Early Results from APOKASC

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Abstract Asteroseismology and spectroscopy provide complementary constraints on the fundamental and chemical properties of stars. I describe the first results from APOKASC, a collaboration between the *Kepler* asteroseismic science consortium (KASC) and the SDSS-III APOGEE survey. These include (1) the first test of asteroseismic scaling relationships in the metal-poor regime using halo and thick disk stars identified in the APOKASC sample; and (2) the calibration of spectroscopic parameters using precise asteroseismic measurements of surface gravity. I also highlight future research avenues that are made possible by this unique sample of thousands of well-characterized red giant stars.

1 Introduction

To understand galaxy formation and evolution, one can either study numerous high-redshift galaxies or examine in detail one nearby galaxy, like the Milky Way. Reconstructing the star formation history of the Milky Way requires detailed knowledge of the fundamental and chemical properties of its constituent stars.

To achieve this goal, the Apache Point Observatory Galaxy Evolution Experiment (APOGEE; Majewski et al. 2010) partnered with the *Kepler* asteroseismic science consortium (KASC) to form APOKASC. APOGEE is a high-resolution, high signal-to-noise, H-band spectroscopic survey that is part of the Sloan Digital Sky Survey III (Eisenstein et al. 2011). APOGEE provides measurements of effective temperature (T_{eff}), surface gravity ($\log g$), metallicity ([M/H]), rotation ($v \sin i$), and radial velocity. In the *Kepler* field, these spectroscopic measurements will be complemented by asteroseismic constraints on mass, radius, and $\log g$, and evolutionary state information, when available (e.g., Bedding et al. 2011; Mosser et al. 2012; Stello et al. 2013).

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In the first year of observations (Ahn et al. 2014), APOGEE observed $\sim$ 1,900 red giants with asteroseismically determined parameters. These data will be made publicly available in the APOKASC catalog (Pinsonneault et al. in prep.). I will describe two early results where the APOKASC dataset has been used to test the asteroseismic (Sect. 2) and spectroscopic (Sect. 3) determination of stellar parameters. I conclude by outlining future areas of investigation.

2 Testing Asteroseismic Scaling Relationships

The APOKASC sample is useful for testing the asteroseismic mass scale. Two asteroseismic observables can be extracted from the power spectrum of oscillating red giants, namely the frequency of maximum power, ν_{max}, and the large frequency separation, $\Delta\nu$. The masses and radii of stars with oscillations driven by surface convection may be estimated using empirical scaling relationships (Ulrich 1986; Brown et al. 1991; Kjeldsen and Bedding 1995):

$$\frac{\Delta\nu}{\Delta\nu_\odot} \simeq \left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{R}{R_\odot}\right)^{-3/2} \tag{1}$$

$$\frac{\nu_{max}}{\nu_{max,\odot}} \simeq \left(\frac{M}{M_\odot}\right)\left(\frac{R}{R_\odot}\right)^{-2}\left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{-1/2}, \tag{2}$$

where $\Delta\nu_\odot = 135.0 \pm 0.1\ \mu Hz$, $\nu_{max,\odot} = 3140 \pm 30\ \mu Hz$, and $T_{eff,\odot} = 5777\ K$ (Pinsonneault et al. in prep.).

These scaling relationships are calibrated based on the Sun and are therefore not guaranteed to work for more evolved stars, like red giants, which have a different internal structure. The accuracy of radii derived with asteroseismic scaling relationships have been examined using interferometry (Huber et al. 2012), *Hipparcos* parallaxes (Silva Aguirre et al. 2012), and RGB stars in the open cluster NGC6791 (Miglio et al. 2012; see Miglio et al. 2013 for a review of constraints).

Eclipsing binaries provide a test of scaling relationships masses. In particular, the metal-rich ([Fe/H]$\sim$ +0.4 dex) open cluster NGC 6791 serves as a prime test case. From measurements of eclipsing binaries near the cluster's main sequence turn-off, the mass of red giant branch stars is inferred to be $M_{RGB} = 1.15 \pm 0.02\ M_\odot$ (Brogaard et al. 2012). Asteroseismic oscillations have been detected for red giant branch stars in this cluster. Scaling relationships yield mass estimates of $M_{RGB} = 1.20 \pm 0.01\ M_\odot$ and $1.23 \pm 0.02\ M_\odot$ from Basu et al. (2011) and Miglio et al. (2012). These mass estimates are sensitive to, for example, the choice of temperature scale. Wu et al. (2014) defined an additional scaling relationship and determined a mass of $M_{RGB} = 1.24 \pm 0.03\ M_\odot$, consistent with previous results.

