Asteroseismic age determination for dwarfs and giants

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Received XXXX, accepted XXXX
Published online XXXX

Key words stars: fundamental parameters – stars: oscillations

Asteroseismology can make a substantial contribution to our understanding of the formation history and evolution of our Galaxy by providing precisely determined stellar properties for thousands of stars in different regions of the Milky Way. We present here the different sets of observables used in determining asteroseismic stellar properties, the typical level of precision obtained, the current status of results for ages of dwarfs and giants and the improvements than can be expected in the near future in the context of Galactic archaeology.

1 Introduction

The wealth of asteroseismic data from the CoRoT (Michel et al. 2008) and Kepler (Gilliland et al. 2010) missions has produced an authentic revolution in the field of stellar astrophysics. Thanks to the detection of oscillating modes in thousands of stars across the HRD, stellar properties can now be determined for large samples of targets with an unprecedented level of precision. This opens the exciting possibility of accurately characterising stellar populations in different regions of the Milky Way to constrain the history of formation and evolution of our Galaxy (e.g., Casagrande et al. 2014; Miglio et al. 2013). Of particular importance in this endeavour are precise age determinations for large cohorts of dwarfs and giants (Casagrande et al. 2015; Chaplin et al. 2014), which can further help the usual kinematic and chemical dissection of the Galactic disc which has so far driven most of the comparisons between observations and simulations of our Galaxy (e.g., Adibekyan et al. 2012; Edvardsson et al. 1993; Haywood et al. 2013; Schönrich & Binney 2009, just to name a few).

We review the methods for determining ages of dwarfs and giants using different asteroseismic datasets and discuss their expected level of precision. All results presented here are based on two of the most sophisticated algorithms currently available for asteroseismic determination of stellar properties: the BAyesian STellar Algorithm (BASTA, Silva Aguirre et al. 2015) and the Bellaterra Stellar Properties Pipeline (Serenelli et al. 2013). Briefly, both methods consist of a Bayesian approach including priors and appropriate weights to account for the volume space of the precomputed grids of models used to construct the probability distribution functions. Different combinations of input observables can be included when determining stellar properties, which we discuss in detail below.

2 Asteroseismic observables

Detection of pulsation modes in dwarfs and red giants depends on the properties of convection in the outer stellar layers (see, Chaplin & Miglio 2013, and references therein). Thus, detectability and data quality of asteroseismic properties for a certain length of observations is linked to the position of the star in the HRD as well as its intrinsic magnitude. We assume in the following that determination of atmospheric parameters $T_{\text{eff}}$ and $[\text{Fe}/H]$ is available for the stars in question.

2.1 The bare minimum

A positive detection of oscillations in dwarfs or giants implies the appearance of a gaussian-shaped excess power in the Fourier transform of the time-series. This feature can be characterised by two so-called global asteroseismic observables: the frequency of maximum power $\nu_{\text{max}}$ and the average large frequency separation $\langle \Delta \nu \rangle$. The latter is the separation between modes of consecutive radial order and same angular degree, and is a measure of the travel time of the wave across the stellar interior. These quantities are related to the surface gravity and mean stellar density (Brown et al. 1991; Ulrich 1986), and thus form the basis of the asteroseismic scaling relations:

$$
\frac{M}{M_{\odot}} \propto \left( \frac{\nu_{\text{max}}}{\nu_{\text{max,0}}} \right)^3 \left( \frac{\langle \Delta \nu \rangle}{\langle \Delta \nu \rangle_{0}} \right)^{-1} \left( \frac{T_{\text{eff}}}{T_{\text{eff,0}}} \right)^{3/2},
$$

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Fractional uncertainties in stellar properties determined using Bayesian schemes and the global seismic parameters. Results for 87 dwarfs and subgiants analysed by Chaplin et al. (2014).

