Astronomy in Focus, XXIXB, Focus Meeting 17
XXIXth IAU General Assembly, August 2015
Piero Benvenuti, ed.

doi:10.1017/S1743921316006347

Asteroseismology for Galactic archaeology: bridging two fields

Luca Casagrande[1], **Victor Silva Aguirre**[2] **and Aldo M. Serenelli**[3]

[1]Research School of Astronomy & Astrophysics, Mount Stromlo Observatory
The Australian National University, ACT 2611, Australia

[2]Stellar Astrophysics Centre, Department of Physics and Astronomy
Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark

[3]Instituto de Ciencias del Espacio (ICE-CSIC/IEEC) Campus UAB
Carrer de Can Magrans, s/n 08193 Cerdanyola del Valls, Spain

`http://www.mso.anu.edu.au/saga`

Abstract. Asteroseismology has the capability of precisely determining stellar properties that would otherwise be inaccessible, such as radii, masses, and thus ages of field stars. When coupling this information with classical determinations of stellar parameters, such as metallicities, effective temperatures, and angular diameters, powerful new diagnostics for Galactic studies can be obtained. An overview of the ongoing Strömgren survey for Asteroseismology and Galactic Archaeology (SAGA) is presented, along with recent results using asteroseismology to investigate the vertical age structure of the Milky Way disc.

Keywords. Galaxy: stellar content, Galaxy: disc, Galaxy: evolution, stars: fundamental parameters, stars: oscillations, surveys, techniques: photometric

1. Introduction

The study of the formation and evolution of our Galaxy is entering its golden age, with a number of spectroscopic and photometric surveys targeting one of its main (baryonic) components: stars. Among the latter, red giants are the ideal targets to decipher the formation history of the Milky Way: on the HR diagram they span a vastly different range of gravities and luminosities, thus probing a large range of distances. Their ages essentially cover the entire history of the Universe, thus making them fossil remnants from different epochs of the formation of the Galaxy. The cold surface temperatures encountered in red giants are the realm of interesting atomic and molecular physics shaping their emergent spectra. This temperature regime is also dominated by convection, which is the main driver of the oscillation modes that we are now able to detect in several thousands of stars thanks to space borne asteroseismic missions such as *CoRoT* and *Kepler/K2* (e.g., Chaplin & Miglio 2013, for a review). By measuring oscillation frequencies in stars, asteroseismology allows us to measure fundamental physical quantities, masses and radii in particular, which otherwise would be inaccessible in single field stars, and which can be used to obtain information on stellar distances and ages (e.g., Silva Aguirre *et al.* 2012, 2015; Miglio *et al.* 2013). In particular, global oscillation frequencies not only are the easiest ones to detect and analyze, but are also able to provide the aforementioned parameters for a large number of stars with an accuracy that is generally much better than achievable by isochrone fitting in the traditional sense (see e.g., Silva Aguirre *et al.* 2013; Lebreton *et al.* 2014a,b).

Asteroseismology thus provides a powerful and new complementary tool for photometric and spectroscopic stellar surveys. In fact, while it is relatively straightforward to derive some sort of information on stellar surface temperature and chemical composition simply from colours and/or spectra (and in many cases even detailed abundances), that is usually not the case when it comes to masses, radii, distances and, in particular, stellar ages. Even when accurate astrometric distances are available to allow comparison of stars with isochrones, the derived ages are still highly uncertain, and statistical techniques are required to avoid biases (e.g., Pont & Eyer 2004; Jørgensen & Lindegren 2005; Serenelli *et al.* 2013). Furthermore, isochrone dating is meaningful only for stars in the turnoff and subgiant phase (e.g., Nordström *et al.* 2004; Casagrande *et al.* 2011), where stars of different ages are clearly separated in the HR diagram. This is in contrast, for example, to stars on the red giant branch, where isochrones with vastly different ages can fit equally well observational constraints such as effective temperatures, metallicities and surface gravities within their errors (e.g., Soderblom 2010, for a review).

The capability of asteroseismology to deliver reliable stellar ages for red giants is thus a major game-changer for Galactic studies, allowing us to put a timeline on the events which have shaped the Milky Way through the cosmic history. For the first time we are in the position to robustly investigate the interplay between age and chemistry across stellar populations, a key question in all major surveys of Galactic Archaeology. With this purpose in mind we have started the Strömgren survey for Asteroseismology and Galactic Archaeology: SAGA.

