The Gaia–ESO Large Public Spectroscopic Survey

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The Gaia–ESO Public Spectroscopic Survey has completed about one third of the data taking and continues to acquire high-quality spectroscopy, with both Giraffe and UVES, of representative samples of all Galactic stellar populations, including open clusters — young and old, nearby and distant, interior and exterior to the Sun — and field stars in the Galactic Halo, the thick Disc, the thin Disc and the Galactic Bulge. A large sample of stars in the Solar Neighbourhood, selected to include all possible ages and metallicities, is also being observed with UVES. This will be the first such large internally homogeneous study of the Milky Way stellar populations. Besides the intrinsic range of exciting scientific results, the Gaia–ESO Survey is also a pathfinder for future massive Gaia follow-up. Equally importantly, we are building an ESO-wide community of stellar spectroscopists, sharing, optimising, refining and cross-calibrating complementary approaches, strengths and experience. Internal Science Verification has started with several results demonstrating the huge potential of the survey and the first release of spectra to ESO has occurred.

An introductory overview of the Gaia–ESO survey was presented in *Messenger* 147 (Gilmore et al., 2012). Briefly, the survey is obtaining high-quality spectra with Giraffe at several wavelength settings, depending on the stellar type, high-resolution (HR) spectra ($R \sim 20\,000$) of some 100 000 cluster and field stars down to $V = 19$, with parallel Ultraviolet and Visual Echelle Spectrograph spectra (UVES; $R \sim 47\,000$) obtained in each field for brighter stars. Data-taking began at the end of 2011, and will continue for four years until the ESO progress review. A wealth of kinematic and abundance information, along with astrophysical parameters will be obtained for the bulk of our targets, facilitating the impressive range of science foreshadowed in our earlier article.

One of the special features of the Gaia–ESO survey is that a wider range of stellar types (from O- to M-type, from pre-main sequence to evolved stars, from very low to solar and super solar metallicity) is being observed than was attempted in previous large surveys, and that we are working at very much higher spectral resolution. These aspects make it necessary and desirable that a large consortium of groups is involved, implementing many spectrum analysis methods and approaches. The consortium has grown to nearly 400 members, from nearly 100 institutes. The survey project is structured in 19 working groups, each dedicated to the different aspects. Five of these groups focus on spectrum analysis and benefit from the contribution of several analysis teams. We communicate through our web page[1], newsletters, regular meetings and telecons, and with an actively used internal wiki.

Target selection and preparation of the observations are now in a routine phase. So far our efforts have been dominated by optimising the data reduction and radial velocity pipelines, as well as by the challenge of ensuring that all the many analysis approaches are internally consistent and that we are able to combine astrophysical parameters and abundances from many groups appropriately. None of these turn out to be trivial. For the Giraffe spectra, Jim Lewis at the Cambridge Astronomy Survey Unit (CASU) has developed a new special-purpose reduction pipeline, taking the data from "as acquired" to "ready for analysis" (Gilmore et al., 2013, in preparation). For UVES spectra we have been working closely with ESO, in particular with Andrea Modigliani, to remedy the difficulties with the reduction pipeline, which has now been successfully achieved (Sacco et al., 2013, in preparation). These substantial pipeline developments will of course benefit the entire ESO community. Considerable effort has also been invested in radial velocity pipelines and quality assessment, since precise radial velocities are critical for several of the top-level science goals.

An early lesson from working with many analysis teams was the critical need to have a well-understood, common, suitable line-list for the analyses, a common set of model atmospheres and a common grid of synthetic spectra. All of these have been made available to the analysis groups and are regularly updated thanks to the efforts of dedicated teams. Another (expected) challenge was that of combining, intelligently, astrophysical parameters and elemental abundances from many pipelines and for different types of stars. This remains work in progress, but one significant (planned) advance has been a focus on observations — largely in twilight — of the Gaia benchmark stars. This list of well-studied stars, with good coverage across parameter space, has been under development as part of the Gaia mission preparation. By combining our efforts, much progress has been made both with optimising the Gaia benchmark star parameters, but also ensuring that Gaia and Gaia–ESO will be calibrated onto a consistent scale (c.f., Jofre et al., 2013).

