SF2A 2019
P. Di Matteo, O. Creevey, A. Crida, G. Kordopatis, J. Malzac, J.-B. Marquette, M. N'Diaye, O. Venot (eds)

STELLAR SPECTROSCOPIC SURVEYS: OVERVIEW, EXPECTATIONS AND ACHIEVEMENTS

M. Van der Swaelmen[1], L. Magrini[1], V. Hill[2] and G. Kordopatis[2]

Abstract. Multi-fibre spectrographs have made possible the run of large spectroscopic surveys targeting 10^5 to millions of Milky Way (MW) stars. The targeted stars belong to the main stellar structures of our Galaxy and mostly sample stellar evolutionary stages from the (pre-)main-sequence to the red giant branch. Their primary aim is to harvest a vast amount of data (radial velocities, stellar parameters, abundances) in order to constrain the formation and evolution of the MW. We will focus on two spectroscopic surveys France is involved in. First, we will briefly introduce the WEAVE spectroscopic survey, that will soon start to observe at the William Herschel Telescope, and show from simulations what can be expected in terms of chemical abundances. Second, we will highlight the relevance and usefulness of such large project by reminding some of the results obtained within the Gaia-ESO survey.

Keywords: Surveys, Techniques: spectroscopic, Galaxy: abundances, Instrumentation: spectrographs

1 Massive spectroscopic surveys in the recent era

1.1 A short history of spectroscopy in astronomy

Physicists and astronomers have started to use spectroscopy since 1666, the year when Newton obtained the first documented solar spectrum using a prism. However, one has to wait until the 19th century to see the birth of stellar spectroscopy. In 1802, Wollaston is the first to observe few dark lines in the solar spectrum but he failed at understanding their nature. In 1814, Fraunhofer invented the modern spectroscope and with this new instrument, he was able to detect and to label hundreds of absorption lines in the solar spectrum, some of these lines being still called the Fraunhofer lines today. He understood that those dark lines are intrinsic to the nature of the stars and by comparing the spectra of various stars, he showed that stars are different from each other: the first step towards stellar spectroscopy was made.

A technological step (ability to record a spectrum) and a scientific step (nature of the absorption lines) were still to be made in the second half of the 19th century. Stellar spectroscopy took advantage of the progress made by photographic techniques. Thus, the first successful recording of the solar spectrum was made by Becquerel in 1842 using a daguerreotype while the first record of a stellar spectrum (Vega) on a photographic plate was obtained by Draper in 1872. It was an important achievement to allow the comparison of spectra between two stars or over time. One the other hand, the understanding of Fraunhofer's lines took also several decades. Fraunhofer noticed that the solar D lines have wavelengths close to that observed in some flame spectra and Foucault understood in 1849 that a given element may produce an emission or an absorption line at the same wavelength. However, Kirchhoff is the first to identify sodium in the solar spectrum in 1859 and later, he and Bunsen identified a handful chemical species in the solar spectrum by comparing it to the flame and spark spectra of various salts. Similarly, Huggins and Miller recorded the spectra of various distant stars and identified some of the chemical elements present in their atmospheres. They demonstrated that the chemical species found on Earth are found elsewhere in the Universe and that stars do have different chemical compositions. Huggins also attempted for the first time to measure the radial velocity of a star using Doppler shifts, a field that greatly benefited from Vogel's contributions afterwards. Stellar spectroscopy was born!

---

[1] INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125, Firenze, Italy
[2] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Bd de l'Observatoire, CS 34229, 06304, Nice Cedex 4

As in other fields of science, the systematic cataloguing of objects (and their classification) is a necessary step towards the understanding of their intrinsic properties. In the early years of stellar spectroscopy, small catalogues of spectra were already being built. They allowed to highlight resemblances and differences between stars and led to the first stellar classifications (e.g, Rutherfurd, Secchi). However, the first efforts for a massive spectroscopic survey of the skies were carried out at Harvard College Observatory by Pickering and his invaluable "Harvard computers", women coworkers – among which Fleming, Maury, Cannon, Leavitt – who classified manually more than 200 000 stars and whose studies shed new lights on the nature of stars. While Pickering and Fleming started the work in 1886, 10 351 stars were already catalogued in 1890 and $\sim$ 225 000 stars were published between 1918 and 1924 in the final version of the Henry Draper Catalogue. The catalogue was extended to $\sim$ 359 000 stars in 1949. The curious reader may have a look at the excellent book by Hearnshaw (2009) for a more detailed history of stellar spectroscopy.