\[
\frac{R}{R_{\odot}} \sim \left( \frac{v_{\text{max},\odot}}{v_{\text{max},\odot}} \right) \left( \frac{\langle \Delta v \rangle}{\langle \Delta v \rangle_{\odot}} \right)^{-2} \left( \frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right)^{1/2},
\]

where \( \langle \Delta v \rangle_{\odot} \), \( v_{\text{max},\odot} \) and \( T_{\text{eff},\odot} \) are the solar values. The global seismic parameters are what we call the bare minimum, that is the minimum amount of information that can be extracted from the time-series analysis given a positive detection. It is clear from Eqs. 1 and 2 that when these data are available, a direct estimation of the stellar mass and radius can be obtained (e.g., Silva Aguirre et al. 2011; Stello et al. 2008). These scaling relations seem to hold well for radius determinations (e.g., Huber et al. 2012; North et al. 2007; Silva Aguirre et al. 2012; White et al. 2013), while confirmation of masses is still under way using clusters and binaries.

In order to determine ages for stars using the global seismic parameters, BASTA and BeSPP compare these quantities and the atmospheric parameters to those predicted by grids of models. Figure 1 shows the results obtained for the sample of 87 dwarfs and subgiants from Chaplin et al. (2014) where spectroscopic \( T_{\text{eff}} \) and \([\text{Fe/H}]\) are available, resulting in median uncertainties of \( \sim 2.2\% \), \( \sim 5.5\% \), and \( \sim 25\% \) in radius, mass, and age respectively (see Fig. 1). This level of precision is a factor of two better than the median uncertainty ranges between \( \sim 30\% \) and \( \sim 30\% \) depending on the evolutionary phase (see Section 2.3 below).

2.2 Improvements for dwarfs and subgiants: individual frequencies

When the signal-to-noise ratios in the observations are high enough, it is possible to isolate the individual peaks in the power spectrum and perform what is known as “boutique” modelling of the targets (e.g., Lebreton & Goupil 2014; Metcalfe et al. 2010; Silva Aguirre et al. 2013). In these cases, instead of fitting for the global asteroseismic parameters the Bayesian schemes aim at reproducing either the individual frequencies of oscillations or combinations of them. The first approach usually relies on an empirical surface correction to account for incomplete modelling of the outer stellar layers in 1-D hydrostatic codes (e.g., Kjeldsen et al. 2008), while the latter suppresses the influence of these layers by building frequency ratios (Roxburgh & Vorontsov 2003).

Recently Lebreton & Goupil (2014) showed that the most precise asteroseismic ages for dwarfs are those obtained using the frequency ratios as fitting observables as they are sensitive to the innermost layers of the star. The first homogeneous analysis of the 33 highest SNR Kepler exoplanet-host stars was made by Silva Aguirre et al. (2015) using BASTA to reproduce these ratios, and the results are shown in Fig. 3. The median uncertainties in radius, mass, and age are of \( \sim 1.1\% \), \( \sim 3.3\% \), and \( \sim 14\% \) respectively, al-
most a factor of two better than those obtained with
the global seismic parameters for these type of stars.

The number of targets where this type of analysis is
possible will increase to close to 100 dwarfs thanks to
the upcoming Kepler LEGACY sample (Lund et al., in
preparation; Silva Aguirre et al., in preparation). Although still
far too low for Galactic studies, this sample will be
the best characterised asteroseismic set available for the
near future, and by virtue of being well distributed in the HRD
its comprising stars will serve as benchmark for calibrating
the properties of other stars where asteroseismic data are not
available.

In the case of subgiant stars, their rapid core contraction
after the main-sequence phase results in coupling be-
tween the pure acoustic and pure gravity modes cavities.
Thus, non-radial frequencies of oscillations can present a
mixed character behaving as g-modes in the stellar core
and p-modes in the outer layers (e.g., Aizenman et al. 1977).
This behaviour results in a deviation from the asymptotic
behaviour of pure p-modes, and the magnitude of that devi-
ation can provide strong constraints on the core properties
(and thus age) of subgiant stars. Initial investigations have
found correlations between this mixed-mode character and
stellar mass (e.g., Benomar et al. 2012; Deheuvels & Michel
2011), but more studies are needed to properly characterise
the sensitivity of these type of pulsations to stellar structure
and the systematics involved in determining stellar proper-
ties by using them as the observables to fit.