2. SAGA

The purpose of SAGA is to uniformly and homogeneously observe stars across most of the *Kepler* and some *K2* fields in the Strömgren *uvby* system,to derive stellar parameters and provide new benchmark fields for Galactic studies, similar to the solar neighbourhood. Details on survey rationale, strategy, observations and data reduction are provided with the first data release (Casagrande *et al.* 2014a).

Observations are conducted with the Wide Field Camera on the 2.5-m Isaac Newton Telescope (INT), which in virtue of its large field of view and pixel size is ideal for wide-field optical imaging surveys. The purpose of SAGA is to obtain good photometry (i.e. few hundredths mag) for *all* stars in the magnitude range where *Kepler/K2* measures oscillations in most stars, i.e. $10 \lesssim y \lesssim 14$. This requirement can be easily achieved with short exposures on a 2.5-m telescope. Indeed, all stars for which *Kepler* measured oscillations are essentially detected in our survey (with a completeness $\gtrsim 95\%$). SAGA is magnitude complete to about $y \simeq 16$ mag, and stars are still detected at fainter magnitudes ($y \simeq 18$), although with increasingly larger photometric errors and incompleteness. With SAGA it is thus straightforward to build a magnitude complete and unbiased photometric catalog down to $y \simeq 16$ mag, against which we can benchmark the sample of stars with measured *Kepler* oscillations. This makes our photometric survey unique to recover the *Kepler* selection function of seismic targets (Casagrande *et al.* 2015). In fact, the goal of the *Kepler* mission was to optimize the scientific yield with regard to the detection of Earth-size planets in the habitable zone of stars (Batalha *et al.* 2010). When it comes to seismic targets, entries were based on a number of heterogeneous criteria (although this is not the case anymore for *K2*). Understanding the selection function is mandatory to infer properties of Galactic populations, making SAGA complementary to other ground based follow up studies of asteroseismic targets (see e.g. Casagrande 2015, for the rationale behind photometric parameters, and a brief discussion of pros and cons between photometric and spectroscopic surveys).

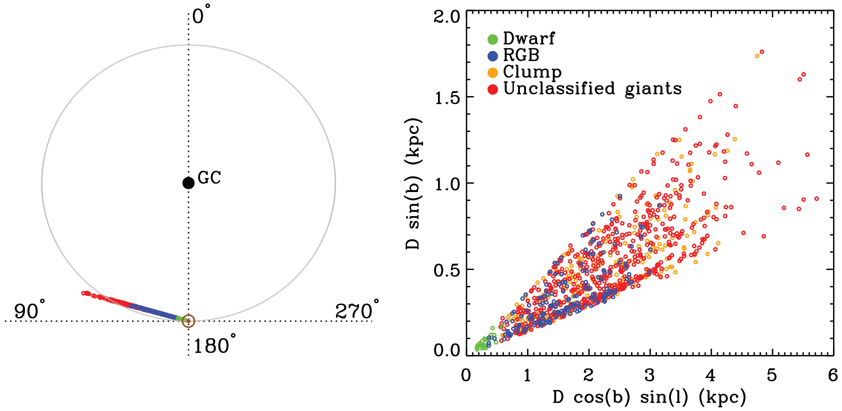

Figure 1. Location of SAGA targets in the Galaxy. Stars with different seismic classification have different colours, as labelled. *Left panel:* face-on view in Galactic coordinates, where the distance of each seismic target from the Sun (D) is projected along the line of sight $D\ \cos(b)$ having direction $l \simeq 74°$ and Galactic latitude b. The distance between the Galactic Centre (GC) and the location of the Sun ($\odot$) is marked by the solar circle (in brown). Galactic longitudes (l) at four different angles are indicated. *Right panel:* same stars as function of Galactic height $Z = D\ \sin(b)$ and projected across the $l = 90°$ direction. Different colors identify stars with different seismic classification, as discussed in Section 3.

