Photometric stellar parameters for asteroseismology and Galactic studies

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Abstract Asteroseismology has the capability of delivering stellar properties which would otherwise be inaccessible, such as radii, masses and thus ages of stars. When coupling this information with classical determinations of stellar parameters, such as metallicities, effective temperatures and angular diameters, powerful new diagnostics for both stellar and Galactic studies can be obtained. I review how different photometric systems and filters carry important information on classical stellar parameters, the accuracy at which those parameters can be derived, and summarize some of the calibrations available in the literature for late-type stars. Recent efforts in combining classical and asteroseismic parameters are discussed, and the uniqueness of their intertwine is highlighted.

1 Introduction

Late-type stars (broadly FGKM) are long-lived objects and can be regarded as snapshots of the stellar populations that are formed at different times and places over the history of our Galaxy. The fundamental properties of a sizeable number of these stars in the Milky Way enable us to directly access different phases of its formation and evolution, and for obvious reasons, stars in the vicinity of the Sun have been preferred targets to this purpose, both in photometric and spectroscopic investigations (e.g., Gliese 1957; Wallerstein 1962; Twarog 1980; Strömgren 1987; Edvardsson et al. 1993; Nordström et al. 2004; Reddy et al. 2006; Casagrande et al. 2011; Bensby et al. 2013). Properties of stars in the solar neighbourhood, in particular ages and metallicities, are still the main constraint for Galactic chemo(dynamical) models and provide important clues to understand some of the main processes at play in galaxy formation and evolution (e.g., Matteucci & Francois 1989; Portinari et al.)

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A common feature of all past and current stellar surveys is that, while it is relatively straightforward to derive some sort of information on the chemical composition of the targets observed (and in many cases even detailed abundances), that is not the case when it comes to stellar masses, radii, distances and, in particular, ages. Even when accurate astrometric distances are available to allow comparison of stars with isochrones (assuming other parameters involved in this comparison – such as effective temperatures and metallicities – are also well determined), the derived ages are still highly uncertain, and statistical techniques are required to avoid biases. Furthermore, isochrone dating is meaningful only for stars in restricted regions of the HR diagram (e.g., Soderblom, 2010, for a review).

By measuring oscillation frequencies in stars, asteroseismology allows us to measure fundamental physical quantities, masses and radii \textit{in primis}, which otherwise would be inaccessible in single field stars, and which can be used to obtain information on stellar distances and ages (e.g., Chaplin & Miglio, 2013, for a review). In particular, global oscillation frequencies (see Section 3) 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.

Thanks to space-borne missions such as CoRoT (Baglin & Fridlund, 2006) and Kepler (Gilliland et al., 2010), global oscillation frequencies are now robustly detected in few hundreds main-sequence and subgiant, and several thousands giant stars (e.g., De Ridder et al., 2009; Stello et al., 2013). Asteroseismology is thus emerging as a new tool for studying stellar populations, and initial investigations in this direction have already been done (Chaplin et al., 2011; Miglio et al., 2013b). However, until now asteroseismic studies of stellar populations had only coarse information on classical stellar parameters such as effective temperatures ($T_{\text{eff}}$) and metallicities ([Fe/H]). Coupling classical parameters with seismic information, not only improves the seismic masses and ages obtained for stars (Lebreton & Montalban, 2009; Chaplin et al., 2014), but it also allows to address other important questions, both in stellar (e.g., Deheuvels et al., 2012; Silva Aguirre et al., 2013) and Galactic (e.g., Casagrande et al., 2014a) evolution.

To fully harvest the potential that asteroseismology brings to studies in these areas, classical stellar parameters are thus vital. Both photometry and spectroscopy are able to deliver those parameters, each of these techniques having its own pros and cons (see e.g., Bessell, 2005; Asplund, 2005, for reviews). At the risk of being over-simplistic, one can say that a stellar spectrum encodes a lot of information on stellar parameters (for the sake of this review $T_{\text{eff}}$, [Fe/H] and log $g$), but those are usually strongly coupled to each other. Realistic model atmospheres, the input atomic and molecular physics, the line formation modelling and last but not the least the resolution and the signal-to-noise of the observations are all crucial to decipher the spectral fingerprints. On the contrary, photometric indices do (part of) the analysis for us, although more often than not with lower precision than spectroscopy, and they crucially depend on how a given magnitude is translated into a physical...
flux (i.e. on the photometric standardization and absolute calibration) and/or on the availability of realistic photometric calibrations linking a colour index (or a combination of those) to a given stellar parameter (which indeed could have been derived from spectroscopy, or better whenever possible via fundamental measurements). Interstellar extinction can seriously limit the power of photometric techniques for objects located outside of the local bubble, unless detailed reddening maps are used to correct for it (e.g., Zasowski et al. 2012; Schlafly et al. 2013; Lallement et al. 2014).

