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The WEAVE Galactic Archaeology surveys

and RR Lyrae variable stars within

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Abstract. The ESA *Gaia* mission has brought about a revolution in our understanding of the Milky Way system. Spectroscopic surveys obtaining accurate radial velocities and elemental abundances for stars that are too faint for *Gaia*'s Radial Velocity Spectrometer are, however, an essential complement to exploit the *Gaia* data to their full potential. In this article, we review the plans for Galactic Archaeology surveys with WEAVE, the project for a wide-area multi-object survey spectrograph currently undergoing commissioning on the 4.2-m William Herschel Telescope at the Observatorio del Roque de los Muchachos. We first give an introduction to the instrument, the various planned surveys and the modalities to ask for observing time. Then we describe the plans for the Galactic Archaeology surveys, in particular those that will target RR Lyrae variable stars.

Key words. Stars: Spectroscopic survey – Stars: RR Lyrae

1. The WEAVE project and instrument

The WHT Enhanced Area Velocity Explorer (WEAVE, Dalton et al. 2012, 2016a) is a next-generation wide-field spectroscopic survey facility for the 4.2m William Herschel Telescope (WHT) at the Observatorio del Roque de los Muchachos on La Palma, Spain. We refer the reader to Jin et al. (2022) for a complete description of the design of the WEAVE spectrograph and of the organisation, science drivers, and design of the WEAVE Surveys; here we include only a brief description of some of the salient features of these aspects.

The WEAVE facility comprises a new 2-degree (diameter) field-of-view prime-focus corrector system with 940-960 fibres (depending on the plate), 20 individually deployable "mini" integral field units (mIFUs) each made by 37 fibres and with a 11 arcsec ×12 arcsec field-of-view, and a single integral field unit (large IFU, LIFU) deployable on axis, composed by 547 fibres and with a field-of-view of 90 arcsec × 78 arcsec. The diameter of the individual fibres is 1.3 arcsec for the MOS and mini-IFU modes and 2.6 arcsec for the large IFU mode. The fibres feed a dual-beam spectrograph, providing a low resolution (LR) mode with coverage from 3660Å to 9590Å at a spectral resolution of $R \sim 5000$ in a single exposure, and a high resolution (HR) mode with $R \sim 20000$ covering a more restricted wavelength range.

WEAVE's conception was the combined result of two main aspects. One was the need for intermediate-resolution, wide-field multi-object spectrographs with high multiplex capabilities to provide the spectroscopic follow-up allowing full exploitation of the data from the *Gaia* mission as well as precision-cosmology experiments (Gaia Collaboration et al. 2016)[1]. The other one was the realisation by the Isaac Newton Group of telescopes (ING) that such a survey instrument would be crucial for the ING long term's vision.

After interactions with the community, the science case[2] for such facility at the WHT extended beyond the initial two pillars of *Gaia* spectroscopic follow-up and precision cosmology, and now spans a wide-range of science cases that have resulted in eight different surveys to be carried out with WEAVE:

- a survey of stars in the Milky Way, with the aim of providing radial velocities and elemental abundances for stars in a magnitude regime where *Gaia* will not be able to provide these measurements;
- a survey on characterising young and massive stellar populations and the interstellar medium of the Milky Way;
- a survey of the white dwarf population in the Milky Way;
- a survey of the stellar and gaseous kinematics and physical properties of gas-rich galaxies, as optical complement to the Apertif HI surveys of the local Universe;
- a survey probing the evolution of galaxies from the cores of rich clusters to their environs;
- a survey providing the first detailed view of the stellar population properties of galaxies at z = 0.3–0.7 as a function of galaxy mass and environment;
- a survey providing redshifts and galaxy properties of LOFAR's radio sources;
- a survey of large-scale structure using quasar absorption lines and that extends the study of gaseous environments to larger scales and earlier epochs.

