The K2 Galactic Archaeology Program Data Release 3: Age-abundance Patterns in C1–C8 and C10–C18

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Abstract

We present the third and final data release of the K2 Galactic Archaeology Program (K2 GAP) for Campaigns C1–C8 and C10–C18. We provide asteroseismic radius and mass coefficients, κR and κM, for ∼19,000 red giant stars, which translate directly to radius and mass given a temperature. As such, K2 GAP DR3 represents the largest asteroseismic sample in the literature to date. K2 GAP DR3 stellar parameters are calibrated to be on an absolute parallactic scale based on Gaia DR2, with red giant branch and red clump evolutionary state classifications provided via a machine-learning approach. Combining these stellar parameters with GALAH DR3 spectroscopy, we determine asteroseismic ages with precisions of ∼20%–30% and compare age-abundance relations to Galactic chemical evolution models among both low- and high-α populations for α, light, iron-peak, and neutron-capture elements. We confirm recent indications in the literature of both increased Ba production at late Galactic times as well as significant contributions to R-process enrichment from prompt sources associated with, e.g., core-collapse supernovae. With an eye toward other Galactic archeology applications, we characterize K2 GAP DR3 uncertainties and completeness using injection tests, suggesting that K2 GAP DR3 is largely unbiased in mass/age, with uncertainties of 2.9% (stat.) ± 0.1% (syst.) and 6.7% (stat.) ± 0.3% (syst.) in κR and κM for red giant branch stars and 4.7% (stat.) ± 0.3% (syst.) and 11% (stat.) ± 0.9% (syst.) for red clump stars. We also identify percent-level asteroseismic systematics, which are likely related to the time baseline of the underlying data, and which therefore should be considered in TESS asteroseismic analysis.

Unified Astronomy Thesaurus concepts: Red giant stars (1372); Nucleosynthesis (1131); R-process (1324); S-process (1419); Galactic archaeology (2178); Stellar ages (1581); Asteroseismology (73)

Supporting material: machine-readable tables

1 Introduction

Studies of Galactic chemical evolution have mostly focused on targets in the solar neighborhood, in which stars are relatively easy to observe, and which was the sole domain, historically, of precise parallaxes and, therefore, stellar ages...
Here and throughout the paper we use the standard notation $[X/Fe] \equiv \log_{10}\left( \frac{X}{Fe} \right) - \log_{10}\left( \frac{Fe}{H} \right)$.

26 Here and throughout the text, when we mention Gaia radii, we refer to the radius values provided as part of Gaia DR2; the latter are not as accurate as we require here, because they do not account for extinction and assume inhomogeneous temperatures. See Section 4 for details.
derive ages based on these calibrated asteroseismic masses in order to compare abundance enrichment histories of low- and high-$\alpha$ populations with Galactic chemical evolution models from Kobayashi et al. (2020a).

2. Data

2.1. Asteroseismic Data

In this data release, we add asteroseismic data from C2, C3, C5, C8, and C10–C18 to the results from C1 of K2 GAP DR1 (Stello et al. 2017) and C4, C6, and C7 of K2 GAP DR2 (Zinn et al. 2020). In what follows, we describe the procedure used to derive the asteroseismic values for the stars in these new campaigns, and we also describe how the results from all of the campaigns have been combined together.

The majority of K2 GAP targets were chosen to satisfy simple color and magnitude cuts, with a minority being chosen based on surface gravity selections from spectroscopic surveys —APOGEE (Majewski et al. 2010), SEGUE (Yanny et al. 2009), and RAVE (Steinmetz et al. 2006). Most of the campaigns have targets that were chosen based on a $J - K_s > 0.5$ color cut and a magnitude cut of $9 \lesssim V \lesssim 15$, where the visual magnitude was computed from Two Micron All Sky Survey photometry according to

$$V \approx K_s + 2((J - K_s) + 0.14) + 0.256e^{2(J - K_s)},$$

which is a relation introduced by De Silva et al. (2015). The targets were prioritized for the most part by ranking targets in order of brightest to faintest visual magnitude, with higher priority being given to targets selected based on spectroscopy.