Internal as well external calibration also depends heavily on observations of many stars in many clusters, both open and globular, where we also complement our observations with re-analysis of ESO archive spectra. We are also planning synergies with other large spectroscopic surveys globally (RAdial Velocity Experiment [RAVE]; GALactic Archaeology with HERMES [HERMES/GALAH]; Baryon Oscillation Spectroscopic Survey/ Sloan Extension for Galactic Understanding and Exploration [BOSS/SEGUE]; Apache Point Observatory Galactic Evolution Experiment [APOGEE]) to share our calibrations and lead towards a new era of consistent stellar spectroscopic parameters. A further dataset, which is ideal for calibration, and of high scientific interest in meeting some of the original Gaia–ESO scientific goals, is the use of giant stars observed by CoRoT, for which asteroseismic gravities are available.

Making all this progress has taken some time, but Gaia–ESO is now in its first internal SV phase. A few scientific early highlights are noted below. However, our progress so far in so short a time makes us confident that this combination of European space and ground data for enhanced science is a small foretaste of what is to come when Gaia is combined with the current ESO imaging and planned spectroscopic surveys, and other complementary surveys. Each of these Gaia–ESO developments noted above is a major advance. All are currently being prepared for publication.

Early Science: Clusters

The top-level scientific goals for the cluster component of Gaia–ESO include the understanding of how clusters form, evolve and dissolve into the Milky Way field, to be obtained through the investigation of: internal cluster kinematics and dynamics; the calibration of the complex physics that affect stellar evolution; and the detailed study of the properties and evolution of the Milky Way thin Disc. With this aim, a very large sample of clusters and cluster stars will be observed, covering the age–distance–metallicity–position–density parameter space. Early focus has been put both on young, nearby regions and on intermediate–old more distant clusters, in order to start addressing all the main science topics in the Science Verification phase.

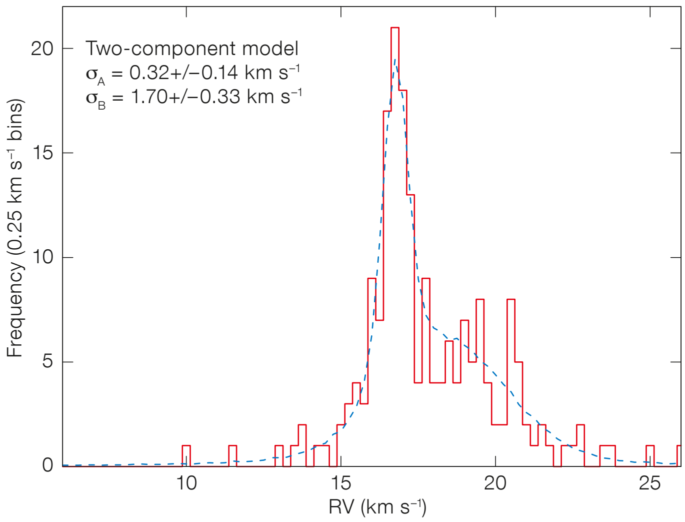

Figure 1. The radial velocity distribution of young, lithium-selected members of the γ Velorum association (red histogram), along with the best-fitting model (blue curve), consisting of two Gaussian distributions convolved with a model of the RV uncertainties and a contribution from binaries. The width of the distributions is reported in the figure.