2.3 Improvements for red giants: period spacing

As was mentioned previously, mixed-modes carry informa-
tion about the stellar core of stars that would otherwise be
inaccessible to us. Of particular interests is the possibility of
distinguishing between first ascent (RGB) and clump red
giants, two classes of stars which occupy almost the same
region in the HRD thus making determination of their stel-
lar properties by isochrone placement extremely challeng-
ing. Asteroseismology offers a window towards the struc-
tural region where these type of stars exhibit differences:
while RGB stars have a radiative helium core surrounded by
a hydrogen-burning shell, clump stars burn helium in their
convective cores.

Detection of non-radial mixed modes by the CoRoT
satellite (De Ridder et al. 2009) opened the possibility of
extracting information from the mixed-modes in red giants.
While p-modes are equally separated in frequency by ap-
proximately the average large frequency separation (Δν),
g-modes are equally separated in period with a character-
istic spacing dependent on the convective properties of the
acoustic cavity. In other words, two red giants of very simi-
lar interior structure but one having a convective instead of
a radiative core will show a different value of this period spac-
ing (see, Christensen-Dalsgaard 2014, for a detailed expla-
nation). Observational evidence came from the Kepler
and CoRoT satellites, where Bedding et al. (2011) and Mosser
et al. (2011) showed that RGB and clump stars form two
distinct sequences when comparing their measured mixed-
mode periods period spacing.

Figure 3 shows the age determination for a Kepler tar-
get when information on the evolutionary phase is available.
Implemented as a Bayesian prior, knowing that the star be-
longs to the RGB sequence obviously favours one of the
peaks in the distribution and further constrains the age de-
termination. A similar result was found by Casagrande et al.
(2015), where the authors showed that ages with uncertain-
ties of ~10-20% where obtained for stars with a conclusive
RGB identification from their period spacing. Uncertain-
ties are slightly larger (up to ~30%) in ages for clump stars
due to the unconstrained efficiency of mass-loss close to the
RGB tip. Work is in progress to better determine its impact
using asteroseismology of open clusters giants (e.g., Miglio
et al. 2012).

3 Conclusion and outlook

Asteroseismology is starting to deliver precise sets of stellar
parameters for large cohorts of stars in different regions of
the Milky Way. These data sets promise to become the new
benchmarks for comparison of chemodynamical models go-
ing beyond the local volume covered by solar neighbour-
hood samples such as the Geneva-Copenhagen survey. We
have described the methods to determine stellar properties
using asteroseismology, in particular ages, based on dif-
ferent sets of inputs depending on data quality and availability.
Ages of dwarfs, giants, and subgiants can currently be de-
termined to a level of ~20-30% while further improvements
can be made when individual frequencies or evolutionary
classifications are available. The possibilities for conducting
Galactic studies using these technique are immense consid-
ering the lines of sights currently being observed by the K2
mission (Stello et al. 2015), and the upcoming all-sky sur-
vey from the TESS satellite (Ricker et al. 2015).
Fig. 4  Probability density function of age for a red giant star determined using a Bayesian scheme and the global seismic parameters $\nu_{max}$, $\langle \Delta \nu \rangle$, complemented with $T_{eff}$, and [Fe/H]. Grey are depicts the age distribution when no information is available about the evolutionary stage (labelled All) while inclusion if this information as a Bayesian prior is plotted in red (labelled RGB).

Acknowledgements. Funding for the Stellar Astrophysics Centre is provided by The Danish National Research Foundation (Grant agreement no.: DNRF106). The research is supported by the ASTERISK project (ASTERoseismic Investigations with SONG and Kepler) funded by the European Research Council (Grant agreement no.: 267864). V.S.A. acknowledges support from VILLUM FONDEN (research grant 10118). A.M.S acknowledges support from the grants ESP-2013-41268-R (MINECO) and 2014SGR-1458.

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