Concerning $T_{\text{eff}}$, photometric techniques are usually superior to spectroscopy (modulo reddening), while the latter can provide exquisite detailed abundances impossible for photometry, as well as radial velocities (important for kinematic studies). On the other hand, using modern CCD cameras, (wide) field imaging is very efficient even compared to multi-fiber spectroscopy and can go several magnitudes fainter. Field imaging also has the advantage that minimal pre-selection is made on targets, thus greatly simplifying the selection function for the purpose of population and Galactic studies: all stars that fall in a given brightness regime are essentially observed. It is thus obvious that photometry and spectroscopy, rather than being in competition with each other, are complementary. Without further entering the merit of one or another technique, it suffices to say that in the following of this review I shall concentrate exclusively on stellar parameters derived from photometry.

2 Photometric stellar parameters

Photometric systems and filters carry information on various fundamental stellar properties and also when studying more complex systems, integrated magnitudes and colours of stars can be used to infer the properties of the underlying stellar populations. To this purpose, filter systems are designed to sort out regions in the stellar spectra where variations of the atmospheric parameters leave their characteristic traces with enough prominence to be detected in photometric data. Starting from the influential papers by Johnson (1966) and Stromgren (1966) describing the basis of broad- and intermediate-band photometry, a large number of systems exists nowadays, and more are coming into place with the advent of extensive photometric surveys (e.g., Bessell 2005, for a review).

Broad-band colours are most of the times tightly correlated with the stellar effective temperature, although metallicity, and to a minor extent surface gravity ($\log g$) also play a role, especially towards the near ultraviolet and the Balmer discontinuity (e.g., Eggen et al. 1962; Ridgway et al. 1980; Bell & Gustafsson 1989; Alonso et al. 1996; Casagrande et al. 2010b). On the other hand, intermediate- or narrow-band photometry centred on specific spectral feature(s) can have a much higher sensitivity to a given stellar parameter (e.g., Stromgren 1966; Wing 1967; McClure & van den Bergh 1968; Golay 1972; Mould & Siegel 1982; Worthey et al. 1994). While broad-band photometry can be easily used to map and study sizable stellar populations and/or large fraction of the sky also at faint luminosities (e.g., Stetson et al. 1998; Bedin et al. 2004; Ivezić et al. 2007; Saito et al. 2012),
intermediate- and narrow-band photometry are more limited in this respect, although still very informative (e.g., Mould & Bessell [1982], Bonnell & Bell [1982], Yong et al. [2008], Arnadóttir et al. [2010]).

In principle, determining stellar parameters from photometric data is a basic task, yet empirical calibrations are often limited to certain spectral types and/or involve substantial observational work. In recent years, considerable efforts have been invested in newly deriving empirical calibrations linking photometric indices to effective temperatures (e.g., Casagrande et al. [2006, 2008], González Hernández & Bonifacio [2009], Casagrande et al. [2010b, 2012], Pinsonneault et al. [2012]). The latter have often been derived in a semi-fundamental way via the InfraRed Flux Method (IRFM), which nowadays can be easily implemented on stars, thanks to large photometric infrared surveys such as 2MASS or WISE (Cutri et al. [2003], Cutri & et al. [2012]). Particular attention is now being paid to the absolute zero-point of the $T_{\text{eff}}$ scale, using both solar twins (e.g., Casagrande et al. [2010b], Datson et al. [2012]) and interferometry (e.g., Huber et al. [2012]). Up until now, the major obstacle in making full use of interferometric measurements was the limited brightness regime sampled by those, essentially limited to relatively nearby and bright stars (the easiest targets to spatially resolve), which are saturated in most of the modern photometric surveys (2MASS in particular). This dichotomy has prevented from safely extending well calibrated relations to the faint stars targeted in large spectroscopic and photometric surveys. This obstacle has now been alleviated with dedicated near infrared photometric observations of interferometric targets (Casagrande et al. [2014a]). It is also worth mentioning the increasing spatial resolution of interferometers, thanks to optical beam combiners (Ireland et al. [2008]) and repeated, careful observations which are pushing the limit for reliable angular diameters down to about 0.5 mas (e.g., Huber et al. [2012], White et al. [2013]). This finally allows to target fainter stars having good 2MASS photometry, and directly test a number of effective temperature scales. Caution, however, must be used when indirectly testing a $T_{\text{eff}}$ scale via colour relations, as well as when assessing the reliability of interferometric measurements, especially at sub-milliarcsec level. As shown in Casagrande et al. [2014a], when using certain colour relations, rather different effective temperature scales can be compatible with a given subset of interferometric data. A more conclusive comparison is obtained when deriving $T_{\text{eff}}$ in a more robust way such as via the IRFM, which, after a critical evaluation of the systematics involved, is able to deliver 1% accuracy (or better) in effective temperatures and angular diameters.

