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The Gaia-ESO Survey Astrophysical Calibration

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Abstract. The Gaia-ESO Survey is a wide field spectroscopic survey recently started with the FLAMES@VLT in Cerro Paranal, Chile. It will produce radial velocities more accurate than Gaia's for faint stars (down to $V \simeq 18$), and astrophysical parameters and abundances for approximately 100 000 stars, belonging to all Galactic populations. 300 nights were assigned in 5 years (with the last year subject to approval after a detailed report). In particular, to connect with other ongoing and planned spectroscopic surveys, a detailed calibration program — for the astrophysical parameters derivation — is planned, including well known clusters, Gaia benchmark stars, and special equatorial calibration fields designed for wide field/multifiber spectrographs.

1. The Gaia-ESO Survey

Gaia-ESO is a public spectroscopic survey (Gilmore et al. 2012), targeting $\geq 10^5$ stars, systematically covering all major components of the Milky Way, from halo to star forming regions, providing the first homogeneous overview of the distributions of kinematics and elemental abundances. This alone will revolutionise knowledge of Galactic and stellar evolution: when combined with Gaia astrometry the survey will quantify the formation history and evolution of young, mature and ancient Galactic populations. With well-defined samples, it will survey the bulge, thick and thin discs and halo components, and open star clusters of all ages and masses. The FLAMES spectra will: quantify individual elemental abundances in each star; yield precise radial velocities for a 4-D kinematic phase-space; map kinematic gradients and abundance - phase-space structure throughout the Galaxy; follow the formation, evolution and dissolution of open clusters as they populate the disc, and provide a legacy dataset that will add enormous value to the Gaia mission and ongoing ESO imaging surveys.

1.1. Scientific aims

How disc galaxies form and evolve, and how their component stars and stellar populations form and evolve, are among the most fundamental questions in contemporary astrophysics (Kormendy et al. 2010; Peebles 2011; Komatsu et al. 2011). The Gaia-ESO survey will contribute to those key questions, by revolutionising our knowledge of the formation and evolution of the Milky Way Galaxy and the stars that populate it. Because stars form in associations and clusters rather than singly, understanding star formation in the Milky Way also implies studying cluster formation.

The key to decoding the history of galaxy evolution involves chemical element mapping, which quantifies timescales, mixing and accretion length scales, and star formation histories; spatial distributions, which relate to structures and gradients; and kinematics, which relates to both the felt but unseen dark matter, and dynamical histories of clusters and merger events (Freeman & Bland-Hawthorn 2002). With Gaia, and calibrated stellar models, one will also add ages. Manifestly, very large samples are required to define all these distribution functions and their spatial and temporal gradients.

With more than 10^5 stars and 100 clusters, each with complete 6D space mapping when combined with Gaia, and with the addition of astrophysical parameters ($T_{\rm eff}$, $\log g$, [M/H]), abundance ratios (iron-peak and α-elements, plus other species for 10 000 stars), and of ages for clusters, the Gaia-ESO Survey is the dataset needed to answer those questions. The expected scientific output is enormous, and a brief summary of the main survey goals is reported in the following.

Clusters and stellar evolution. Theories of cluster formation range from the highly dynamic through to quasi-equilibrium and slow contraction scenarios. These different routes lead to different initial cluster structures and kinematics (Jackson & Jeffries 2010). Whilst hydrodynamic and N-body simulations are developing, a fundamental requirement is an extensive body of detailed observations. A complete comparison requires precise position and velocity phase-space information resolving the internal cluster kinematics ($\leq$0.5 km/s).

Moreover, each star cluster provides a (near-)coeval snapshot of the stellar mass function, suitable for testing stellar evolution models from pre-main sequence phases right through to advanced evolutionary stages. Much of the input physics in stellar models can be tested by its effects on stellar luminosities, radii and the lifetimes of different evolutionary phases. Homogeneous spectroscopy will provide estimates of stellar parameters and reddening for large samples of stars over a wide range of masses, in clusters with a wide range of ages and mean chemical compositions.

The halo and the Bulge. Recent surveys have revealed that the halos of both our own and other Local Group galaxies are rich in substructures (Belokurov et al. 2006). These not only trace the Galaxy's past, but have enormous potential as probes of its gravitational field and hence as tracers of the still very uncertain distribution of dark matter (Helmi 2004). High precision radial velocities for many stars at latitudes $|b| > 30°$ will lead to the discovery of more substructures. Their abundance patterns will indicate clearly whether a given structure represents a disrupted object and of which type, or has formed dynamically by resonant orbit-trapping. The kinematics of streams will place tight constraints on the distribution of dark matter.