The majority of the targeted stars were observed by K2, and follow the target selection functions, with a few exceptions. Notably, the priorities of C7 targets were mistakenly reversed during the Kepler office target list consolidation. For details of the effects of this on the C7 selection function, see Zinn et al. (2020) and Sharma et al. (2019); the selection functions for all of the campaigns are described in S. Sharma et al. (2021, in preparation). In addition, module 4 failed while taking data in C10. We therefore excluded data from this module in C10 because of the short duration of the data collection before the failure; modules 3 and 7 had already failed by the time when the K2 mission had begun, and so there are no data for these modules in K2 GAP. These missing modules can be seen in the K2 GAP DR3 footprint shown in Figure 1.

There are known systematics in the K2 light curves that require special processing beyond the raw light curves produced by the K2 office. In particular, the K2 satellite repositioned itself every $\sim$6 hr to maintain pointing following the partial failure of its gyroscope system. These thruster firings induce trends in the light curves that would hinder asteroseismic analysis. The light curves used in our analysis were therefore detrended from the raw K2 data using the EVEREST pipeline (Luger et al. 2018) for all of the observed K2 GAP target stars, except C1, for which we used the K2SFF pipeline (Vandenburg & Johnson 2014), and the targets classified as extended in the Ecliptic Plane Input Catalog (EPIC; Huber et al. 2016), which were not processed by EVEREST. C10 suffered a failure of module 4 shortly into the start of the campaign, and so we did not use data from targets on module 4. C11 was separated into two parts due to a roll angle correction, such that some stars had light curves only for one part of the campaign; when available, we combined the light curves of the two parts for the same target. C18 lasted about 50 days, due to the spacecraft running low on fuel, and has correspondingly reduced-quality data. C19 only had about a week’s worth of data with pointing comparable to the previous campaigns, and, as such, we have not considered the data from C19 in this data release.

Following this detrending, we removed nonasteroseismic variability using a boxcar high-pass filter with a width of 4 days, and performed sigma clipping to reject flux values more than 4-$\sigma$ discrepant. For the campaigns new to this data release, we additionally regularized the spectral window function by inpainting any gaps in the light curves according to the algorithm of García et al. (2014) and Pires et al. (2015).

2.2. Spectroscopic Data

APOGEE DR16 (Ahumada et al. 2020) spectroscopic data have been used to calibrate the asteroseismic data (Section 4). APOGEE DR16 is part of Sloan Digital Sky Survey IV (Blanton et al. 2017), which is described in Ahumada et al. (2020). APOGEE observes in the $H$-band using the
high-resolution ($R \sim 22,500$) APOGEE spectrograph (Wilson et al. 2019) mounted on the Sloan Foundation 2.5 m telescope (Gunn et al. 2006) at Apache Point Observatory. APOGEE observes about half of its targets in the disk, with Galactic latitude $b \lesssim 16^\circ$, with dedicated selections of the bulge, halo, and special programs comprising the rest of its observing allotment. Targets are selected according to color–magnitude cuts of $J - K_s \geq 0.5$ and $7 \lesssim H \lesssim 14$, across the sky (Zasowski et al. 2013, 2017). The data are reduced according to Nidever et al. (2015), using the APOGEE Stellar Parameters and Chemical Abundances Pipeline (Holzman et al. 2015; García Pérez et al. 2016). The final stellar parameter calibration and validation process is discussed by Holtzman et al. (2018).

GALAH data have been used for our analysis of age-abundance patterns (Section 5). GALAH is an optical spectroscopic survey targeting stars in the Galactic disk with $12 < V < 14$ and $|b| > 10^\circ$ (Martell et al. 2017). The survey operates from the 3.9 m Anglo-Australian Telescope at Siding Spring Observatory in Australia, using the HERMES multi-object spectrograph (Sheinis et al. 2014). The HERMES high-resolution ($R \sim 28,000$) spectra are reduced according to the procedure documented in Kos et al. (2017). GALAH DR2 presented spectroscopic parameters from the Cannon (Ness et al. 2015), trained on a subset of $\sim 11,000$ stars (Heiter et al. 2015; Buder et al. 2018) using Spectroscopy Made Easy (SME; Valenti & Piskunov 1996; Piskunov & Valenti 2017). In this work, we use abundances from GALAH DR3, which improves upon GALAH DR2 by deriving stellar parameters and abundances for all stars directly through the spectroscopic analysis code SME, which performs on-the-fly spectrum synthesis calculations; this reduces potential bias from selection effects in the Cannon training process (e.g., Holzman et al. 2018). The SME analysis code utilizes grids of precomputed non-LTE departure coefficients for thirteen chemical elements; these grids and the models they are based on are presented by Amarsi et al. (2020, and references therein) and are publicly available (Amarsi 2020).