1.2 Spectroscopic surveys over the last two decades

The previous section recalled the reader that the idea of carrying out a spectroscopic survey is not very new in astronomy and the crucial need of a vast amount of (photometric, spectroscopic, etc) data was recalled in Freeman & Bland-Hawthorn (2002). Thus, another era of large spectroscopic surveys has started in the early 2000s and one notes an intensification since 2010. Such audacious projects have been made possible by the building of large apertures and the advent of multi-object spectrographs allowing to record simultaneously the spectra of few 100 to few 1000 stars in one single exposure. Numerous spectroscopic surveys have been designed and have been/are/will soon be carried out. They differ by their spectral resolution from low- ($R \leq\sim 5000$) to mid- ($\sim 7000 \leq R \leq\sim 15\,000$) and high-resolution ($R \geq\sim 20\,000$)*. They differ also by their spectral coverage, from the UV to mid-infrared.

The very first post-2000 spectroscopic surveys are RAVE (Steinmetz 2003) and SEGUE (Beers et al. 2004; Yanny et al. 2009) started in 2003 and 2004, respectively. RAVE ran for ten years at Anglo-Australian Telescope and recorded more than 570 000 spectra at $R = 7500$ for more than 483 000 stars belonging to the Milky Way (MW) and the Magellanic Clouds (MCs). SEGUE obtained spectra at $R = 1800$ for 240 000 targets between 2004 end 2008 and was complemented by SEGUE-2 and its 140 000 targets. Among the other notable terminated surveys, one finds: APOGEE (Apache Point Observatory; Majewski et al. 2010) and its 10^5 stars observed at $R \sim 22\,500$ in the range [15 100, 17 000 Å]; Gaia-ESO (Very Large Telescope; Gilmore et al. 2012; Randich et al. 2013) and its 10^5 stars observed with the mid- ($R \sim 20\,000$) and high-resolution ($R = 47\,000$) FLAMES spectrographs in various wavelength ranges; LEGUE (the MW part of the LAMOST survey; Guo Shoujing Telescope; Newberg et al. 2012) and its 10^7 stars and galaxies (as of DR5) observed at $R = 1800$ in the range [3690, 9100 Å].

Many surveys are still ongoing: GALAH (Anglo-Australian Telescope; Anguiano et al. 2014) aiming at observing 10^6 stars of the MW at $R = 28\,000$ in four wavelength windows; APOGEE-2 (Apache Point Observatory + Iréńée du Pont Telescope; Majewski et al. 2016) aiming at observing 3×10^5 stars of the MW and the MCs; Gaia RVS (Gaia space probe; for the Gaia mission: Prusti 2012; for the RVS: Katz et al. 2004; Wilkinson et al. 2005) will obtain the spectra around the near-infrared Ca II triplet at $R = 11\,500$ and is expected to provide radial velocities for 150×10^6 stars and basic chemical composition for 2×10^6 stars (Recio-Blanco et al. 2016). On the other hand, DESI (Kitt Peak; DESI Collaboration et al. 2016) is designed as a high-redshift spectroscopic instrument and is mainly a tool for cosmology; however, it will observe MW stars during the bright time of the survey and is expected to provide us with low-resolution spectra for 10^7 stars.

A new generation of facilities is also being built and new spectroscopic surveys will start *tomorrow*: WEAVE (William Herschel Telescope; Dalton et al. 2012), 4MOST (VISTA Telescope; de Jong et al. 2019) and MOONS (VLT; Cirasuolo & MOONS Consortium 2016). These new surveys will take care to have numerous common targets to ease inter-survey calibrations. Tests are also carried out to upgrade LEGUE with a higher resolution of 7500 (Liu et al. 2019). In the near future ($\sim$ 2030), the community will benefit from the Maunakea Spectroscopic Explorer (McConnachie et al. 2014), a dedicated 10m-class telescope which will record about 4400 spectra at once ($\sim$ 1100 at high-resolution and $\sim$ 3300 at low-/mid-resolution) resulting in the production of millions of spectra every few weeks. France has a long-term involvement into stellar spectroscopy and has been or is contributing to the following surveys: RAVE, Gaia-ESO, Gaia RVS, DESI, WEAVE, 4MOST, MOONS and MSE.