2.1   Current Results: Probing the Metal-Poor Regime

These tests of the standard scaling relationships have been confined to metallicities close to solar ($-0.5 \lesssim$ [Fe/H] $\lesssim +0.4$). However, the scaling relationships take no account of metallicity. Because metallicity could potentially influence mode excitation and damping and opacity-driven changes in convective properties, stellar properties derived using scaling relationships need to be verified over a wide range of metallicities. The APOKASC sample enabled the first test of mass estimates from asteroseismic scaling relationships in the low-metallicity regime (Epstein et al. 2014).

In the first year of APOGEE observations in the *Kepler* field, there were nine stars with measured asteroseismic parameters, reliable spectroscopic measurements, and [M/H]< -1 dex. We differentiated between halo and disk stars by computing the 3D space velocities and adopting $v_{tot,LSR} = 180$ km/s as the kinematical division between stars classified as halo and disk populations (Venn et al. 2004). We considered metal-poor stars with disk kinematics to be members of the thick disk.

Halo and metal-poor thick disk stars have a variety of independent constraints on their mass and age. The combined evidence from isochrone fits to globular clusters, e.g., Gratton et al. (1997), the white dwarf cooling sequence, e.g., Hansen et al. (2002), the radioactive decay of uranium and thorium, e.g., Sneden et al. (1996), and the imprint left by the MSTO on the stellar temperature distribution function (Jofré and Weiss 2011), places halo stars as being 10 Gyr or older. Metal-poor, α-enhanced members of the Galactic disk have been found to be 8 Gyr or older (Bensby et al. 2013; Haywood et al. 2013). We converted these age constraints into mass constraints using Dartmouth stellar isochrones (Dotter et al. 2008). The mass range associated with these age constraints is shown as the gray bands in Fig. 1. These mass ranges are consistent with the mass measurements of the eclipsing binary found in the metal-poor thick disk globular cluster 47 Tuc (Thompson et al. 2010). The width of these bands includes uncertainties in the input physics, including the assumed helium abundance, heavy element mixture, nuclear reaction rates, equation of state, opacity, model atmosphere, and heavy element diffusion rate (see van Saders and Pinsonneault 2012 for details).

Figure 1 shows that the masses determined using asteroseismic scaling relationships, asteroseismic parameters from the APOKASC catalog, and spectroscopic temperatures are a weighted average of ΔM$= 0.17 \pm 0.05$ M$_\odot$ higher than expectations. Possible explanations for this mass discrepancy are fully detailed in Epstein et al. (2014). For example, shifts in the temperature scale and contamination of this red giant branch sample by more evolved (e.g., horizontal branch or asymptotic giant branch) stars work to increase the mass difference. Two published theoretically motivated corrections (White et al. 2011; Mosser et al. 2013) reduce the mass estimates by as much as ~ 5 %. Differences between methods of determining $\Delta \nu$ and ν_{max} can shift ΔM by as much as 0.04 M$_\odot$ for these stars. Epstein et al.
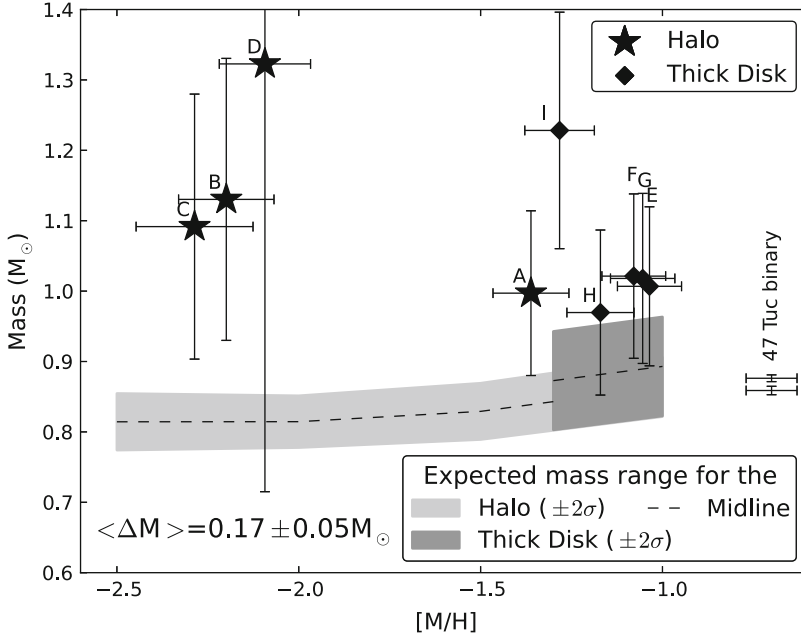
Fig. 1 Mass determined using standard asteroseismic scaling relationships [see Eqs. (1) and (2)], asteroseismic parameters from the APOKASC Catalog (Pinsonneault et al. in prep.), and spectroscopic temperatures from APOGEE. The expected mass ranges based on astrophysical priors for halo and thick disk stars are indicated by the *light* and *dark gray bands*, respectively. See Pinsonneault et al. (in prep.) for a description of the method used to determine $\Delta\nu$ and ν_{max} and their uncertainties

also note a difference between masses derived using scaling relationships compared with ν_{max}-independent techniques (Bedding et al. 2006; Deheuvels et al. 2012).