3. Methods

3.1. Asteroseismic Radius and Mass Scaling Relations

Given the large sample size of the K2 GAP targets, it is not feasible to fit individual modes for each star in order to determine their mass and radius. Instead, we condense the modes’ information into two quantities, which can be measured relatively straightforwardly and which are related to the mass and radius of a star through so-called scaling relations.

The first of these quantities, the frequency at maximum acoustic power, $\nu_{\text{max}}$, is thought to be related to the acoustic cutoff frequency, and therefore to the surface gravity of the star (Brown et al. 1991; Kjeldsen & Bedding 1995; Chaplin et al. 2008; Belkacem et al. 2011). Assuming that this relation holds homologously across evolutionary state, this implies a scaling relation of the form

$$\frac{\nu_{\text{max},\odot}}{\nu_{\text{max},\odot}} \approx \frac{M/M_\odot}{(R/R_\odot)^2 \sqrt{(T_{\text{eff},\odot}/T_{\text{eff},\odot})}}.$$  

(1)

The second quantity of interest, the large frequency separation, $\Delta \nu$, describes the frequency difference between modes of consecutive radial order that share the same degree. A second, independent scaling relation relates $\Delta \nu$ to the average stellar density (Ulrich 1986; Kjeldsen & Bedding 1995):

$$\frac{\Delta \nu}{\Delta \nu_{\odot}} \approx \sqrt{\frac{M/M_\odot}{(R/R_\odot)^3}}.$$  

(2)

The latter scaling relation is well understood theoretically, and is valid, strictly speaking, in the limit of large radial order.

However, given a stellar structure model, one can compute the expected $\Delta \nu$ at the observed radial order, as well as $\Delta \nu$ in the limit of large radial order, and therefore derive a correction factor, $f_{\Delta \nu}$, to translate the observed $\Delta \nu$ to the large radial order $\Delta \nu$ that enters into Equation (2) (e.g., White et al. 2011; Sharma et al. 2016). We therefore use a modified version of Equation (2):

$$\frac{\Delta \nu}{f_{\Delta \nu} \Delta \nu_{\odot}} \approx \sqrt{\frac{M/M_\odot}{(R/R_\odot)^3}}.$$  

(3)

Note that these corrections do not take into account frequency shifts due to the approximations of adiabatic thermal structures and mixing length theory that are widely used in stellar evolution models (e.g., Jørgensen et al. 2020, 2021). However, such considerations are secondary adjustments to $f_{\Delta \nu}$ given the empirical success of $f_{\Delta \nu}$ in producing agreement between asteroseismic radii and masses with independent estimates (e.g., Huber et al. 2017; Brogaard et al. 2018; Zinn et al. 2019b).

We opt to use the $f_{\Delta \nu}$ corrections from Sharma et al. (2016), which are computed on a star-by-star basis according to the star’s properties (e.g., temperature, metallicity, etc.), by interpolation in a grid of theoretically computed $f_{\Delta \nu}$. The asfgrid code for computing $f_{\Delta \nu}$ values is publicly available (Sharma & Stello 2016; Sharma et al. 2016).

In analogy with the corrections to the $\Delta \nu$ scaling relation, there are observational indications that the $\nu_{\text{max}}$ scaling relation of Equation (1) should also be modified to include a correction to the observed $\nu_{\text{max},\odot}$, $f_{\nu_{\text{max},\odot}}$ (Epstein et al. 2014; Yildiz et al. 2016; Huber et al. 2017; Viani et al. 2017; Kallinger et al. 2018). For this reason, we use a modified $\nu_{\text{max}}$ scaling relation:

$$\frac{\nu_{\text{max}}}{f_{\nu_{\text{max}},\odot} \nu_{\text{max},\odot}} \approx \frac{M/M_\odot}{(R/R_\odot)^2 \sqrt{(T_{\text{eff},\odot}/T_{\text{eff},\odot})}}.$$  