*The boundaries between low-, mid- and high-resolution are somewhat arbitrary and may change depending on the astronomy field. Here the numbers correspond to what is often meant in the context of stellar spectroscopy.

The outputs of recent spectroscopic surveys are individual spectra (few 10^5 to few 10^7), radial velocities, atmospheric parameters and global/detailed chemical compositions. They sample the kinematics and chemistry of different populations (MW thin/thick disks, bulge, halo, clusters), different galaxies (Magellanic clouds for APOGEE-2 and 4MOST), different evolutionary phases (main-sequence and RGB, mainly). Their aims are to characterise stellar populations and Galactic structures and constrain the chemical/dynamical history of the MW (or MCs). The size of all these surveys and the number of phase space dimensions they probe are breathtaking, especially when one compares them to the $\sim 225\,000$ stars of the Henry Draper Catalogue collected over three decades.

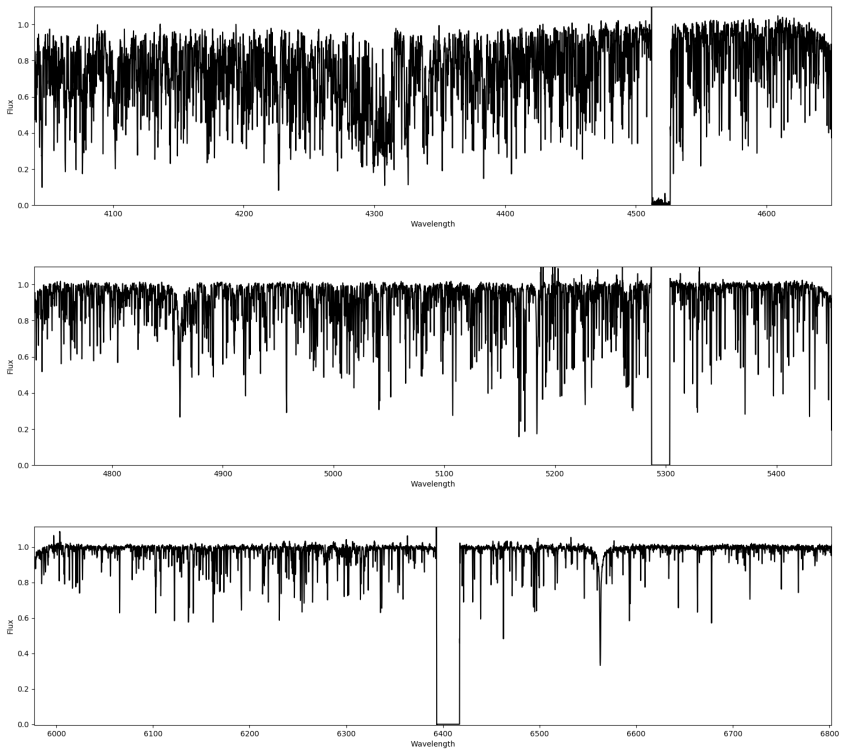

Fig. 1. From top to bottom: example of simulated WEAVE blue, green and red spectra for a mildly metal-poor giant. The signal-to-noise ratio is larger than 90.

2 The WEAVE survey

The WEAVE survey (Dalton et al. 2012) will be carried out at the William Herschel Telescope in La Palma. It will therefore give access to the Northern sky. The facility is made of 1000 fibres feeding a low- and high-resolution spectrographs. The low-resolution mode offers a resolution of 5000 and observes from the UV to the near-IR, over two wavelength windows [3660, 6060 Å] and [5790, 9590 Å]. The high-resolution mode offers a resolution of 20 000 and two configurations: the blue + red arms ([4040, 4650 Å] and [5950, 6850 Å]) or the green + red arms ([4730, 5450 Å] and [5950, 6850 Å]). It is thought to complement the Gaia phase space and in particular to provide accurate radial velocities, stellar parameters and abundances for targets fainter than $G = 12$, the faintest targets reached by WEAVE being of magnitude $G = 20$.