2.2 Upcoming Work

The second year of APOGEE observations will include additional metal-poor stars, enabling a better statistical test of the mass offset at low-metallicity. Detailed frequency modeling of metal-poor stars in the APOKASC sample will help to calibrate masses derived using scaling relationships. The influence of Eq. (2) on asteroseismic mass estimates also merits investigation. Theoretical corrections, e.g., White et al. (2011), have been computed for $-0.2 <$ [Fe/H] $< +0.2$; work is underway to extend similar models to lower metallicity.
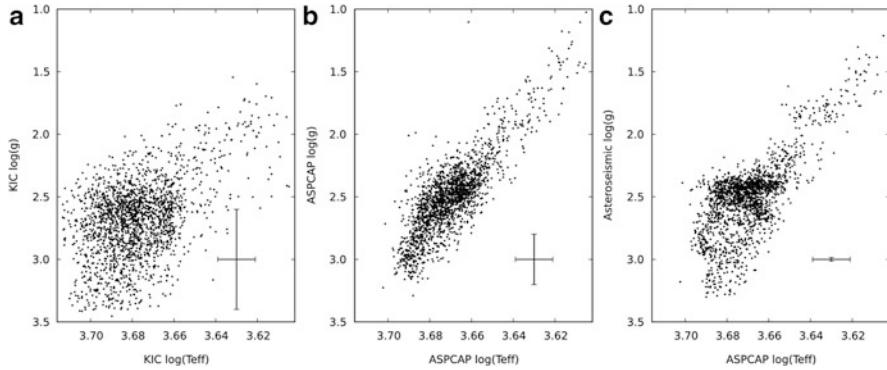
Fig. 2 A comparison of the ASPCAP sample's log g and T_{eff} distribution on the red giant branch, as determined using different measurement techniques. (**a**) Parameters were taken from the Kepler Input Catalog, which is based on photometric inputs Brown et al. (2011). (**b**) Spectroscopic parameters were derived using the ASPCAP. (**c**) Spectroscopic T_{eff} and asteroseismic log g from the APOKASC Catalog (Pinsonneault et al. in prep.). The typical uncertainty is shown in the *lower right*

3 Calibrating Stellar Parameters from Atmospheric Models

Many studies have investigated the accuracy of asteroseismic gravities for evolved stars and have found good agreement between asteroseismic and spectroscopic techniques (e.g., Morel and Miglio 2012; Thygesen et al. 2012). Asteroseismic log g have been shown to be largely model independent (Gai et al. 2011) and robust to using different approaches to derive oscillation parameters and incorporating corrections to the $\Delta\nu$ scaling relationship [Eq. (1)] (Hekker et al. 2013).

The APOGEE survey used the asteroseismic log g as an independent check on the log g derived using the APOGEE Stellar Parameters and Chemical Abundances Pipeline (ASPCAP) (Mészáros et al. 2013). The ASPCAP determines stellar parameters (including log g) and abundances by performing a χ^2 minimization in a grid of synthetic spectra. Mészáros et al. defined an empirical correction to the ASPCAP log g based on combined constraints from asteroseismology and open/globular cluster stars for application to the larger APOGEE sample (Mészáros et al. 2013).

Future Applications and Conclusions

The APOKASC sample represents the largest set of joint asteroseismic and spectroscopic constraints available to date. Figure 2 shows the impact of these improved constraints on the H-R diagram. The precise asteroseismic log g measurements make possible the identification of features, like the red clump and red bump, in a sample of field stars.

The detection of mixed-modes (Bedding et al. 2011; Mosser et al. 2012; Stello et al. 2013) can distinguish between helium-core-burning and hydrogen-shell-burning stars. This information will be useful for identifying stellar populations and probing their properties as a function of a Galactic position and age. Bayesian estimates of stellar age (e.g., Serenelli et al. 2013) based on APOKASC's and asteroseismic constraints will help to reconstruct the star formation history of the Milky Way through diagnostics, such as the age-metallicity relationship.

Additionally, the locus of the red giant branch will provide an excellent test of stellar interior models. For example, we can test whether adopting a solar mixing-length for stars is consistent with asteroseismic measurements across a range of mass, [M/H], and $\log g$ (e.g., Bonaca et al. 2012). The power of precise asteroseismic $\log g$ (Sect. 3) could also be harnessed to constrain stellar model atmospheres.

The APOKASC collaboration offers a treasure trove of information that will enable studies of both stellar physics and stellar populations for years to come.

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