(4)

Although progress is being made in terms of making robust theoretical predictions of $\nu_{\text{max}}$ (e.g., Belkacem et al. 2013; Zhao et al. 2016; Zhou et al. 2020), it cannot yet be computed, based on first principles, to the precision required to be useful, as can be done for $\Delta \nu$. We therefore make empirical estimates of $f_{\nu_{\text{max},\odot}}$ in Section 4 for red giant branch (RGB) and red clump (RC) stars, which, in practice, are scalar values such that we can think of $f_{\nu_{\text{max},\odot}}$ as indistinguishable from a modified $\nu_{\text{max},\odot}$.

The solar reference values in Equations (3) and (4) should, in theory, be measured using the same analysis as one would use to measure $\nu_{\text{max}}$ and $\Delta \nu$. Therefore, each pipeline has different solar reference values, which are listed in Table 1. We assume here a solar temperature of $T_{\text{eff},\odot} = 5772K$ (Mamajek et al. 2015).

By rearranging Equations (3) and (4), the radius scaling relation is found to be

$$\frac{R}{R_\odot} \approx \left(\frac{\nu_{\text{max}}}{f_{\nu_{\text{max}},\odot} \nu_{\text{max},\odot}} \left(\frac{\Delta \nu}{f_{\Delta \nu} \Delta \nu_{\odot}}\right)^{-2} \frac{T_{\text{eff}}}{T_{\text{eff},\odot}}\right)^{1/2}.$$  

(5)

28 http://www.physics.usyd.edu.au/k2gap/Asfgrid/
and to converge before performing a 3σ clipping to remove the stellar red noise; with a mean corresponding to \( \nu_{\text{max}} \) for A2Z, BAM, BHM, CAN, and COR, or heavily smoothing the excess to localize the frequency of its peak as \( \nu_{\text{max}} \) for SYD; and (3) identifying \( \Delta \nu \) using either individually fitted modes (CAN) or some version of the autocorrelation function (A2Z, BAM, BHM, CAN, COR, and SYD). For more details of implementation and methodologies of these pipelines in the context of K2, please see Stello et al. (2017) and Zinn et al. (2020).

We follow the procedure laid out in K2 GAP DR2 to derive average asteroseismic parameters for each star. This method is similar to the one adopted for the APOKASC-2 sample, which is described in Pinsoneau et al. (2018). In short, we rescale each of the pipeline \( \nu_{\text{max}} \) and \( \Delta \nu \) values such that the average values for the entire sample across all of the pipelines are the same, which requires an iterative approach and results in averaged values for each star, denoted by \( \langle \nu_{\text{max}} \rangle \) and \( \langle \Delta \nu \rangle \). Three modifications have been implemented here compared to the methodology described in Zinn et al. (2020). First, the A2Z \( \Delta \nu \) values are not incorporated into the \( \langle \Delta \nu \rangle \), due to a significant systematic offset from the other pipeline values. Second, for stars that were observed during more than one campaign, variance-weighted averages for each pipeline are computed before proceeding, such that there is only one measurement per star. Third, whereas previously the sigma clipping was done at the end of each iteration, we now allow the average \( \nu_{\text{max}} \) to converge before performing a 3σ clipping and continuing the iteration process. For each star that has at least two pipeline values returned, we take the average \( \nu_{\text{max}} \), \( \langle \nu_{\text{max}} \rangle \), and adopt the scatter in those \( \nu_{\text{max}} \) values as the uncertainty on \( \nu_{\text{max}} \). The same exercise is performed for \( \Delta \nu \), to compute \( \Delta \nu \) and \( \langle \Delta \nu \rangle \). In so doing, we are assuming that the different pipelines have systematic differences in the \( \Delta \nu \) and \( \nu_{\text{max}} \) measurements that tend to cancel each other out when averaged together. This exercise is conducted separately for RGB and RC stars, based on the evolutionary states computed using the machine-learning approach described in Hon et al. (2017, 2018). In brief, the machine-learning approach takes advantage of the fact that RGB and RC stars exhibit differences in the observed mode structure (Bedding et al. 2011). These differences are detectable by visual inspection, and are therefore amenable to being learned by machine-learning algorithms. The classifier developed by Hon et al. (2017, 2018) uses a convolutional neural network—an architecture optimized for image processing—to learn characteristic red giant and red clump mode features that are present in power spectra rendered as 2D images. In this work, evolutionary states are assigned arbitrarily at the initial iteration, and in subsequent iterations, for stars with defined \( \langle \Delta \nu \rangle \) and \( \langle \nu_{\text{max}} \rangle \), machine-learning evolutionary states are assigned. The final iteration proceeds only with stars with a defined \( \langle \Delta \nu \rangle \) and \( \langle \nu_{\text{max}} \rangle \). As part of this process, each pipeline has assigned scale factors—\( X_{\nu_{\text{max}}} \), \( X_{\Delta \nu} \), \( X_{\text{RA2Z}} \), \( X_{\text{BHM}} \), \( X_{\text{BAM}} \), and \( X_{\text{SYD}} \)—that describe by how much the pipeline-specific solar reference value (Table 1) should be multiplied to put on the \( \langle \nu_{\text{max}} \rangle \) and \( \langle \Delta \nu \rangle \) scale for RGB stars and RC stars, respectively. These modified solar reference values are provided in Table 3. Here, we also indicate the analogous scaling factors from APOKASC-2 (Pinsoneau et al. 2018), where differences are the result of a slightly different methodology and not working with the same pipelines: BAM was not a part of the APOKASC-2 analysis. It is also likely that significant differences were introduced in the pipeline’s