The WEAVE Science Team, or Survey Consortium, is the body responsible for preparing and executing a five-to-seven years survey, and currently consists of over 500 members[3].

WEAVE underwent its preliminary design review in the first trimester of 2013, with the final design review from 2014 to 2015 (up to 2018 for some of the subsystems). Both the science case and the plans for implementing these into surveys underwent reviews, with the "Survey readiness review" being successfully passed in January 2020. Since May 2022, WEAVE is mounted at the WHT prime focus, after several events had significantly complicated the schedule (as the Covid-19 pandemic, Brexit, and the eruption of the Cumbre Vieja volcano on La Palma). The first scientific light is foreseen before the end of 2022, with surveys starting in early 2023. At the time of writ-

[1] As identified by the ASTRONET Wide-Field Spectroscopy Working Group, `https://www.astronet-eu.org/sites/default/files/d26-vsdef-2.pdf` and by the European Telescope Strategic Review Committee, `https://www.astronet-eu.org/sites/default/files/plaquettet2_4m-final-2.pdf`

[2] publicly available at `https://ingconfluence.ing.iac.es/confluence/display/WEAV/Science)`

[3] For an overview of the project and Science Team composition: `http://www.ing.iac.es/weave`

ing, WEAVE is undergoing the commissioning of the LIFU mode.

WEAVE surveys will take up to 70% of the time on WHT, while 30% will be retained as open time for allocation by the time allocation committees. There is therefore the opportunity for PI programmes requiring the use of WEAVE. Since unmounting WEAVE implies taking off the top end of the WHT, which is a feasible but complex operation, it is plausible that during the first 2 years from the start of the WEAVE surveys the 30% open time will be only devoted to observations with WEAVE (see ING webpages).

2. The WEAVE Galactic Archaelogy survey

The WEAVE Galactic Archaeology (GA) survey is the largest of the eight WEAVE surveys in terms of fibre hours. It makes exclusively use of the MOS mode, at both LR and HR, and it is the first one of the ground-based *Gaia* follow-up spectroscopic surveys to benefit and being based on target selection informed by data from the (early) third data release of *Gaia* (Gaia Collaboration et al. 2021, 2022).

It was designed to complement *Gaia* in two primary ways: by providing radial velocities (with an expected precision of ±1-2 km s^{-1}), effective temperature, surface gravity and metallicity (the latter with an expected precision ±0.2 dex) for ∼ 1.8–2.6 million targets in the magnitude range 16 < G < 20.7, i.e. in the regime where *Gaia* is providing 5D astrometric information; and yielding accurate measurements of abundance ratios covering the main nucleosynthetic channels (light elements, α-, Fe-peak, and s- and r-process neutron-capture elements), to better than ±0.05–0.2 dex, depending on the element and stellar type, and radial velocities (to better than ∼ ±0.5 km s^{-1}) for ∼ 1.1–1.6 million stars in the magnitude range 12 < G < 16, in which *Gaia* is providing the full 6D phase-space information.

Importantly, the stellar atmospheric parameters derived by the WEAVE GA surveys can be used to derive spectro-photometric distances (see Thomas & Battaglia 2022, for the methodology that will be applied to the targets observed within WEAVE GA surveys) where *Gaia* parallaxes become too uncertain; this will significantly enhance the volume over which we can explore the properties of our Galaxy. To make an example, at G=20 the volume encompassed by an horizontal branch star or by a K-giant star of absolute V-mag = −2 (in absence of interstellar absorption) reaches to heliocentric distances of 70-80 kpc or in excess of 200 kpc, respectively.

These samples of millions of spectra, coupled to the *Gaia* astrometric information and multi-band photometric information from ground-based surveys, will be used to address what are amongst the most outstanding open questions in the formation and evolution of our Galaxy, for example: How was the Milky Way mass assembled? In what relation are the stellar components of the Milky Way, and how did they evolve from the earliest times to present-day? What is the relative contribution of accreted systems to the stellar halo and what properties did these systems have? What is the shape of the gravitational potential of the Milky Way out to large distances, and how lumpy is it? What is the Galactic disc potential in detail, and how important are deviations from axisymmetry and stationarity? What are the origins of the chemical elements in the Galaxy?