The importance of securing the zero-point of the $T_{\text{eff}}$ scale is far from being a technicality. In fact, a systematic shift of 100 K in effective temperatures implies a shift of about 0.1 dex on spectroscopically derived metallicities. This, e.g., has implications in determining the peak of the metallicity distribution function in the solar neighbourhood, with a number of consequences for Galactic chemical evolution models as well as for interpreting the Sun in a Galactic context (Casagrande et al. [2011]). A sound setting of the $T_{\text{eff}}$ scale is crucial also for other reasons, e.g., in comparison with theoretical stellar models (VandenBerg et al. [2010]) or to derive absolute abundances (Meléndez et al. [2010]).
The use of solar twins is also helpful to accurately set the zero-points of the [Fe/H] scale (e.g., Meléndez et al., 2010b; Datson et al., 2012; Porto de Mello et al., 2013). Excellent photometric metallicities can be derived from intermediate-band colours such as the Geneva, the DDO and the Strömgren system. The latter is probably the most popular one (also thanks to the observational efforts of Olsen and collaborators, and a shallow all-sky survey such as the Geneva-Copenhagen Survey), with a number of [Fe/H] calibrations existing in the literature, both for dwarfs (Olsen, 1984; Schuster & Nissen, 1989; Haywood, 2002; Nordström et al., 2004; Twarog et al., 2007; Casagrande et al., 2011) and giants (Faria et al., 2007; Calamida et al., 2007; Grebel & Richtler, 1992; Hilker, 2000; Casagrande et al., 2014b). These calibrations are built upon samples of stars with measured spectroscopic [Fe/H]; Casagrande et al. (2011) put efforts in deriving a photometric metallicity scale built upon spectroscopic measurements having \(T_{\text{eff}}\) consistent with the absolutely calibrated scale of Casagrande et al. (2010b). As a result of these works, the peak of the metallicity distribution function in the solar neighbourhood has shifted around the solar value. The super solar regime of most photometric metallicity calibrations is still partly unexplored (in particular for giants), while on the metal-poor side Strömgren indices lose any sensitivity to [Fe/H] below about \(-2\) dex in the rather featureless spectra of hot subdwarfs (Casagrande et al., 2011). However, this does not seem to be the case for cool metal-poor red giants (Adén et al., 2011; Casagrande et al., 2014b).

While the low sensitivity of broad-band colours to [Fe/H] and \(\log g\) makes them ideal for the sake of deriving \(T_{\text{eff}}\), it also implies that those broad-band filters are less than optimal for obtaining photometric metallicities (see e.g., Árnadóttir et al., 2010, for the performances of a number of Strömgren and broad-band metallicity calibrations). A few broad-band metallicity calibrations are available, in particular for the Sloan system (Ivezić et al., 2008), and they strongly rely on having measurements in the ultraviolet/blue (around 3500 Å).

The Strömgren system is also able to deliver \(\log g\) in late-type stars by measuring the Balmer discontinuity. More than providing a precise measurement, it essentially allows to discriminate between dwarf and giant stars, which for some investigations it is already a very valuable information (e.g., Árnadóttir et al., 2010). However, for the sake of asteroseismology, a photometric or spectroscopic determination of \(\log g\) in late-type stars is of little importance, since exceedingly precise surface gravities can be derived using seismic masses and radii, as I discuss further below.