\begin{table}[h]
\centering
\small
\begin{tabular}{lcc}
\hline
Pipeline & \( \nu_{\text{max}} \) & \( \Delta \nu \) \\
\hline
A2Z & 3097.33 & 134.92 \\
CAN & 3140 & 134.92 \\
COR & 3050 & 134.92 \\
SYD & 3000 & 135.1 \\
BAM & 3094 & 134.84 \\
BHM & 3050 & 134.92 \\
\hline
\end{tabular}
\caption{Solar Reference Values for each Pipeline Contributing to K2 GAP DR3}
\end{table}
| EPIC ID    | \(\nu_{\text{max}}\) \(\mu\text{Hz}\) | \(\Delta\nu_{\text{max}}\) \(\mu\text{Hz}\) | \(\nu_{\text{eff}}\) \(\mu\text{Hz}\) | \(\Delta\nu_{\text{eff}}\) \(\mu\text{Hz}\) | \(\sigma_{\nu_{\text{max}}}\) \(\mu\text{Hz}\) | \(\sigma_{\nu_{\text{eff}}}\) \(\mu\text{Hz}\) | \(\nu_{\text{max, A2Z}}\) \(\mu\text{Hz}\) | \(\Delta\nu_{\text{max, A2Z}}\) \(\mu\text{Hz}\) | \(\nu_{\text{max, BHM}}\) \(\mu\text{Hz}\) | \(\Delta\nu_{\text{max, BHM}}\) \(\mu\text{Hz}\) | \(\nu_{\text{max, CAN}}\) \(\mu\text{Hz}\) | \(\Delta\nu_{\text{max, CAN}}\) \(\mu\text{Hz}\) | \(\nu_{\text{max, SYD}}\) \(\mu\text{Hz}\) | \(\Delta\nu_{\text{max, SYD}}\) \(\mu\text{Hz}\) | \(\Delta\nu_{\text{eff}}\) \|K\| | \(\sigma_{\nu_{\text{eff}}}\) \|K\| | \(\nu_{\text{max}}\) \|A2Z\| | \(\nu_{\text{max}}\) \|BHM\| | \(\nu_{\text{max}}\) \|CAN\| | \(\nu_{\text{max}}\) \|SYD\| |
|-----------|-----------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 210306475 | 28.041 1.274 1.485 | 5 3.495 0.112 0.176 | 3 1.026 0.008 3.405 | 28.575 30.053 26.808 | 27.801 ... | 29.351 ... | 3.361 3.568 ... | ... | ... | 3.553 4797 134 | −0.266 0.300 | ... |
| 210307958 | 28.380 0.933 1.308 | 5 3.965 0.134 0.100 | 3 1.032 0.014 3.842 | 27.964 30.233 ... | 29.399 28.349 28.369 ... | 3.352 ... | 4.112 3.925 ... | 4750 138 | −0.359 0.260 | ... |
| 210314554 | 30.482 1.054 1.669 | 6 4.171 0.064 0.129 | 5 1.017 0.019 4.102 | 29.055 31.776 31.093 | 30.745 31.639 31.693 ... | 4.201 4.169 4.268 4.112 | 4953 174 | −0.510 0.330 | ... |
| 210315825 | 38.454 0.341 1.990 | 6 6.093 0.059 0.096 | 5 1.025 0.013 5.944 | 59.632 59.091 59.795 | 59.671 58.958 59.540 ... | 6.064 6.175 6.083 6.123 | 6.018 4827 180 | −0.298 0.300 | ... |
| 210318976 | 24.052 0.501 1.350 | 5 3.541 0.043 0.083 | 2 1.031 0.014 3.434 | 24.821 25.012 ... | 23.772 24.539 ... | 24.162 ... | ... | ... | 3.568 3.507 4680 | 140 | −0.199 0.260 |