The Galactic archaeology component of WEAVE is divided into a low- (LR) and a high-resolution (HR) surveys. They will be the first spectroscopic surveys to use the Gaia DR2 as input catalogue. The LR survey will provide for the observed stars their atmospheric parameters, radial velocities and, at least, global abundance estimates while the HR survey will also provide detailed chemical abundances for more than ten species. The LR survey is divided into two sub-surveys: the LR-Halo survey will map the MW halo and search for stellar streams, as remnants of past accretion events; the LR-Disk survey will study the disk dynamics. The HR survey is also divided into two sub-surveys: the HR-Open-clusters will target open clusters in the disk and study, for instance, their dynamical evolution and role in stellar migration; the HR-chemo-dynamical will probe the MW thin/thick disks and halo and will constrain the chemical evolution and mass assembly of the MW. In total, LR and HR surveys will observe more than four millions of MW stars.

The choice of the configuration (blue+red arms – BR – or the green+red arms – GR) is constrained by the kind of science we are interested in and, in turn, by which chemical species are needed. Figure 1 shows the simulated WEAVE blue, green and red spectral chunks for a mildly metal-poor giant. Those spectra have been generated in the context of the operation rehearsal (OpR3). They are based on the synthetic spectral library by de Laverny et al. (2012) and simulate the resolution, signal-to-noise ratio and spectral shape of the WEAVE spectra at the end of the optical and data reduction chain.

We used a set of 3000 spectra, at various level of signal-to-noise ratio, corresponding to stars sampling the Hertzsprung-Russell diagram, over the FGK spectral types and over the dwarf and giant luminosity classes, to test which is the best configuration when it comes to study carbon, nitrogen and neutron-capture elements. We chose to study the detectability of these elements because of their importance in both stellar and galactic evolution. For instance, C and N in evolved stars trace the mixing processes and their abundance ratio can be used as a proxy for stellar ages (see, e.g. Casali et al. 2019). On the other hand, neutron-capture elements are produced by different processes and with different timescales, tracing the Galactic chemical evolution. Their ratio over alpha elements, as e.g. [Y/Mg], can be also used to measure stellar ages (e.g., Titarenko et al. 2019).

Figure 2 shows examples of fit of Ba, La and Eu atomic lines as well as molecular CH and CN bands. Our study shows that the blue spectra are indispensable to measure C and N. The blue and red spectra give access to some Ba, La and Eu lines. However, the determination of Ba and Eu abundances in the photosphere of main-sequence stars will rely on the blue lines only (the red lines are weaker and will likely lead to firm detections only in the spectra of giants). We note that the blue spectra tend to be more crowded by atomic lines and molecular bands than the green or the red spectra, which could hamper the normalisation and thus, impact the accuracy/precision of abundances determinations. On the other hand, we recall that the BR and the GR configurations perform similarly when it comes to derive Fe or α-elements abundances.

