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Overview and Validation of the Asteroseismic Modeling Portal v2.0

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ABSTRACT

The launch of NASA's Kepler space telescope in 2009 revolutionized the quality and quantity of observational data available for asteroseismic analysis. While Kepler was able to detect solar-like oscillations in hundreds of main-sequence and subgiant stars, the Transiting Exoplanet Survey Satellite (TESS) is now making similar observations for thousands of the brightest stars in the sky. The Asteroseismic Modeling Portal (AMP) is an automated and objective stellar model-fitting pipeline for asteroseismic data, which was originally developed to use models from the Aarhus Stellar Evolution Code (ASTEC). We briefly summarize an updated version of the AMP pipeline that uses Modules for Experiments in Stellar Astrophysics (MESA), and we present initial modeling results for the Sun and several solar analogs to validate the precision and accuracy of the inferred stellar properties.

OVERVIEW

The Asteroseismic Modeling Portal (AMP) was originally released in 2009 (Metcalfe et al. 2009; Woitaszek et al. 2009), and several minor revisions followed as the quality of asteroseismic data from the Kepler mission gradually improved (Mathur et al. 2012; Metcalfe et al. 2014; Creevey et al. 2017). The optimization approach used a parallel genetic algorithm (GA; Metcalfe & Charbonneau 2003) to match a given set of observations with models from the Aarhus stellar evolution and pulsation codes (Christensen-Dalsgaard 2008a,b). Below we briefly summarize a major revision of AMP (v2.0), which couples the same optimization method to the MESA (Paxton et al. 2019) and GYRE (Townsend & Teitler 2013) codes. We focus on differences in the underlying physics, updated treatments and methods that are distinct from previous versions, and the initial validation using the Sun and several solar analogs.

INPUT PHYSICS AND METHODS

The choices of input physics for AMP 2.0 are almost all the defaults in MESA release 12778. MESA's default equation of state is predominantly a blend of OPAL (Rogers & Nayfonov 2002) and SCVH (Saumon et al. 1995). Opacities are taken from OPAL (Iglesias & Rogers 1993, 1996) at high temperature ($\log T \geq 3.88$), from Ferguson et al. (2005) at low temperature ($\log T \leq 3.80$), and blended smoothly between these temperature ranges. The solar mixture is that of Grevesse & Sauval (1998) and nuclear reaction rates are taken from NACRE (Angulo et al. 1999). Convective heat and composition transport is described using the mixing-length model by Cox & Giuli (1968). The mixing-length parameter itself is left free in the optimization. Mixing by convective overshooting, when included, is modeled using an exponentially-decaying diffusion coefficient (Freytag et al. 1996; Herwig 2000), whose extent is also a free parameter. By default, the coefficient is fixed at zero (i.e., there is no mixing by convective overshooting). Finally, the atmosphere is included in the stellar model by placing the outermost mesh-point at optical depth $\tau = 10^{-4}$ and applying a boundary condition corresponding to a gray Eddington atmosphere. This is equivalent to describing the atmosphere (where $\tau < 2/3$) with the Eddington $T(\tau)$ relation. Gravitational settling of helium and metals are modeled using the prescription of Thoul et al. (1994). Although gravitational settling improved the quality of standard solar models, it is known to erroneously predict that all metals and helium are drained from the surfaces of stars with masses $M \gtrsim 1.2\ M_\odot$. We therefore compute gravitational settling at full efficiency for $M < 1.1\ M_\odot$, zero efficiency for $M \geq 1.2\ M_\odot$ (i.e., we disable it), and an efficiency that decreases linearly between $1.1\ M_\odot$ and $1.2\ M_\odot$.