The WEAVE GA survey is organised into four independent programmes (sub-surveys), according to the spectral resolution of the observations (LR or HR) and the stellar populations or Galactic locations targeted, and therefore of the components that will be preferentially explored:

– The 'high latitude survey' (GA-LRhighlat), which focuses on the stellar halo and thick disc and known substructures there-in, i.e. streams and dwarf galaxies. In its 'wide-area' part, it aims for a spatial coverage of 6000-8500 deg^2, at $\delta > 0$ degrees, $|b| > 20$ degrees and in regions of low interstellar absorption; most of the area is expected to be covered contiguously. Several target categories will be followed-up; the most numerous ones will be old main sequence turn-off

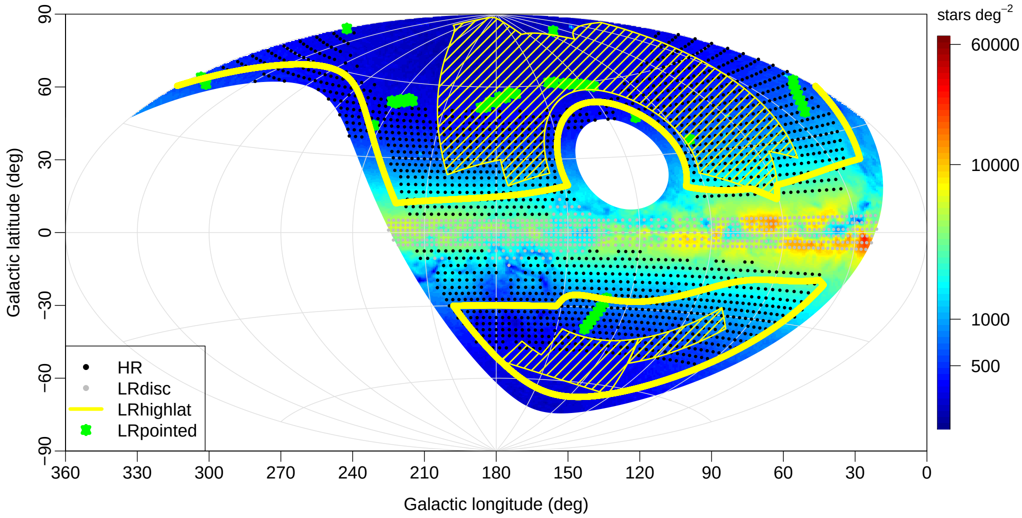

Fig. 1. Goal footprint of the WEAVE GA-HR, GA-LRdisc and GA-LRhighlat (including the pointed part) surveys (see legend) in Galactic coordinates in an Aitoff projection overlaid on a *Gaia* DR3 density map.

stars and candidate red giants, but also multiple categories of rare targets will be observed, such as (but not limited to) blue horizontal branch stars, blue stragglers, extremely metal-poor stars (e.g. from Pristine: Starkenburg et al. 2017), hyper-velocity stars, RR Lyrae variables (e.g. Clementini et al. 2022), and the bright portion of members of known streams (e.g. Martin et al. 2022). In its 'pointed part', observations within LRhighlat will go deeper over a smaller area, specifically around 5 known dwarf galaxies and around regions of particular interest in 4-6 known streams, with multiple exposures; in this case the target selection is optimized for each of the different systems, in order to maximize the return in terms of member stars.