In simulations of galaxy formation, mergers tend to produce substantial bulges made of stars that either formed in a disc that was destroyed in a merger, or formed during a burst of star formation that accompanied the merger (Abadi et al. 2003). Such "classical" bulges are kinematically distinguishable from "pseudo-bulges" that form when a disc becomes bar unstable, and the bar buckles into a peanut-shaped bulge (Peebles 2011; Kormendy et al. 2010). In common with the great majority of late-type galaxies, the Galaxy's inner bulge appears to be a pseudo-bulge, but ΛCDM simulations suggest that it should also host a classical bulge, perhaps that observed at larger radii. By studying the kinematics and chemistry of K giants at $|b| > 5°$ we will either confirm the classical bulge or place limits on it which will pose a challenge to ΛCDM theory.

The discs. Thick discs seem common in large spiral galaxies (Gilmore & Reid 1983; Yoachim & Dalcanton 2006). Are they evidence that the last major merger event occurred very much longer ago than is expected in standard cosmologies? Are they artifacts of thin disc dynamical evolution? Are they both or neither of these? How did the metallicity of the ISM evolve at very early times? How does this vary with Galactocentric distance? Do major infall events occasionally depress the metallicity of the ISM17? The Gaia-ESO Survey will determine quantitative kinematics and abundance patterns for large samples of thick disc F ang G stars over one outer radial and three vertical scale lengths to help elucidate these key questions in Galaxy formation and evolution.

The selected sample of ≃5000 F and G stars (see below) within 1 kpc from the Sun covers both thin and thick discs, and all ages and metallicities. Using field stars and clusters, where ages are also known, the Gaia-ESO Survey will explore the region from about 6 to more than 20 kpc in Galactocentric distance, and will trace chemical evolution as a function of age and Galactocentric radius across a disc radial scale length. These are key inputs to models for the formation and evolution of the Galaxy disc. Current estimates suffer from poor statistics, inhomogeneous abundance determinations and absence of data at key ages and orbits (Nordström et al. 2004). The Gaia-ESO Survey will also address current disc structure, that which hosts the star formation. Spiral structure is fundamental to the dynamics of the disc: it dominates the secular rise in the random velocities of stars, and may even cause radial migration of stars and gas (Antoja et al. 2010). Currently, we are not even clear about the global morphology of our spiral structure, and the information we have on its dynamics largely relates to gas, not stars. We will initiate a study of the kinematic distortion in the disc potential due to the bar/spirals by measuring some 1000s of radial velocities down key arm, inter-arm and near-bar lines of sight.

1.2. Survey organization

The survey has approximately 300 co-investigators, and the work is structured in a series of documents agreed with ESO, principally the Survey Management Plan and the Survey Implementation Plan. Fig. 1 shows the work organization flow, where each WG (Working group) is indicated.

The obtained raw data will become publicly available through the ESO archive as soon as they are obtained. There will be different advanced data products releases:

- semestral data releases: will begin 12 months after observations started (31 December 2011) and they will refer to all targets that were completed six months before the release date; they will contain reduced 1D spectra with variance, radial velocity with uncertainty, basic target information (including variability);
- annual data releases: they will start 18 months after observations started and will refer to all targets that were completed six months before the release data; they will contain astrophysical parameters determination for the single stars and for the clusters as a whole;
- final data release: containing the full determinable set of astrophysical parameters for each individual target, and for the open clusters as systems, with updated and consistent calibration.

1.3. Observing strategy

The Gaia-ESO Survey was awarded 300 observing nights (60 nights per year, with the last year subject to approval after a progress review) with FLAMES at the ESO VLT