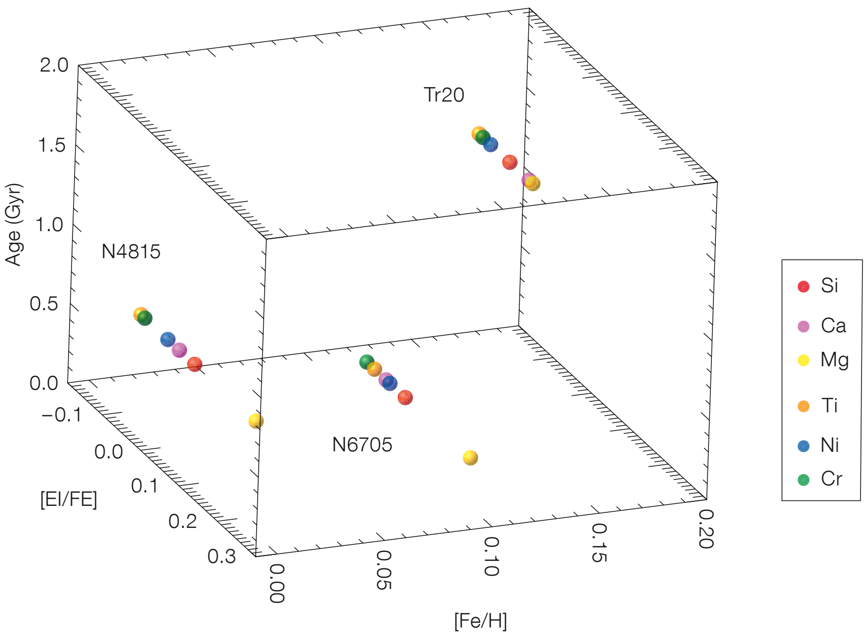

Figure 2. The three-dimensional plot shows the abundance ratios of different elements for the three open clusters NGC 6705, NGC 4815 and Trumpler 20 as a function of [Fe/H] and age. The three clusters have Galactocentric distances of 6.3, 6.9 and 6.88 kpc, respectively.

One of the currently debated issues is whether young clusters are characterised by kinematic substructures and/or radial velocity gradients. In turn this question is related to the initial conditions and the mechanism of cluster formation. Gaia–ESO observations of γ Velorum, a 5–10 Myr old, nearby association, located in the very composite Vela complex, have indeed confirmed that our radial velocity (RV) measurements have high enough precision to resolve velocity substructures (Jeffries et al., 2013, in preparation). Specifically, the RV distribution of members of the association plotted in Figure 1 shows that the excellent radial velocity precision (~ 0.3 km s^{-1}) of Gaia–ESO resolves the distribution into (at least) two sub-components, a very narrow one, probably in virial equilibrium, and a significantly broader and super-virial one. The narrower component appears to be more centrally concentrated around the massive binary star at the centre of the association. Interestingly, different tracers suggest that the low-mass stars are older than 10 Myr, while the massive binary cannot be as old as this. Whereas this result needs further investigation in the framework of different model predictions, on the one hand it implies a complex star formation history in the association and, on the other hand, it proves the potential of Gaia–ESO for this type of study.

The determination of precise abundances in open clusters represents a valuable tool for the study of the formation and evolution of the thin Disc, as clusters are rare fossils of its past star formation history. Naively, one would expect that abundances of open clusters with similar ages and positions in the Galaxy are similar, and also match those of the field stars at similar distances from the Galactic Centre. However, observations are revealing differences (see, e.g., Yong et al., 2005, 2012; De Silva et al., 2007) and these differences, if confirmed, may contain important information about, e.g., the place where the clusters were born, the homogeneity of the Disc at any Galactocentric distance at the epoch when the cluster formed, etc. In this context Gaia–ESO will allow, for the first time, a comparison of different populations based on homogeneous analysis. The first three intermediate-age/old clusters observed in the survey (NGC 6705, NGC 4815, Trumpler 20) have already enabled an initial step in this direction. Figure 2 shows that each cluster is characterised by unique features with respect to the others. These differences must be signatures of the intrinsic characteristics of the chemical composition of the interstellar medium from which each cluster was born, even if at present the three clusters are located at similar distance from the Galactic Centre. Comparison with the field population, in particular with the inner Disc stars, and with models of Galactic evolution seems to support the hypothesis that at least one of these clusters has migrated from its original birthplace (Magrini et al., 2013).

