on atmosphere and evolution models. The important point is that with Gaia we will have many other systems with well determined masses, luminosities, and radii, distributed all over the HR diagram. This will allow stringent tests of the models.

Another contribution of Gaia will be to bring accurate distances for a rich variety of clusters. Clusters are a very powerful way of testing stellar evolution models, as different physical processes dominate the isochrones shape in different parts of the HR diagram. The lower main sequence is impacted by the uncertainties in the calculation of spectra and atmosphere models. The description of convection affects the main sequence around solar-type stars, and rotation and overshooting affect the upper main sequence, and the turn-off, not to forget the effect of the equation of state, opacities, and nuclear reaction rates. The calibration of models on a large number of clusters will open the way to exciting science, as can be seen in the case of the best studied cluster, the Hyades. In addition to the very precise Hipparcos dynamical parallaxes, the presence of the spectroscopic eclipsing binary HD 27130, with very accurate masses and luminosities, allows to delineate the He content of the stars from the isochrones fit (Lebreton et al. 2001). As a consequence of the fit of the tight observational sequence Lebreton et al. (2001) can also discuss details of the physical ingredients used in the models (mixing-length parameter, model atmospheres, equation of state). This illustrates well what will be possible with the Gaia data on clusters.

4 Gaia and the determination of accurate chemical abundances

The chemical composition of stars is a central piece of information, and considerable work has been devoted to improve the quality of the determinations that are made though the analysis of stellar spectra. Most of the time the stellar parameters $T_{\rm eff}$ and $\log g$ are derived from the spectra together with the abundances. However, model atmospheres suffer from approximations (e.g. LTE) that may induce systematic errors in the results. One enlightening example is given by the case of Procyon, a single-lined nearby binary, for which an astrometric determination of the gravity ($\log g = 4.05$), strongly disagrees with a spectroscopic determination based on the ionization equilibrium of iron ($\log g = 3.6$), as is discussed in detail by Fuhrmann et al. (1997). This is a well known manifestation of NLTE: the Fe I/Fe II, or any other element ratio depend critically on inelastic collisions with hydrogen. The cross-sections are not well known, and extremely difficult to calculate or to measure for many atoms, although progress has been made recently (Barklem et al. 2011). The Drawin (1969) approximation of the H-collision cross-sections is commonly used, often with a scaling factor, $\mathrm{S_H}$, with values from 0 (no collisions), to about 3, which tends towards the LTE situation. Korn et al. (2003) derived a value $S_{\rm H} = 3$ from a careful study of iron lines in a few (4) reference stars with known distances (thus L), $T_{\rm eff}$ (thus R), and masses (thus g). They show that the set of fundamental parameters (of which the distance is a critical one) is only compatible with the NLTE Fe I/Fe II ratio calculated using $S_{\rm H} = 3$. This kind of work can be done today only on a small number of stars. Gaia will provide very large such samples, that will allow a breakthrough in this domain, especially if combined with interferometric and astero-seismologic data.

5 Transport processes and abundance anomalies

The increasing quality of observational data, and refinements in analysis techniques have unveiled abundance peculiarities that require new mechanisms to be taken into account, i.e. mixing, and diffusion. The work of Spite et al. (2007) on field metal-poor red giant stars uncovered two well-separated groups, one with a high N/C, and a low ^{12}C/^{13}C ratios, and no detectable Li, showing the sign of CN-processing, and mixing. In higher metallicity stars ([Fe/H]=-1.5), Gratton et al. (2000) showed that extra mixing happens at the bump, as explained by thermohaline mixing (Charbonnel & Zahn 2007; Cantiello & Langer 2010). In the more metal-poor stars of the Spite et al. (2007) sample, however, unmixed stars are found above the bump and mixed stars seem to exist below the bump. In addition variation in Al and Na abundances indicate very deep mixing in some cases. Firm conclusions cannot be drawn, as there exist the possibility that the spectroscopically derived gravities may suffer from uncertainties. More importantly the distances, and thus the luminosities may be in error. Also, the position of the bump is dependent on metallicity and not well defined yet at very low metallicity. Some stars of the sample might also be AGB or RHB stars and not on the RGB. Halo stars are within reach of Gaia, and this question should be settled once good distances are secured for a large number of field metal-poor stars.

5.1 The case of Li

Another illuminating example of the contribution of Gaia to stellar physics concerns element diffusion inside stars. The radial chemical composition of stars is not homogeneous, even outside the regions where nuclear reactions operate. In radiative zones, gravitational settling competes with radiative acceleration leading to sometimes strong abundance gradients. The surface composition of a star does not always reflect its inner content. This is particularly critical in the case of Li, the surface abundance of which measured in very metal-poor stars is a factor of 2 or 3 lower than the primordial abundance that is compatible with standard BBN and the WMAP measurements of the cosmic microwave background (Sbordone et al. 2010). Current models including diffusion predict moderate abundance modifications, due to the inclusion of additional turbulent mixing which is unfortunately tuned with a free parameter. The calibration of the amount of turbulent mixing was made by Korn et al. (2006, 2007) using a sequence of stars in the NGC 6397 cluster. The model tuned to match the observed Mg, Ca, Ti, and Fe abundances does explain sub-primordial Li in these cluster stars, offering a solution to this Li problem, as was already suggested by Richard et al. (2005). This work needs to be extended to more metal-poor stars, as the amount of turbulent mixing might be metallicity dependent. As shown in Sbordone et al. (2010) the Spite plateau dissolves at metallicities below -2.5, and even more below [Fe/H]=-3.0, further deepening the mystery of primordial Li. To study the effect of element diffusion at such low metallicities demands to know precisely the evolutionary status of field stars, the distances, and luminosities of which are poorly known. Again, Gaia data will be decisive in the solution of this question.