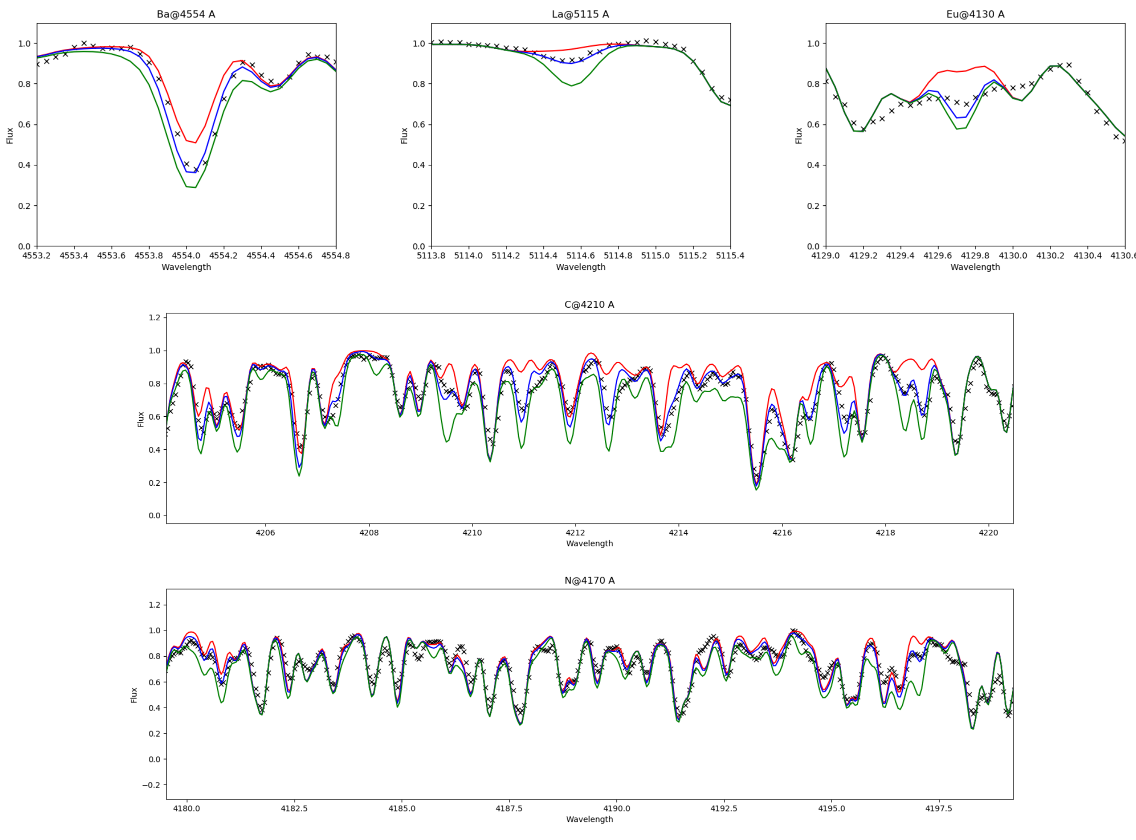

Fig. 2. From top to bottom, left to right: example of absorption line fitting for Ba, La, Eu, C (CH bands) and N (CN bands). The star shown here is the same as in Fig. 1. Black crosses stand for the simulated WEAVE spectra. The blue lines correspond to the best fit while the green and red lines correpond to syntheses obtained for [X/Fe] = ±0.3.

3 Achievements of spectroscopic surveys: example of the Gaia-ESO survey

The Gaia-ESO survey (Gilmore et al. 2012; Randich et al. 2013) is a ground-based mid- and high-resolution spectroscopic survey carried out at VLT, Chile with the multi-object spectrograph FLAMES (Pasquini et al. 2000). It aimed at recording the spectra for 10^5 stars belonging to the Galactic bulge, thin/thick disks, halo, clusters. About 90 % of the spectra have been obtained with GIRAFFE at a resolution ranging from $\sim$ 18 000 to $\sim$ 21 500 (depending on the chosen setup) and 10 % obtained with UVES at a resolution 47 000. The observing campaign is now over and the sixth (and final) data release is expected by 2020. The final release contains 700 000 individual spectra, most of the targets having two or four exposures. The survey covers the range of V magnitude from 10 to 20 with a median at 15.

The Gaia-ESO survey legacy will be significant and multiple. One should not underrate the contributions of the Gaia-ESO surveys in terms of methods and techniques. First, it was an ideal laboratory to assess good practices for future large surveys: the use of numerous calibrators, like radial velocity standards or Gaia benchmark stars, to control the results internally and externally; the use of a single source of atomic and molecular data that were checked and shared before starting any spectral analysis; etc. Its organisation in analysis nodes was also challenging since a single set of stellar parameters and abundances had to be forged out of a dozen of sets. Homogenisation procedures had to be designed and to this end, a flag dictionary had to be used in order for the nodes to report issues and comments along with the results and their errors. The flags have proven their usefulness to identify and fix problems and also to make choice during the homogenisation phase (Van der Swaelmen et al. 2018b). Numerous analysis tools and pipelines have been developed in the context of the Gaia-ESO survey and this algorithm legacy might be re-used for or adapted to future surveys, like WEAVE. The Gaia-ESO survey catalogue brings numerous primary products to the community: spectral library, radial velocities, atmospheric parameters, chemical abundances for the main nucleosynthetic families. Finally, the Gaia-ESO survey has addressed a number of fundamental topics in astronomy: stellar nucleosynthesis (e.g., Magrini et al. 2018), stellar evolution (e.g., Lagarde et al. 2019), abundance gradients (e.g., Spina et al. 2017), kinematics (e.g., Rojas-Arriagada et al. 2014), stellar migration (e.g., Hayden et al. 2018), thin/thick disk transition (Kordopatis et al. 2015), spectroscopic binaries (Merle et al. 2017), ages of clusters, interstellar medium, etc. Eighty refereed publications can be listed so far and many more are still expected.