Note. Astroseismic values rescaled for scalar offsets among pipelines are denoted by a prime (the pipeline-specific solar reference scale factors are listed in Table 3); mean \(\nu_{\text{max}}\) and \(\Delta\nu\) values for each star across all pipelines are denoted by \(\langle\nu_{\text{max}}\rangle\) and \(\langle\Delta\nu\rangle\); the standard deviations of these values for each star across all pipelines are denoted by \(\sigma_{\nu_{\text{max}}}\) and \(\sigma_{\Delta\nu}\), and are the adopted uncertainties for K2 GAP DR3. \(\nu_{\text{eff}}\) and \(\Delta\nu_{\text{eff}}\) are conservative estimates of statistical uncertainties based on the reported pipeline statistical uncertainties. \(\nu_{\text{max, A2Z}}\) are computed by perturbing the EPIC temperature and metallicities in a Monte Carlo procedure. Note that \(\sigma_{\nu_{\text{max}}}\) are not provided for EPIC ID 240289249 and EPIC ID 255193028, which have anomalously large EPIC temperature uncertainties. \(\langle\nu'_{\text{max}}\rangle\) values have an evolutionary state-dependent correction applied to align their astroseismic radii with the Gaia radii, per Section 4. Pipeline-specific rescaled values, \(\nu_{\text{max}}\) and \(\Delta\nu\), are only provided for targets for which at least two pipelines returned concordant results, and otherwise have a blank entry; the numbers of pipelines returning valid results for \(\nu_{\text{max}}\) or \(\Delta\nu\) are denoted by \(N_{\nu_{\text{max}}}\) and \(N_{\Delta\nu}\). A2Z, \(\Delta\nu\) values are not provided, since A2Z \(\Delta\nu\) values do not contribute to \(\langle\Delta\nu\rangle\). See the text for details.

(This table is available in its entirety in machine-readable form.)
### Table 3
Solar Reference Value Scale Factors and Solar Reference Values