Early Science: Milky Way

The Milky Way aspects of the Gaia–ESO survey include the field star populations, and special calibration efforts. Much early focus in the Milky Way fields, driven by the available sky, was on the properties of the thick Disc. Topical issues here include the issue of discreteness between the thick and thin Disc in element ratio data at a given abundance of [Fe/H]. This has implications for the history of the Milky Way, strongly supporting the formation of the thick Disc as a discrete event early in the history of the Galaxy. All recent high-quality spectroscopic studies have shown such discreteness, though this result has been challenged by some analyses of very large low-precision surveys, especially SEGUE, where the claim is that the earlier surveys were highly biased. There is also much

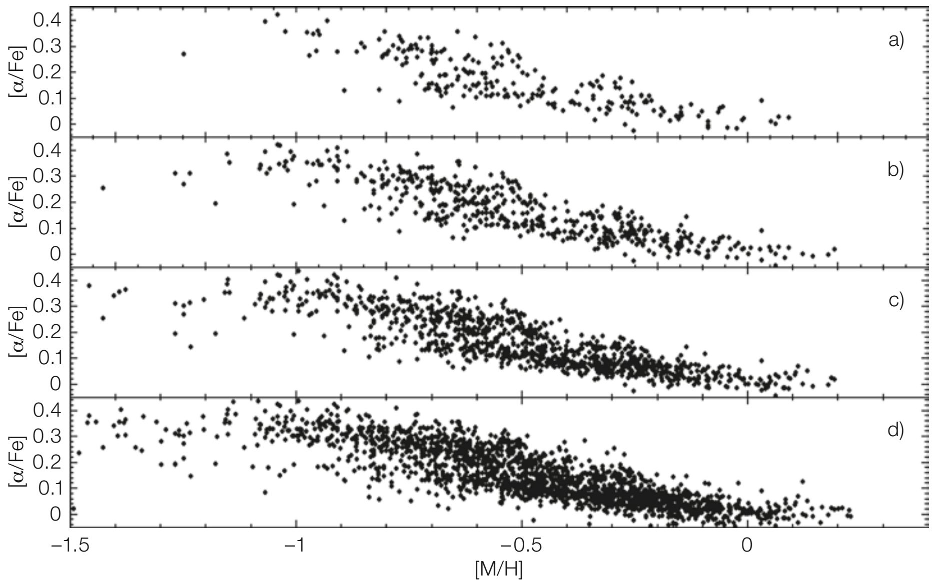

Figure 3. α-elements over iron abundance as a function of metallicity for four different sub-samples of stars with increasing errors in the abundance determination. Panel a) shows the results for stars with errors in [M/H] and [α/Fe] smaller than 0.07 dex and 0.03 dex respectively (209 stars); panel b) for errors smaller than 0.09 dex and 0.04 dex in [M/H] and [α/Fe] (505 stars); panel c) illustrates the values for 1008 stars with errors smaller than 0.15 dex and 0.05 dex respectively; panel d) shows all stars with errors in T_{eff} lower than 400 K, errors in log *g* lower than 0.5 dex and a spectral signal-to-noise ratio higher than 15 for the HR10 configuration (1952 stars).

ongoing confusion over the radial scale length of the thick Disc, with the answer being sensitively dependent on one's definition. Gaia–ESO has a well-defined selection function, and carefully avoids all the usual sample biases, so is ideally suited to provide a definitive result. The first Gaia–ESO results are shown in Figure 3, which shows [α/Fe] *vs*. [Fe/H] from Giraffe spectra, with the different panels selected only by measurement error. Bimodality is indeed apparent (Recio Blanco et al., 2013). A supplementary study, led by student Kohei Hattori, uses a new dynamical analysis technique to deduce the local in-plane kinematics of stars far from the Sun (Figure 4). These kinematic dispersions are directly, although non-trivially, related to population scale length. This study suggests that the high-α (thick Disc) stars do merge into a thin-Disc-like vertical scale height a few kiloparsecs exterior to the Sun.