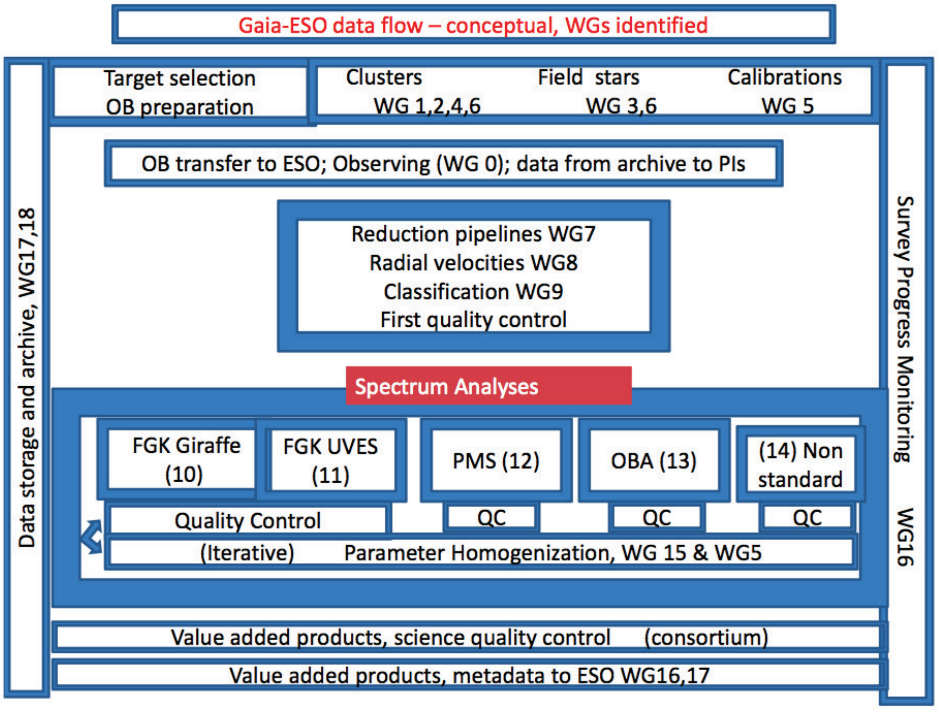

Figure 1. An overwiev of the Gaia-ESO Survey data flow system.

(Very Large Telescope). FLAMES (Pasquini et al. 2002) feeds fibers to two spectrographs: UVES (Dekker & D'Odorico 1992), with a resolution of R≃47 000, receives 8 fibers and GIRAFFE, with a resolution ranging from R≃15 000 to 20 000, receives 132 fibers. Part of the fibers are dedicated to the sky, and a few special fibers are illuminated by wavelength calibration lamps, allowing for a radial velocity determination to better than 100 m/s. Observations started in December 2011.

A selection of the order of 10^5 stars belonging to all Galactic components will be obtained from exisiting photometric surveys such as 2MASS (Skrutskie et al. 2006), VISTA (Saito et al. 2010), SDSS (Aihara et al. 2011) and from dedicated photometries either found in the literature (Dias et al. 2002; Kharchenko et al. 2005, to name a few) or specifically derived from public archival data. Observations are restricted to +10°≥Dec≥–10° whenever possible, to minimize airmass limits, and to 9≥V≥19 mag (where for V>17 mag only radial velocities will be measured).

The primary targets in the various Galactic components will be:

- bulge: ≃10 000 K giants belonging to the red clump (I≃156 mag), for an abundance analysis of iron-peak and α-elements with both UVES and GIRAFFE;

- halo and thick disk: F and G stars, with 17≥r≥18 mag, for iron-peak and α-elements down to [Fe/H]≃–1.0 dex; stars belonging to known streams (e.g., Sgr) will be targeted; the halo targets are expected to be many thousands, as are the thin+thick disk stars;

- outer thick disk (2–4 kpc fonr the Sun): F and G stars, with 25% of the fibers allocated to candidate K giants ($r \leq 18$ mag) for studying the warp and the Monoceros stream;
- thin disk dynamics: six fields at $I \leq 19$ mag will target red clump stars for disk spiral arm/bar dynamics, and only radial velocities will be obtained;
- Solar neighborhood: UVES parallel observations of approximately 5000 G stars within 1 kpc from the Sun, for a detailed abundance analysis of all available elements in the 4800–6800 Å range.
- Open clusters: a total of ~100 clusters of all ages (excluding the embedded phase) will be observed, choosing high-probability members of all spectral types — as appropriated — from O to K dwarfs and giants, and including unveiled PMS (Pre-Main Sequence) stars; the faintest targets will provide accurate radial velocities, the brightest ones a detailed chemical abundance analysis;
- calibration fields: these are discussed in Sect. 2;
- archival data: the Gaia-ESO Survey will analyse all ESO archival data consistent with the observing set-ups and the scientific goals of the survey.

2. Astrophysical calibration

This conference was focused mainly on the standardization and calibration of physical quantities, such as the flux or the wavelength, that can be directly measured, and on the impact of factors that make those measures difficult, such as the effect of the atmosphere.