- The 'low resolution disc survey' (LRdisc). This explores 500 line-of-sight in the range $|b|$ <5 deg (apart from a few tiles) and 21<l [deg]<225, with a number of exposures per tile that ranges from one to five, depending on the specific region probed and science goal. The targets are mainly red clump stars in the inner disc and giants towards the outer disc, for a total of ~0.7-1.1 million stars. Nonetheless it will also include some RR Lyrae variables (see next section for more information).
- The HR chemo-dynamical survey ('HR'): This survey will cover about 4000–5600 deg^2, not contigously, at intermediate and high Galactic latitudes to complement *Gaia*'s phase-space information with full chemical information, and probing the three major Galactic populations: the thin and thick discs and the halo. The target selection function is based on *Gaia* DR3 (or from later releases) absolute magnitudes and their associated uncertainties, and will include all stars with absolute magnitudes M_G < 4.5. It will also include at high priority targets of special interest, such as very and extremely metal-poor stars with prior information on metallicity (e.g. from Pristine: Starkenburg et al. 2017), RR Lyrae (e.g. Clementini et al. 2022) and Cepheid (e.g. Ripepi et al. 2022) variable stars, known exoplanet hosts, bright members of known streams (e.g. Martin et al. 2022), and stars with high tangential velocities to increase the halo fraction in the sample.
- The Open Clusters survey ('OC'): This is a survey (mostly in high resolution) of a sizeable sample (~ 120) of old and young open

clusters and tiling three cluster-formation regions.
In addition to the above, an 'Astrophysical calibration' programme is also planned, with the aim of providing a careful validation and accurate calibration of the derived atmospheric parameters, measured abundance ratios and radial velocities so that the data from the aforementioned four GA subsurveys will be on the same scale. These observations will include globular clusters, well-studied open clusters, field giant stars with stellar parameters derived from asteroseismic data from the CoRoT (e.g. Anders et al. 2017) or Kepler (e.g. Yu et al. 2018) missions, and field stars (e.g. *Gaia* benchmark stars or stars in previous high-resolution spectroscopy studies Heiter et al. 2015; Hawkins et al. 2016; Soubiran et al. 2016).

All together, the WEAVE-GA surveys are expected to deliver an amazing sample of spectra for over 4 million stars over a large volume in our Milky Way!

3. RR Lyrae variables in WEAVE

RR Lyrae variable stars are widely regarded as one of the best tracers of the old and metal-poor component of the Milky Way. As such they will be among the stellar targets included in the WEAVE GA surveys, with the aim of enabling determinations of their line-of-sight velocities and chemical composition.

Given their pulsating nature and the fact that WEAVE observations will catch the target RR Lyrae stars at different phases, a specific post-processing will be carried for these targets, with the aim of determining their barycentric line-of-sight velocity and the equivalent width of absorption lines of different chemical elements. These aspects were covered in a dedicated talk by N. Britaviskiy at the same conference and are not included here. In this contribution, we concentrate on the aspects concerning the selection of RR Lyrae variables in the WEAVE GA surveys.

RR Lyrae variables will be specifically targetted in GA-LRhighlat, GA-HR, and GA-LRdisc (see Fig. 1 for an overview of the goal footprint, subject to small adjustments, of these sub-surveys). In particular, they most abundantly will be observed within GA-LRhighlat, given the fainter magnitude regime explored. In both GA-LRhighlat, GA-HR the main source of selection will be the *Gaia* DR3 vary_rrlyrae table, complemented with the PS1 RR Lyrae sample by Sesar et al. (2017).

Fig.2 shows the target densities of *Gaia* DR3 RR Lyrae variable candidates in the approximate region of the sky encompassing the GA-LRhighat and GA-HR observations. As it is possible to see, RR Lyrae variables are rare, about 1.7 stars per square degree at phot_g_mean_mag> 16 and 0.5 stars per square degree at phot_g_mean_mag< 16, therefore the approach will be to target them as high priority stars, together with the other categories of very low density targets. Nonetheless, the expectation is that a 5-7 years survey should yield LR spectra for more than 10000 RR Lyrae variables and that 1000-2000 such targets can be fed to GA-HR.