Prospects

The Gaia–ESO Large Public Spectroscopic Survey has become the first large European collaboration of stellar spectroscopists, working together to identify opportunities, strengths and limitations in the way we have approached the science challenges in stellar populations, and understanding the evolution of the Galaxy and its constituents. We are learning to work as the galaxy survey community does. This opportunity to learn and respect each other, building a stronger, more expert, more efficient ESO community in a key science area, is arguably one of the most important achievements of Gaia–ESO. There are immediate community-wide quantitative benefits, in data reduction pipelines, standard stars, atomic and molecular line-lists, calibrations, and so on, which are already being realised. The impressive range of scientific papers being prepared from the available SV data will soon be public, and demonstrate the substantial scientific advances being facilitated by this ESO survey.

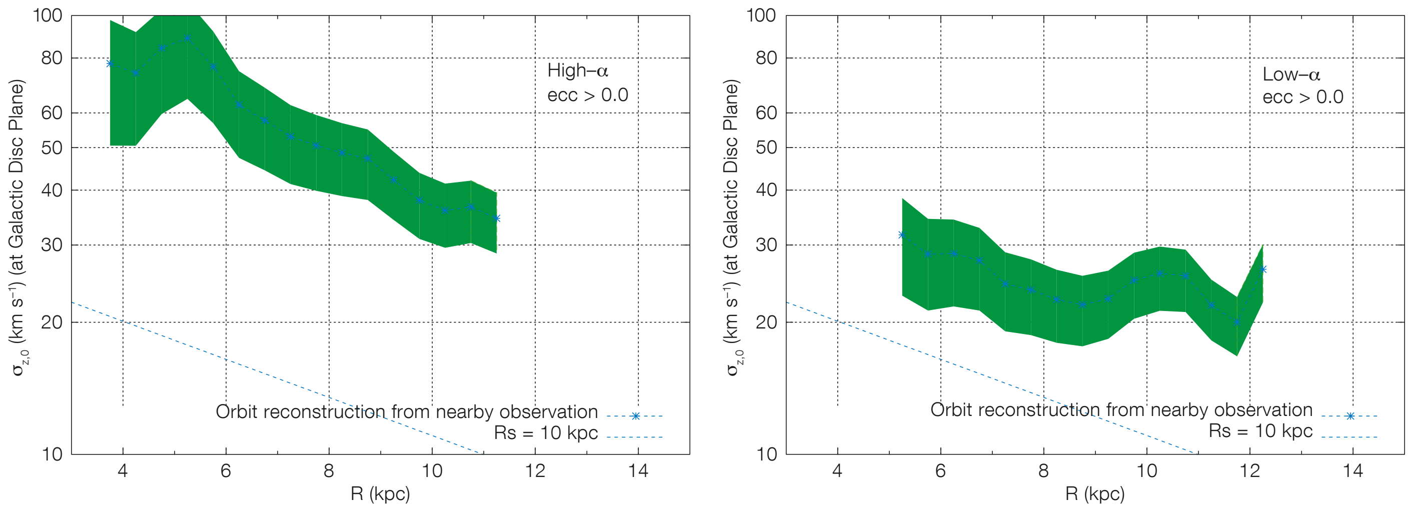

Figure 4. Reconstructed radial profile of $\sigma_{z,0}$ (the velocity dispersion in the *z*-direction at the Galactic Plane) from the Gaia-ESO survey is shown (in green) for high-α (left) and low-α (right). As a reference, the curve $\sigma_{z,0}(R)$ = const. × $e^{[-R/(10\ kpc)]}$, is also shown.

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Links

[1] Gaia-ESO Survey web page: www.gaia-eso.eu