However other astrophysical quantities are derived in a much more indirect way, by combining direct measurements (for example equivalent width of absorption lines, or oscillator strengths measured for the corresponding transitions) on sophisticately treated data with theoretical models (for example stellar atmospheric models). The resulting astrophysical parameters ($T_{\rm eff}$, $\log g$, [Fe/H], [α/Fe], and other abundance ratios) — that will be derived in the Gaia-ESO Survey — also need their own calibration. However, an astrophysical calibration is based on the comparison of measurements that are often of comparable quality to each other, and ultimately can be described as the effort of estimating the systematic uncertainties underlying a set of indirect measurements.

The basic example of astrophysical calibrator in the case of high-resolution abundance analysis of stellar atmospheres, is the Sun. It is studied with a much higher precision, with much better data (because it is extremely bright) and by many different groups with different technicques. Thus, all astronomers deriving an abundance analysis of solar type stars, analyze the Sun as well with the same method, and compare their results with the consensus solar abundance set. However, the Sun is a good calibrator only for solar metallicity dwarfs, and there is of course no guarantee that it will be as good for metal-poor giants, for example.

Thus, the Gaia-ESO survey dedicates a fraction of the time (approximately 100 h) to observations of calibrators with various purporses. These are:

- a selection of stars for radial velocity calibration mainly from Crifo et al. (2010), a large catalogue of stars which are stable to 300 m/s and that will be used for the radial velocity calibration of Gaia as well;

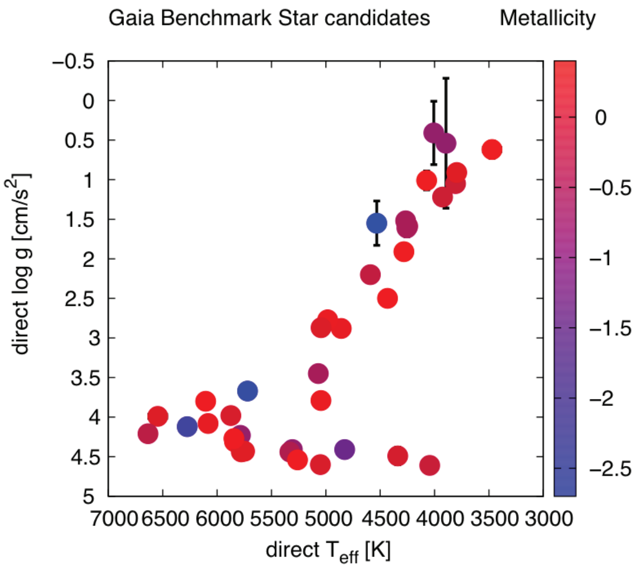

Figure 2. The Gaia benchmark stars, with their direct measurements of $T_{\rm eff}$ and log*g* (courtesy of U. Heiter).

- a selection of stars covering the parameters space of the Milky Way field pointings (Fig. 2); these have their parameters determined independently and as directly as possible (i.e., using parallaxes, diameter measurements and so on) and are also used to calibrate the parametrizer algorithms of the Gaia pipelines;

- a selection of templates peculiar stars of types which may fall into our selection windows, including barium and carbon stars, r- and s-process enhanced stars (e.g., from Alksnis et al. 2001);

- a set of approximately 30–50 globular and open clusters, which will cover the entire metallicity scale covered by the Gaia-ESO Survey; these are chosen as external calibrators among the best studied clusters in the literature, and contain objects in common with other ongoing or planned spectroscopic surveys (e.g., RAVE, HERMES, APOGEE, see also Lane et al. 2011; Frinchaboy et al. 2010);

- a set of internal calibrators, typically relatively young open clusters, containing stars of different spectral types, to link different abundance analysis methods, such as those employed for hot stars (O, B, and A), cool stars (F, G, K, and even M stars), or PMS stars of all spectral types; nearby open and globular clusters will ensure the link between dwarfs and giants;

- a set of pre-defined fields around the celestial equators and possibly at the Ecliptic Pole, containing a mix of objects with different characteristics, to be used as calibrating fields for stellar spectroscopic surveys carried out with wide field multi-object spectrographs; two of these fields are in the areas surveyed by the Corot mission, in the direction of the Galactic center and anti-center (Gazzano et al. 2010).

Thus, the Gaia-ESO Survey will maximise its legacy value by providing all the tools to link its measurements with past and future studies, ultimately with the goal of combining all the large stellar spectroscopic sturveys together.

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