Bayesian distances and extinctions for giants observed by *Kepler* and APOGEE

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**Abstract.** We present a first determination of distances and extinctions for individual stars in the first release of the APOKASC catalogue, using a revised and extended version of the Bayesian tool PARAM.

**Key words.** stars: distances, stars: fundamental parameters

1. Introduction

A number of massive high-resolution spectroscopy surveys are presently being conducted as part of a major community effort to reveal the evolution and present structure of our Milky Way galaxy. As demonstrated by several authors (e.g., Binney et al. 2014), spectroscopic parameters coupled with photometry can provide distance estimates for all of the observed stars, especially when the surface gravity, $\log g$, is well-constrained.

In order to verify and improve distance determinations for these spectroscopic surveys, we are working on a very special sample of stars – the APOKASC sample – that should provide an important reference set for many ongoing and future spectroscopic surveys. This unique data set results from a collaboration between *Kepler* Asteroseismic Science Consortium (KASC, Kjeldsen et al. 2010) and Apache Point Observatory Galactic Evolution Experiment (APOGEE, Majewski et al. in preparation), which itself is part of the third phase of the Sloan Digital Sky Survey (SDSS-III, Eisenstein et al. 2011). Almost 2,000 red giants targeted by the *Kepler* satellite mission (Borucki et al. 2010) have been observed by APOGEE during the first year and included in the SDSS-III Data Release 10 (Ahn et al. 2014). They correspond to the sample presented in Pinsonneault et al. 2014 and discussed in the present work. The APOGEE spectra provide accurate determinations of effective temperatures, $T_{\text{eff}}$, and chemical abundances of several elements (García Pérez et al. in preparation).

Solar-like oscillations are excited in cool stars, and the natural periods for low density red giants are sufficiently long for them to be easily detected with the *Kepler* cadence. For solar-like oscillators with pulsations excited in the turbulent outer layers, two global asteroseismic parameters can be extracted: the aver-
age large frequency separation, $\Delta \nu$, and the frequency of maximum oscillation power, $\nu_{\text{max}}$. The former is the dominant frequency separation of the near-regular pattern of high overtones and depends on the mean density $\bar{\rho}$ of the star (Vandakurov 1968), consequently on its mass $M$ and radius $R$, $\Delta \nu \propto \bar{\rho}^{1/2} \propto M/R^3$. The latter is the frequency of maximum power of the Gaussian-like modulation of the mode amplitudes, which is related to the acoustic cutoff frequency of the star, and therefore to its fundamental parameters (Brown et al. 1991), $\nu_{\text{max}} \propto gT_{\text{eff}}^{-1/2} \propto (M/R^2)T_{\text{eff}}^{-1/2}$. This information is straightforwardly converted into intrinsic luminosities, $L = \frac{4\pi R^2\sigma T_{\text{eff}}^4}{c^2}$, where $\sigma$ is the Stefan-Boltzmann constant. When $L$ is combined with a bolometric correction, an extinction, and the observed apparent magnitude in a given passband, a so-called ‘direct measurement’ of the distance is possible (see e.g., Miglio et al. 2013).

We adopt a Bayesian method implemented as an extension to the PARAM code (da Silva et al. 2006), which estimates stellar properties by comparing observational data with the values derived from stellar models, in this case a data set of theoretical isochrones, PARSEC v1.14 (Bressan et al. 2012), from the Padova-Trieste stellar evolution group. PARAM was extended to build a well-sampled grid of stellar models including seismic properties. From the $T_{\text{eff}}$, metallicity, $\Delta \nu$, and $\nu_{\text{max}}$ measurements, PARAM derives a probability density function (PDF) for the following stellar parameters: $M$, $R$, $\log g$, age, $\bar{\rho}$, and absolute magnitudes in several passbands. The latter is used to derive distances $d$ (in parsec) via the distance modulus $d = 10^{0.2m_{\lambda}} + 10^{0.4(M_{\lambda} - M_{\lambda}^0)}$, where $m_{\lambda}$, $M_{\lambda}$, and $A_{\lambda}$ are the apparent magnitude, absolute magnitude, and extinction in a passband denoted by $\lambda$, respectively. Assuming further that all $A_{\lambda}$ are related by a single interstellar extinction curve expressed in terms of its V-band value (that is, $A_{\lambda}(A_V)$), this equation can be used to derive the total extinction, $A_V$, and $d$ simultaneously.

The method is explained in details in the previous report and in Rodrigues et al. (2014), as well as the sample used. In this report, we will present the main results in the Section 2.