### 3 Seismic stellar parameters

Late-type stars span a vastly different range of gravities and luminosities on the HR diagram and thus have very different internal structures. As a result, they probe a plethora of distances, and are preferential targets of past and current Galactic surveys. Be it a dwarf or a giant, their cold surface temperatures are the realm of interesting atomic and molecular physics shaping the emergent spectra. The determina-
tion of their physical properties based on the emerging flux (appropriately filtered by the transmission functions of the photometric systems in use) has been the subject of the previous Section. This temperature regime is dominated by convection, which is then the main driver underlying the fundamental oscillation modes we are now able to detect with asteroseismology (“bloody F stars” excluded from now on).

Stellar oscillations driven by surface convection are visible in the power spectrum of time series photometry as a series of Lorentzian-shaped peaks whose peak height has an approximately Gaussian shape (Chaplin & Miglio, 2013). Two quantities can be readily extracted from this oscillation pattern, without the need for individual frequency determinations (e.g., Ulrich, 1986; Brown et al., 1991): the large frequency separation $\Delta \nu$ (the average separation between peaks of the same spherical angular degree $l$ and consecutive radial order $n$), and the frequency of maximum amplitude $\nu_{\text{max}}$ (located in correspondence of the Gaussian peak). These two frequencies are tightly correlated to the stellar mass, radius and $T_{\text{eff}}$ via the so called scaling relations (e.g., Hekker et al., 2009; Stello et al., 2009; Miglio et al., 2009). Provided we have a measurement of $T_{\text{eff}}$ (see previous Section), it thus follows that the global oscillation frequencies $\Delta \nu$ and $\nu_{\text{max}}$ are able to provide the stellar mass and radius. This is known as the direct method. Another approach is to use stellar models and search for the best solution (using different flavours of frequentist, bayesian, MCMC, etc. inference) to a number of observed properties, among which (but not exclusively) $\Delta \nu$, $\nu_{\text{max}}$ and $T_{\text{eff}}$: this is known as the grid-based method (e.g., Silva Aguirre et al., 2012; Chaplin et al., 2014).

Understandably, a good deal of effort is currently invested to test the accuracy of the scaling relations and derived stellar properties, or whether scaling relations have any dependence on other parameters such as e.g., metallicity (e.g., White et al., 2011). Radii derived from scaling relations have been shown to be accurate to better than about 5% in dwarfs and subgiants (e.g., Huber et al., 2012; Silva Aguirre et al., 2013; White et al., 2013), while masses are better than 10% (at least around solar metallicity, but see Epstein et al., 2014 for the metal poor regime), but are also less tested (see e.g., Miglio et al., 2013a, for a summary). Thus, while awaiting for further tests, for the asteroseismic scaling relations we can adopt the motto “Se non è vero, è ben trovato!”

4 A match made in heaven

From the discussion in the previous Section, it is obvious that combining global oscillation frequencies to classical stellar parameters discloses us very elusive stellar properties, such as radii and masses, which would be otherwise impossible to measure in single field stars. Also, photometric angular diameters and seismic radii can be used to derive distances with a quality comparable to that provided by the Hipparcos satellite (Silva Aguirre et al., 2012). With this information (masses in particular)

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1 Even if it is not true, it is well conceived.
we are thus in the position to derive stellar ages in a more sophisticated fashion than via classical isochrone fitting. Using the grid-based method, Chaplin et al. (2014) have derived seismic ages for more than 500 main-sequence and sub-giant stars using only $\Delta \nu$, $\nu_{\text{max}}$, and photometric $T_{\text{eff}}$. The median uncertainty in the parameters derived by Chaplin et al. (2014) is $\lesssim 0.02$ dex in log $g$, 4.4% in radius and $\sim 11\%$ in mass. This implies ages with a median uncertainty of 34%; for comparison, this uncertainty is about the best it can be achieved for field main-sequence and sub-giant stars in the absence of seismology, when high-quality parallaxes, $T_{\text{eff}}$ and [$\text{Fe}/\text{H}$] are available (e.g., Nordström et al., 2004; Casagrande et al., 2011). The above uncertainties in mass and radius reduce by almost a factor of two when [$\text{Fe}/\text{H}$] measurements are available, while the median age uncertainty decreases to 25%, with 80% of the stars having ages determined to better than 30% (while again, for comparison, in a non-seismic studies such as Nordström et al. (2004); Casagrande et al. (2011) only about 50% of stars have ages determined to better than 30%).