Without going into in the gory details of the Strömgren *uvby* system, here it suffices to say that it was designed for the determination of basic stellar parameters with the ultimate purpose of studying Galactic stellar populations (Strömgren 1963, 1987). In this respect, its capabilities have been demonstrated by the Geneva-Copenhagen Survey (GCS, Nordström *et al.* 2004), and SAGA builds on the legacy of the GCS. Similar to the latest revision of the GCS (Casagrande *et al.* 2011), we combine Strömgren metallicities with broad-band photometry to obtain effective temperatures and metallicities for all targets (see next Section). This facilitates the task of placing SAGA and the GCS on the same scale. However, there are also marked differences between the two surveys: the GCS is an all-sky, shallow survey limited to main-sequence and subgiant stars in the solar neighbourhood, all having astrometric distances from *Hipparcos* (up to $\simeq$ 100 pc, and volume limited within $\simeq$ 40 pc). In the GCS, the stellar properties measured in the solar neighborhood can be dynamically stretched across several kpc using kinematics; for example, the age-velocity dispersion measured with the GCS clearly indicates that the age of the Galactic disc increases when moving away from the plane.

The seismic targets in SAGA are primarily giants located between $\simeq$ 1 and $\simeq$ 6 kpc. The results reported in what follows are based on the first data release, which combines asteroseismic and photometric stellar parameters for 989 *Kepler* targets, most of which are red giants. They are located in a stripe covering Galactic latitudes from about 8° to 20°, and Galactic longitudes centred at $l \simeq 74°$, implying nearly constant Galactocentric distances and thus minimizing radial variations (Fig. 1). This sample is thus ideal to study the vertical structure of the disc, and provide a direct measure of the vertical age gradient kinematically inferred from the GCS.

3. Classical and seismic stellar parameters

Within SAGA a novel approach is developed to derive classical and asteroseismic stellar parameters in a fully self-consistent way. Classical stellar parameters are derived from photometry: angular diameters and effective temperatures implementing various broad-band systems into the Infrared Flux Method (Casagrande *et al.* 2006, 2010), and metallicities from Strömgren photometry. Reddening is constrained by calibrating various 3-dimensional reddening maps (Drimmel *et al.* 2003; Amôres & Lépine 2005) to reproduce the value of $E(B-V)$ measured for the open cluster NGC 6819, which is located in the *Kepler* field and observed as part of SAGA.

Stellar oscillations driven by surface convection, such as those observed in the Sun and red giants, are visible in the power spectrum of time series photometry as a series of Lorentzian-shaped peaks whose peak height is modulated in frequency by a Gaussian-like envelope (e.g., Chaplin & Miglio 2013). Two quantities can be readily extracted from this oscillation pattern: the average separation between peaks of the same angular degree and consecutive radial order, the large-frequency separation $\Delta\nu$, and the frequency of maximum amplitude ν_{max}. To extract these global oscillation parameters we have used the analysis pipeline described in Huber *et al.* (2009). Provided the stellar effective temperature is also known, these two global frequencies are related to stellar masses and radii via scaling relations (e.g., Stello *et al.* 2009; Silva Aguirre *et al.* 2011). Also, once a star has evolved on the red giant phase, its age is determined to good approximation by the time spent in the hydrogen burning phase, and this is predominantly a function of mass (although in case of mass-loss, the actual mass measured by seismology will be somewhat smaller than the initial mass which sets the evolutionary timescale). In other words, for red giants stellar mass is a proxy of age. We apply a Bayesian scheme to sets of isochrones to derive expectation values for stellar radii, masses and ages given our input observables (effective temperatures, metallicities, $\Delta\nu$ and ν_{max}). For a large fraction of objects, evolutionary phase classification tells whether a stars is a dwarf, is evolving along red giant branch (RGB) or is already in the clump phase (e.g. Stello *et al.* 2013). The latter distinction is particularly important to derive reliable stellar ages, in particular to single out lower RGB stars, where the effect of mass-loss is negligible.

Comparing seismic radii to angular diameters, we also derive precise distances, which are crucial for studies of Galactic structure. A great deal of effort has also gone into testing the reliability of seismic scaling relations (e.g., Huber *et al.* 2012; Silva Aguirre *et al.* 2012) as well as our angular diameters and flux calibrations (Casagrande *et al.* 2014b; Casagrande & VandenBerg 2014). After a careful assessment of random and systematic errors, total uncertainties on our parameters are of order 82 K in effective temperature, 0.17 dex in metallicity, 0.006 dex in surface gravity, 1.5% in stellar density, 2.4% in radius, 3.3% in distance and 6.0% in mass. Age uncertainties vary depending an the availability of seismic classification or not, but are usually below 30% (Casagrande *et al.* 2014a, 2015). Confidence in the achieved precision is corroborated by the clear separation of first and secondary clump stars in a population of field stars, and by the negligible scatter in the seismic distances and ages among stars belonging to the cluster NGC 6819.