Rather than surveying the available population of RR Lyrae variables as a whole, the GA-LRdisc survey's sample will concentrate on the set of RR Lyrae variables identified by Iorio & Belokurov (2019, 2021) and that are still classified as RR Lyrae variables in Gaia DR3. This is a particularly interesting sample as its spatial distribution, *Gaia* DR2 proper motions and photometric metallicities make them compatible with belonging to a thin-disc configuration. WEAVE's spectra will provide the missing l.o.s. velocity component to quantify the 3D kinematics of the stars lying in this feature as well as enable spectroscopic determinations of their chemical composition; this will allow to investigate further whether these stars are tracing the ancient part of the Milky Way thin-disc or if they trace the young/metal-rich thin disc, for which a proposed explanation invokes binary evolution (Bobrick et al. 2022).

4. Closing words

An exciting time is ahead of us with the start of the next-generation wide-field spectroscopic surveys that have *Gaia* follow-up among their main goals. WEAVE will be one of the major

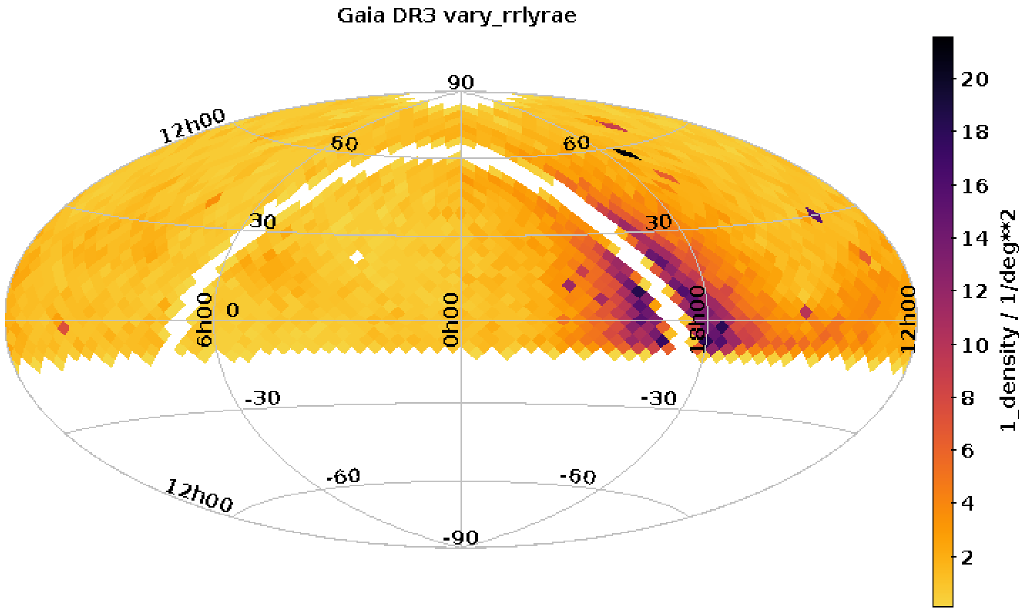

Fig. 2. Density of RR Lyrae variable stars as selected from *Gaia* DR3 vary_rrlyrae catalogue in the range $-10 < \delta < 80$ and $|b| > 5$ deg. The average density is low, about 1.7 stars per square degree at phot_g_mean_mag> 16 and 0.5 stars per square degree at phot_g_mean_mag< 16. The highest density features are due to the central regions of the Galaxy, the Sagittarius stream, some of the dwarf spheroidals satellites of the Milky Way and some globular clusters.

players in this context, with surveys expected to start in the first trimester of 2023. It is the hope of the WEAVE project that the scientific community will make ample use of the wealth of expected WEAVE data, which will be accessible through the WEAVE Archive System via the public data releases. WEAVE will open up new possibilities for the general scientific community also via the PI-programmes that can be proposed for as part of the 30% open time at the WHT.

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