Similar investigations are now carried out using red giant stars, in particular thanks to the APOGEE (Mészáros et al., 2013) and SAGA (Casagrande et al., 2014b) surveys, which based on spectroscopy and photometry respectively, aim at exploiting the full potential of asteroseismology by providing classical stellar parameters. Preliminary investigations (Casagrande et al., 2014b) indicate that uncertainties similar to those derived by Chaplin et al. (2014) apply also for giants, although ages have been still largely unexplored.

There might still be tears in heaven when it comes to fit global oscillation frequencies for the purpose of determining the helium mass fraction $Y$ in (mildly) metal-poor stars (Bonaca et al., 2012). This reminds very closely the issue with fitting another global stellar property in Casagrande et al. (2007), namely the stellar model $T_{\text{eff}}$ scale. Both Bonaca et al. (2012) and Casagrande et al. (2007) could avoid the problem of having unrealistically low values of $Y$ by changing convection prescriptions (namely, the mixing-length value with metallicity). Model boundary conditions (indeed linked to the global oscillation frequencies) and/or opacities could also be among the culprits in the helium problem (Portinari et al., 2010; Casagrande et al., 2010b). This is an interesting possibility, considering the role played by opacities in the current tension on the solar chemical composition (e.g., Asplund et al., 2009; Villante et al., 2013).

5 Conclusions and future perspectives

The combination of classical and seismic parameters enables the enthralling possibility of addressing outstanding questions in Galactic astronomy. In particular, using red giants it is possible to probe distances spanning several kpc across the Galaxy, with a median uncertainty of just a few per cent (Miglio et al., 2013b; Casagrande et al., 2014b). This makes red giants optimal probes for studies of Galactic structure (e.g., Miglio, 2012). In particular, having metallicity information will become increasingly important; not just to improve the precision of seis-
mic parameters as I discussed in the previous Section, but also to allow the study of metallicity and age gradients, as well as the age-metallicity relation in (part of) the Galaxy. Also, when individual abundances will be available from spectroscopy, these will provide stunning new insights/constraints into the chemical enrichment history for these elements.

Until now, deriving reliable ages for red giant stars has been the major limitation, since isochrones with vastly different ages can fit equally well observational constraints such as effective temperatures, metallicities and surface gravities within their errors. However, 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 (e.g., Miglio, 2012). Thus, asteroseismology has the potential of delivering ages where other methods are striving or have failed. Investigations are currently going on to assess whether, and how reliably seismic ages for red giants can be obtained, in particular when seismology also provides the distinction between stars climbing the red giant branch and those in the clump phase (Stello et al., 2013), as well as to estimate the effect of mass-loss on age determination for stars in the clump phase.

It is also worth to mention that while global oscillation frequencies are enough for population studies, beautiful investigations in stellar structure and evolution are made possible by the use of individual frequencies, or a combination of these (e.g., Deheuvels et al., 2013 [Silva Aguirre et al., 2013]. In contrast to global oscillation frequencies, it has been shown that at least for main sequence stars, the use of individual frequencies can yield an accuracy of just a few percent in both mass and radius, and 10% in age (Silva Aguirre et al., 2013). The exploitation of individual frequencies is more demanding, both observationally and theoretically, but rewarding. For future population studies (at least on the main sequence) it is conceivable to develop an “age ladder”: first, achieve the highest possible precision on a number of benchmark stars for which individual frequencies are available (Appourchaux et al., 2012), and then use the parameters so derived as benchmark for stars with only global oscillation frequencies. As last step, asteroseismic ages can then be used to benchmark against classical isochrone fitting. In this context, future asteroseismic missions such as K2 and TESS hold promises in making possible – among other things – to derive seismic parameters (and ages) for all stars in the Geneva-Copenhagen survey (Nordström et al., 2004; Casagrande et al., 2011), a gold standard for Galactic models.

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