To finish, we will recall that such surveys often bring us bonus science that was not among the primary goals. In the case of the Gaia-ESO survey, one can cite the case of spectroscopic binaries. Merle et al. (2017) and Van der Swaelmen (*in prep*, see also Van der Swaelmen et al. 2018a) designed a pipeline to compute narrow cross-correlation functions (CCFs) and analyse them to look for single-, double-, triple-lined spectroscopic binaries. Figure 3 shows the NACRE CCFs for a double-lined spectroscopic binary (SB2). Van der Swaelmen et al. (2018a) derive the mass ratio for 10 % of their SB2. The distribution, shown in Fig. 3, is biased towards 1. This is understood if one recalls that for an SB2, both components are visible in the spectra: this means that they have similar spectral types and since they are co-eval, they have similar masses.

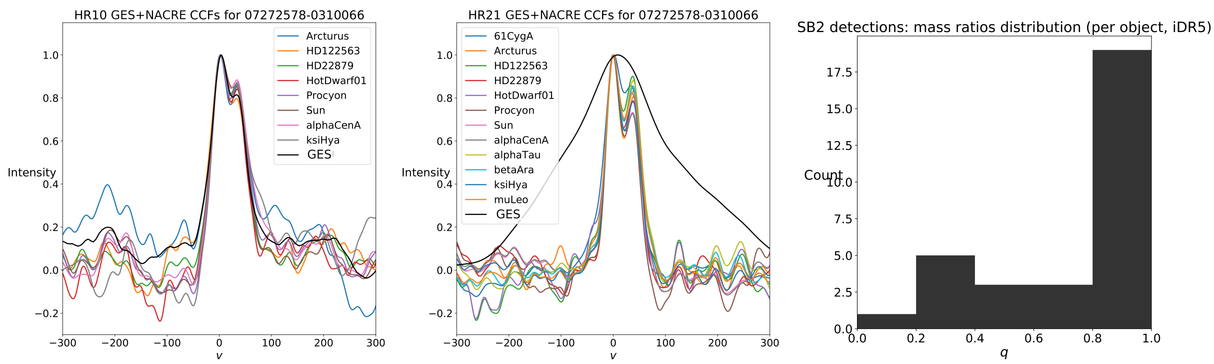

Fig. 3. Left: Example of cross-correlation functions of a Gaia-ESO SB2 observed with the GIRAFFE setup HR10. The black line is the CCF released by the Gaia-ESO while the coloured lines are the NACRE CCFs. **Middle**: Same as left but for an HR21 observation of the same object. The Gaia-ESO CCF does not display the two stellar components while our NACRE CCFs do. **Right**: Mass-ratio distribution for about 10 % of the SB2 detected in the fifth internal data release of the Gaia-ESO survey.

4 Conclusion

Astronomers live in the golden age of stellar spectroscopy. An unprecedented international effort is carried out to increase the number of observed targets and the number of known dimensions of the phase space. The aim is to constrain the chemical evolution and assembly history of the Milky Way. While a number of surveys (RAVE, APOGEE, Gaia-ESO, etc) have reached their conclusion and have shown the usefulness of a large amount of homogeneously obtained physical quantities, a new generation of survey will soon start and will allow us to increase the size of spectroscopic catalogues (and their attached products) by several orders of magnitude. Ground-based spectroscopy is fundamental to complement the Gaia exquisite dataset (proper motions, distances, etc.) and their combination is leading us to major discoveries (e.g., see the use of Gaia and APOGEE by Helmi et al. 2018 to discover Gaia-Enceladus, an ancient merger that likely contributed to the build-up of the inner halo and the thick disk).