4. Selection function and selection effects: dealing with them

Before using our sample of stars for any study dealing with Galactic structure, two questions must be answered. First, we must understand the *Kepler selection function*, i.e. to which extent the asteroseismic sample of giants is representative of the underlying population of giants in the field. In order to do this, we use our Strömgren observations to build an unbiased sample of giants, and benchmark the seismic sample against this unbiased sample. By doing so, we are able to identify the color and magnitude range where the asteroseismic sample can be thought as randomly drawn from the field.

Once clear selection criteria are identified, we must still quantify the probability that a star with certain stellar parameters will be observed. This is due to *target selection*

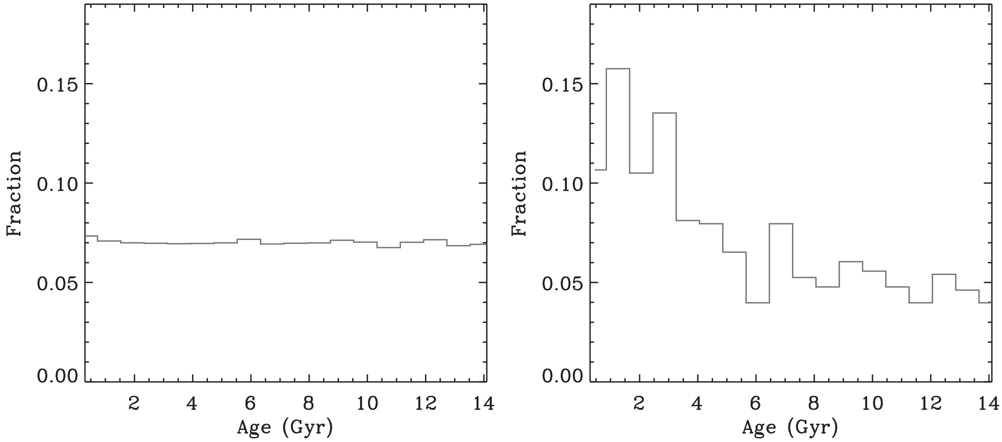

Figure 2. *Left panel:* the probability of observing a given age is $1/\tau_{mas}$ assuming a constant star formation history between 0 and τ_{max}. When generating a synthetic stellar population, this distribution is still traced by low-mass unevolved dwarfs. *Right panel:* the age distribution of the same synthetic stellar population when selecting instead red giant stars as per the Kepler selection function found with SAGA. The use of red giant stars biases the distribution towards young ages, even without assuming any Galactic age gradient.

effects, i.e. how age and metallicity affect the location of a star on the HR diagram, and thus how likely it is that a star of a given age and metallicity will pass our color and magnitude limits. We adopt different approaches to quantify target selection effects. Briefly, we generate synthetic stellar populations with different mass, metallicity, age and distance distributions and see how those are affected by the adopted color and magnitude cuts. Some of the input distributions are motivated by Galactic modelling, whereas other are not. We find that target selection corrections depend on the input distributions to some extent, but in all cases the overall behaviour is similar. Namely, the probability of observing a red giant star decreases when its distance and/or age increase, and its metallicity decreases. Also, the age distribution of red giants is biased towards younger ages. This can be understood thinking to stellar evolutionary timescales (and to the underlying Initial Mass Function). Thus at a given epoch, the age distribution of red giants will favour the presence of more massive (i.e. young) stars.

5. A roadmap for Galactic studies

Once target selection function and target selection effects are understood, it is then possible to use our sample to investigate various properties of the Galactic disc. A discussion of some of these properties can be found in Casagrande *et al.* (2015). Here we focus on one example: if we study stellar ages as function of Galactic height (i.e. distance from the plane of the Galaxy), we see a correlation between the increase in age and that in height. We quantify this correlation using a linear fit, although we are aware that it might not capture the full complexity of the age structure of the Galactic disc. In fact, while the bulk stellar age increases with increasing altitude, there is also a large spread of ages at all heights. Our result indicates the presence of a vertical age gradient in the disc of the Milky Way: its existence has long been inferred by indirect evidence (in particular, the age-velocity dispersion relation. See e.g., von Hoerner 1960; Mayor 1974; Wielen 1977; Holmberg *et al.* 2007; Casagrande *et al.* 2011). With seismic ages we are in a position to measure it directly for the first time. Being able to quantify such a gradient is important in disc formation scenarios, where different mechanisms can produce it. Also, since the mass of a red giant is a proxy for its age, the age gradient is also traced by a mass gradient when using these stars. More importantly, while deriving stellar ages introduces a model dependency, present-day stellar masses are a direct seismic observable, and they provide a model independent signature of the age gradient.