Table 1. Stellar Properties from the Asteroseismic Modeling Portal

	R ($R_\odot$)	M ($M_\odot$)	L ($L_\odot$)	Age (Gyr)	Data Sources
Sun	1.001 ± 0.005	1.00 ± 0.01	0.96 ± 0.08	4.69 ± 0.30	1, 2
18 Sco	0.990 ± 0.009	0.96 ± 0.03	0.95 ± 0.07	4.46 ± 0.43	3, 4, 5
α Cen A	1.226 ± 0.008	1.12 ± 0.02	1.50 ± 0.08	6.27 ± 0.79	6, 7, 8
α Cen B	0.864 ± 0.007	0.92 ± 0.02	0.51 ± 0.06	5.73 ± 1.77	9, 10
16 Cyg A	1.220 ± 0.011	1.06 ± 0.03	1.40 ± 0.11	7.43 ± 0.54	11, 12
16 Cyg B	1.116 ± 0.008	1.04 ± 0.02	1.21 ± 0.08	6.99 ± 0.44	11, 12
β Hyi	1.823 ± 0.031	1.10 ± 0.05	3.50 ± 0.24	6.66 ± 0.56	13

References—(1) Davies et al. (2015); (2) Metcalfe et al. (2015); (3) Bazot et al. (2011); (4) Bazot et al. (2012); (5) Li et al. (2012); (6) de Meulenaer et al. (2010); (7) Thévenin et al. (2002); (8) Kervella et al. (2003); (9) Kjeldsen et al. (2005); (10) Porto de Mello et al. (2008); (11) Lund et al. (2017); (12) Ramírez et al. (2009); (13) Brandão et al. (2011)

Several details of the fitting method described in Metcalfe et al. (2009) have been updated for AMP 2.0. First, the range of metallicities has been slightly reduced from [0.002, 0.05] for ASTEC models to [0.008, 0.05] for MESA. Second, we stop the evolution when the stellar model reaches a minimum $\log g = 3.75$, to speed the computation by excluding the red giant phase. Third, we devised a new age interpolation scheme for the final stellar model. During stellar evolution we monitor the difference y between the observed and modeled frequencies of the lowest-frequency radial mode. When y changes sign, we solve for the root $y = 0$ by applying a bisection algorithm to the numerical time-step. If multiple sign-changes and roots are encountered over the course of the evolution, we pick the one with the smallest χ^2 between observed and modeled radial-mode frequencies. Finally, to match the observed oscillation frequencies we use the two-term correction for surface effects proposed by Ball & Gizon (2014), rather than the empirical correction of Kjeldsen et al. (2008).

DEPLOYMENT AND VALIDATION

The source code for AMP 2.0 is available on GitHub[1], and it is built around MESA release 12778 and GYRE version 6.0. Minor modifications are included for a few routines in the MESA source code, to minimize standard output for parallel runs. We deployed AMP 2.0 on the Stampede2 supercomputer at the Texas Advanced Computing Center, running a set of hybrid MPI-OpenMP jobs for each set of observational data. Each job is an MPI parallel instance of the GA, which spawns an ensemble of 120 tasks. Each task is a 4-core OpenMP parallel instance of a stellar model produced by MESA and GYRE, so each job runs on 480 cores and requires about 12 hours to complete. In practice, these jobs are executed on 10 nodes of Stampede2 (with 48-cores each) because hyper-threading up to 96-cores per node was found to degrade performance significantly. Each run is an ensemble of 4 jobs with different random initialization, so the analysis of each set of observational data requires 40 nodes for 12 hours (480 node-hours per run).

We validated the precision and accuracy of the stellar properties determined from AMP 2.0 by applying it to data sets for the Sun and several solar analogs. References for the adopted observational constraints are given in the final column of Table 1. For this small sample, AMP 2.0 yields a median precision of 0.8%, 2.2%, and 8.4% on the stellar radius, mass, and age, respectively. The accuracy of AMP 2.0 can be judged from the inferred properties of the Sun, which are all consistent with the known solar values. Additional probes of the accuracy include independently determined stellar radii from interferometry (North et al. 2007; Bazot et al. 2011; White et al. 2013; Kervella et al. 2017) and masses for the components of α Cen (Kervella et al. 2016), as well as the consistent stellar ages inferred for the components of α Cen and 16 Cyg. Luminosities inferred from AMP 2.0 tend to be marginally lower than measured values, which may be related to our choice of atmospheric boundary condition.

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[1] https://github.com/travismetcalfe/amp2

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