6 Gaia preparation

Apart from much awaited contributions from Gaia science data, the preparation of the mission itself is developing into a full industry of new tools, and approaches in our way of doing stellar physics.

6.1 Global stellar parametrizers

The paramount size of the sample of RVS data to be analyzed calls for innovative methods to, e.g., quickly derive stellar parameters from spectra (and in the case of Gaia RVS, relatively low resolution, and restricted range spectra). A number of algorithms (Global Stellar Parametrizers - GSP-spec) have been developed based on optimization (minimization of distance between observations and reference spectra), projection (the observations are projected on a set of vectors defined during a learning phase), or classification (pattern recognition). They prove to be very efficient, once tested and calibrated on well studied samples of spectra. The two algorithms Matisse (Recio-Blanco et al. 2006) and Degas using the two latter methods compare well wih published data when applied to spectral libraries (Kordopatis et al. 2011). Their performances are characterized in terms of accuracy depending on the SNR, and the resolution of the spectra, and the position of the star in the HR diagram. Kordopatis et al. (2011) claim that the results are sufficiently accurate down to SNR as low as 20 for galactic archaeology work, opening new horizons in this field. These tools are absolutely indispensable to deal with the extremely large coming surveys, including Gaia. These algorithm are already used to derive stellar parameters ($T_{\rm eff}, \log g$, abundances) from in particular the ESO archive of spectra.

6.2 Large homogeneous samples of stars

As is mentioned above, the accuracy to which GSP's will deliver their results is largely dependent on the spectra their are trained on, and on the stellar parameters attached to them. As GSP's are trained on synthetic spectra that are not error-free, systematic errors in astrophysical parameters (AP) may arise. A high quality external calibration with reference stars is therefore mandatory. A Work Package within CU8 of the DPAC of Gaia ("provide calibration of training data") has undertaken this task. The objective is to determine high quality AP's on an homogeneous scale. A few tens of stars that can be studied at very high resolution with a variety of techniques, but too bright for Gaia, will serve as fundamental calibrators. On this basis, AP's will be differentially determined for 500 to 5000 primary calibrators. Then, thousands of secondary calibrators will allow a large scale validation in a large range of stellar parameters, as, e.g., the 90 000 SDSS stellar spectra discussed by Re Fiorentin et al. (2007). Also, many large samples analyzed in recent years by various authors will be homogenized using the tools described above, coupled with the detailed study of primary calibrators. This is an unprecedented major effort, extremely important to validate stellar models, and that will impact stellar physics at large.

6.3 3D hydrodynamical models, photocenters, and parallax accuracies

The preparation for Gaia also benefits from efforts to develop more ambitious models of stellar atmospheres and interiors. 3D hydrodynamical simulations of red giants and supergiants atmospheres dominated by granulation are now able to make quantitative predictions on the size of granules, their intensity contrast, the shifts and asymmetries affecting spectral line, and their time scales. Chiavassa et al. (2011) have showed that the fluctuations in the position of the photocenter of red supergiants are of the order of a fraction of an AU. This will result in systematic errors in Gaia's parallax determinations of the order of 5%. In return Gaia measurements will help verify these predictions on a large number of stars, which can not be done with, e.g., interferometers from the ground, as it necessitates repeated observations of a number of stars during a few years.

7 Conclusions

Gaia will increase our sample of binary systems with masses known to the 1% level from 100 to about 17 000. It will bring us 11 million stars with parallaxes at the 1% level, to compare with the 700 we have today, of which 100 000 will have a 0.1% accuracy. We will have parallaxes for types of stars for which we have none today (subdwarfs, subgiants). The distance to individual stars in 20 globular clusters (100 to 100 000 stars per cluster) will be determined to better than 10%. It is obvious that this will revolutionize our view of the Galaxy and its evolution. I have shown here that the tremendous Gaia data set, combined with interferometric (R/d), and astero-seismologic (e.g., M/R^3) data will also allow stringent tests, and validations of models of the interior and atmosphere of stars. This will ultimately lead to a much improved quantitative understanding of the physical processes at work in stars.

Stellar physics is a broad field the diversity of which no one can fully embrace. On many topics discussed here I am merely the carrier of others words. Many colleagues helped me while preparing this paper, and without them the task would have been much heavier. Be they all thanked here: Alain Jorissen, Andrea Chiavassa, Andreas Korn, Caroline Soubiran, François Spite, Mathias Schultheis, Monique Spite, Olivier Richard, Patrick de Laverny, and not the least Yveline Lebreton. I thank the AS Gaia and the SF2A for inviting me, and the AS Gaia for providing financial support. Special thanks to Catherine Turon, who so kindly insisted that I gave this talk at the Annual Meeting of the SF2A. I truly enjoyed it.

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