Besides the age gradient, with the parameters so far derived in SAGA we are in the position of addressing a number of questions in Galactic astronomy, such as the age-metallicity relation, and metallicity gradients. Thus, as SAGA expands in size and coverage across Galactic fields, it promises a leading role for Milky Way studies.

References

Amôres, E. B. & Lépine, J. R. D. 2005, AJ , 130, 659
Batalha, N. M., Borucki, W. J., Koch, D. G., *et al.* 2010, ApJ , 713, L109
Casagrande, L. & VandenBerg, D. A. 2014, MNRAS , 444, 392
Casagrande, L., Portinari, L., & Flynn, C. 2006, MNRAS , 373, 13
Casagrande, L., Ramírez, I., Meléndez, J., Bessell, M., & Asplund, M. 2010, A&A , 512, A54
Casagrande, L., Schönrich, R., Asplund, M., *et al.* 2011, A&A , 530, A138
Casagrande, L., Silva Aguirre, V., Stello, D., *et al.* 2014a, ApJ , 787, 110
Casagrande, L., Portinari, L., Glass, I. S., *et al.* 2014b, MNRAS , 439, 2060
Casagrande, L. 2015, Astrophysics and Space Science Proceedings, 39, 61
Casagrande, L., Silva Aguirre, V., Schlesinger, K. J., *et al.* 2015, MNRAS , in press.
Chaplin, W. J. & Miglio, A. 2013, ARA&A , 51, 353
Drimmel, R., Cabrera-Lavers, A., & López-Corredoira, M. 2003, A&A , 409, 205
Holmberg, J., Nordström, B., & Andersen, J. 2007, A&A , 475, 519
Huber, D., Stello, D., Bedding, T. R., *et al.* 2009, Communications in Asteroseismology, 160, 74
Huber, D., Ireland, M. J., Bedding, T. R., *et al.* 2012, ApJ , 760, 32
Jørgensen, B. R. & Lindegren, L. 2005, A&A , 436, 127
Lebreton, Y., Goupil, M.-J., & Montalban, J. 2014, arXiv:1410.5336
Lebreton, Y., Goupil, M.-J., & Montalban, J. 2014, arXiv:1410.5337
Mayor, M. 1974, A&A , 32, 321
Miglio, A., Chiappini, C., Morel, T., *et al.* 2013, MNRAS , 429, 423
Nordström, B., Mayor, M., Andersen, J., *et al.* 2004, A&A , 418, 989
Pont, F. & Eyer, L. 2004, MNRAS , 351, 487
Serenelli, A. M., Bergemann, M., Ruchti, G., & Casagrande, L. 2013, MNRAS , 429, 3645
Silva Aguirre, V., Chaplin, W. J., Ballot, J., *et al.* 2011, ApJ , 740, LL2
Silva Aguirre, V., Casagrande, L., Basu, S., *et al.* 2012, ApJ , 757, 99
Silva Aguirre, V., Basu, S., Brandão, I. M., *et al.* 2013, ApJ , 769, 141
Silva Aguirre, V., Davies, G. R., Basu, S., *et al.* 2015, MNRAS , 452, 2127
Soderblom, D. R. 2010, ARA&A , 48, 581
Stello, D., Chaplin, W. J., Basu, S., Elsworth, Y., & Bedding, T. R. 2009, MNRAS , 400, L80
Stello, D., Huber, D., Bedding, T. R., *et al.* 2013, ApJ , 765, LL41
Strömgren, B. 1963, QJRAS, 4, 8
Strömgren, B. 1987, NATO Advanced Science Institutes (ASI) Series C, 207, 229
von Hoerner, S. 1960, ZAp, 50, 184
Wielen, R. 1977, A&A , 60, 263