References

Anguiano, B., Freeman, K., Bland-Hawthorn, J., et al. 2014, in IAU Symposium, Vol. 298, Setting the scene for Gaia and LAMOST, ed. S. Feltzing, G. Zhao, N. A. Walton, & P. Whitelock, 322–325

Beers, T. C., Allende Prieto, C., Wilhelm, R., Yanny, B., & Newberg, H. 2004, PASA, 21, 207

Casali, G., Magrini, L., Tognelli, E., et al. 2019, arXiv e-prints

Cirasuolo, M. & MOONS Consortium. 2016, in ASPC Series, Vol. 507, Multi-Object Spectroscopy in the Next Decade: Big Questions, Large Surveys, and Wide Fields, ed. I. Skillen, M. Balcells, & S. Trager, 109

Dalton, G., Trager, S. C., Abrams, D. C., et al. 2012, in Proc. SPIE, Vol. 8446, Ground-based and Airborne Instrumentation for Astronomy IV, 84460P

de Jong, R. S., Agertz, O., Berbel, A. A., et al. 2019, The Messenger, 175, 3

de Laverny, P., Recio-Blanco, A., Worley, C. C., & Plez, B. 2012, A&A, 544, A126

DESI Collaboration, Aghamousa, A., Aguilar, J., et al. 2016, arXiv e-prints

Freeman, K. & Bland-Hawthorn, J. 2002, ARA&A, 40, 487

Gilmore, G., Randich, S., Asplund, M., et al. 2012, The Messenger, 147, 25

Hayden, M. R., Recio-Blanco, A., de Laverny, P., et al. 2018, A&A, 609, A79

Hearnshaw, J. 2009, Astronomical Spectrographs and their History

Helmi, A., Babusiaux, C., Koppelman, H. H., et al. 2018, Nature, 563, 85

Katz, D., Munari, U., Cropper, M., et al. 2004, MNRAS, 354, 1223

Kordopatis, G., Wyse, R. F. G., Gilmore, G., et al. 2015, A&A, 582, A122

Lagarde, N., Reylé, C., Robin, A. C., et al. 2019, A&A, 621, A24

Liu, N., Fu, J.-N., Zong, W., et al. 2019, Research in Astronomy and Astrophysics, 19, 075

Magrini, L., Spina, L., Randich, S., et al. 2018, A&A, 617, A106

Majewski, S. R., APOGEE Team, & APOGEE-2 Team. 2016, Astronomische Nachrichten, 337, 863

Majewski, S. R., Wilson, J. C., Hearty, F., Schiavon, R. R., & Skrutskie, M. F. 2010, in IAUS, Vol. 265, Chemical Abundances in the Universe: Connecting First Stars to Planets, ed. K. Cunha, M. Spite, & B. Barbuy, 480–481

McConnachie, A., Murowinski, R., Salmon, D., Simons, D., & Côté, P. 2014, in Proc. SPIE, Vol. 9145, Ground-based and Airborne Telescopes V, 914519

Merle, T., Van Eck, S., Jorissen, A., et al. 2017, A&A, 608, A95

Newberg, H. J., Carlin, J. L., Chen, L., et al. 2012, in ASPC Series, Vol. 458, Galactic Archaeology: Near-Field Cosmology and the Formation of the Milky Way, ed. W. Aoki, M. Ishigaki, T. Suda, T. Tsujimoto, & N. Arimoto, 405

Pasquini, L., Avila, G., Allaert, E., et al. 2000, in Proc. SPIE, Vol. 4008, Optical and IR Telescope Instrumentation and Detectors, ed. M. Iye & A. F. Moorwood, 129–140

Prusti, T. 2012, Astronomische Nachrichten, 333, 453

Randich, S., Gilmore, G., & Gaia-ESO Consortium. 2013, The Messenger, 154, 47

Recio-Blanco, A., de Laverny, P., Allende Prieto, C., et al. 2016, A&A, 585, A93

Rojas-Arriagada, A., Recio-Blanco, A., Hill, V., et al. 2014, A&A, 569, A103

Spina, L., Randich, S., Magrini, L., et al. 2017, A&A, 601, A70

Steinmetz, M. 2003, in ASPC Series, Vol. 298, GAIA Spectroscopy: Science and Technology, ed. U. Munari, 381

Titarenko, A., Recio-Blanco, A., de Laverny, P., Hayden, M., & Guiglion, G. 2019, A&A, 622, A59

Van der Swaelmen, M., Merle, T., Van Eck, S., & Jorissen, A. 2018a, in SF2A-2018, 183–186

Van der Swaelmen, M., Van Eck, S., Gonneau, A., et al. 2018b, in SF2A-2018, 351–353

Wilkinson, M. I., Vallenari, A., Turon, C., et al. 2005, MNRAS, 359, 1306

Yanny, B., Rockosi, C., Newberg, H. J., et al. 2009, AJ, 137, 4377