2. Main results

Most of the observed stars are located within 2 kpc, whereas almost all stars are within 4 kpc. As shown in Fig. 1, there is a trend for stars at larger distances to be cooler than the nearest ones, which is consistent with them being more luminous. Also, high-extinction stars ($A_V \gtrsim 0.4$ mag) are observed at larger distances.

Fig. 2 shows our extinction map. We also compared with the maps derived from the KIC (Brown et al. 2011), from Schlegel, Finkbeiner & Davis (1998, hereafter SFD), and with the RayleighJeans Colour Excess (RJCE, Majewski et al. 2011) method. The comparison with SFD shows some evident similarities in the position of the highly extinguished regions; the
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SFD extinctions tend to be much larger than our values, especially in low-latitude fields. This is expected since SFD gives the extinction at infinity, and not along the line of sight to every star. Our extinction maps turn out to be somewhat smoother than the RJCEs; in addition, they also tend to present smaller AVs. It is interesting to note that RJCE produces larger extinction values towards the high latitude fields of Kepler, where both our and the SFD maps exhibit relatively low-extinction values. The KIC extinctions appear overestimated with respect to our values.

Stars in the NGC 6819 and NGC 6791 clusters provide a useful check of the uncertainties in our methods, since they are expected to be located within a distance interval much smaller than the expected uncertainties. Fig. 3 shows the distance modulus for all cluster members selected by Stello et al. (2011). For NGC 6791, nine stars in APOKASC are classified as seismic members by Stello et al. (2011), and indeed there is a good overlap between their distance modulus PDFs. For NGC 6819, 32 stars selected by the same authors are in the APOKASC sample, out of which 29 were classified as seismic members. It is clear that the PDF of these non-seismic members do not overlap with the others. The modes in the $\mu_0$ PDFs compare well with Basu et al. (2011) who found $\mu_0 = 13.11 \pm 0.06$ mag and $\mu_0 = 11.85 \pm 0.05$ mag, for NGC 6791 and NGC 6819, respectively, as well as with other results in the literature.

Bovy et al. (2014) have recently released the APOGEE red clump catalogue, containing stars which, due to their particular values of $T_{\text{eff}}, \text{spectroscopic } \log g$, metallicity, and 2MASS ($J - K_s$), are very likely red clump stars with a well-defined absolute magnitude. A total of 593 such stars are present in the APOKASC catalogue, and a comparison between our, and the Bovy et al. (2014) distances is presented in the top panel in Fig. 4. The mean relative difference between them is only 0.4%. Such a tight relation between these two distance scales is remarkable, and very encouraging.

We also compared our distances with those estimated in the SAGA catalogue (Casagrande et al. 2014), in which the stellar parameters are estimated in a completely independent way, using a combination of Strömgren photometry, the infrared-flux method, and several extinction estimates. For the 136 stars in common with the APOKASC catalogue, the mean relative difference in distances is only 1.2 %, as shown in bottom panel in Fig. 4.

3. Ongoing work and perspectives

We are also applying the same method for different samples: 1) Anders et al. (in preparation)* – red giant stars with seismic data from CoRoT (Michel et al. 2008) and spectroscopic data from APOGEE; 2) Lagarde et al. (in preparation)* – red giant stars with Hipparcos parallaxes, seismic data from
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Fig. 3. Distances derived for stars in (a) NGC 6791 and (b) NGC 6819. In both cases, the main panel shows the mode $\mu_0$ and 68% credible interval for all cluster members. The solid and dashed lines represent the mean weighted values for all stars, and excluding the outliers denoted by their KIC numbers, respectively. The cyan dots are stars whose $\mu_{0\lambda}$ PDFs are broad or multiple-peaked (for more details see Rodrigues et al. 2014). The smaller sub-panels to the right show the $\mu_0$ PDFs for all cluster members (grey lines). The black lines show the results of deriving the distance modulus PDF of the cluster using the product of all individual PDFs, whose mode and median are shown by the blue and red symbols, respectively.

CoRoT, and spectroscopic data from Morel et al. (2014).

Some steps that we are going to perform are: 1) to implement the PARAM code to estimate stellar properties and distances to all stars in the APOGEE survey without seismic information available; 2) to extend the code to include detailed models of the seismic parameters, which is fundamental to improve the accuracy of the age determinations; 3) to apply the method to the K2 samples, presently collecting asteroseismic data for additional fields across the ecliptic; 4) further examine the properties of the present samples, in terms of their constraints to the Milky Way star formation history and chemical enrichment (as done, e.g. by Miglio et al. 2013) from 2 CoRoT fields.

References
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