| A2Z                          | CAN                          | COR                          | SYD                          | BAM                          | BHM                          | K2 GAP DR3                     |
|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|--------------------------------|
| $X_{\text{max}, \text{RGB, APOKASC2}}$ | $1.00230 \pm 0.00002$       | $1.00820 \pm 0.00002$       | $0.99890 \pm 0.00002$       | $1.00060 \pm 0.00002$       | $\ldots$                     | $\ldots$                      |
| $X_{\text{max,RGB}}$          | $0.9991 \pm 0.0006$         | $0.9953 \pm 0.0003$         | $1.0000 \pm 0.0003$         | $0.9990 \pm 0.0007$         | $1.0027 \pm 0.0003$          | $1.0034 \pm 0.0003$            |
| $\nu_{\text{max,RGB}}$        | $3095 \pm 2 \mu\text{Hz}$  | $3125 \pm 1 \mu\text{Hz}$  | $3050 \pm 1 \mu\text{Hz}$  | $3087 \pm 2 \mu\text{Hz}$  | $3102 \pm 1 \mu\text{Hz}$  | $3060 \pm 1 \mu\text{Hz}$  | $3076 \mu\text{Hz}$ |
| $X_{\Delta \nu, \text{RGB, APOKASC2}}$ | $0.99930 \pm 0.00001$     | $1.00070 \pm 0.00001$     | $1.00510 \pm 0.00001$     | $0.99950 \pm 0.00001$     | $\ldots$                     | $\ldots$                      |
| $X_{\Delta \nu,\text{RGB}}$  | $\ldots$                    | $1.0042 \pm 0.0002$        | $1.0004 \pm 0.0004$        | $1.0001 \pm 0.0012$        | $0.9969 \pm 0.0007$          | $0.9978 \pm 0.0005$            |
| $\Delta \nu_{\text{max,RGB}}$ | $1.00350 \pm 0.00003$      | $1.00670 \pm 0.00002$      | $0.99090 \pm 0.00002$      | $1.00100 \pm 0.00003$      | $\ldots$                     | $\ldots$                      |
| $X_{\text{max,RC, APOKASC2}}$ | $0.9951 \pm 0.0011$        | $0.9935 \pm 0.0006$        | $0.9992 \pm 0.0005$        | $0.996 \pm 0.001$          | $1.0131 \pm 0.0005$         | $1.0024 \pm 0.0006$            |
| $X_{\text{max,RC}}$           | $0.9951 \pm 0.0011$        | $0.9935 \pm 0.0006$        | $0.9992 \pm 0.0005$        | $0.996 \pm 0.001$          | $1.0131 \pm 0.0005$         | $1.0024 \pm 0.0006$            |
| $\nu_{\text{max,RC}}$        | $3082 \pm 4 \mu\text{Hz}$ | $3120 \pm 2 \mu\text{Hz}$ | $3048 \pm 2 \mu\text{Hz}$ | $3077 \pm 4 \mu\text{Hz}$ | $3134 \pm 1 \mu\text{Hz}$  | $3057 \pm 2 \mu\text{Hz}$  | $3076 \mu\text{Hz}$ |
| $X_{\Delta \nu, \text{RC, APOKASC2}}$ | $0.99650 \pm 0.00003$     | $1.01080 \pm 0.00002$     | $0.99600 \pm 0.00001$     | $1.00320 \pm 0.00002$     | $\ldots$                     | $\ldots$                      |
| $X_{\Delta \nu, \text{RC}}$  | $\ldots$                    | $1.0066 \pm 0.0005$        | $1.0101 \pm 0.0005$        | $0.999 \pm 0.002$          | $0.993 \pm 0.002$           | $0.9971 \pm 0.0007$            |
| $\Delta \nu_{\text{max,RC}}$ | $\ldots$                    | $135.81 \pm 0.07 \mu\text{Hz}$ | $135.06 \pm 0.07 \mu\text{Hz}$ | $134.9 \pm 0.3 \mu\text{Hz}$ | $133.9 \pm 0.3 \mu\text{Hz}$ | $134.53 \pm 0.10 \mu\text{Hz}$ | $135.146 \mu\text{Hz}$      |

Note. Solar reference value scale factors and solar reference values (see Section 3), compared to those computed for some of the same pipelines using a similar method with Kepler data (APOKASC-2; Pinsonneault et al. 2018). The adopted solar reference values for K2 GAP DR3 are listed in the last column. A2Z $\Delta \nu$ solar reference value scale factors and solar reference values are not provided, since A2Z $\Delta \nu$ values do not contribute to $\langle \Delta \nu \rangle$; see Table 1 for the default A2Z $\Delta \nu$ value.
asteroseismic scales, due to the difference between the time baselines of Kepler and K2, which we discuss in Section 4.

We list in Table 2 the individual rescaled pipeline values \( \nu_{\text{max}} \) and \( \Delta \nu' \). As in K2 GAP DR2, we do not list \( \nu_{\text{max}} \) or \( \Delta \nu' \) if that pipeline value is sigma-clipped in the averaging procedure. We correct the pipeline-specific \( \Delta \nu' \) as well as \( \langle \Delta \nu' \rangle \) with theoretical \( \frac{\Delta \nu}{\nu_0} \) from Sharma et al. (2016), using the EPIC temperatures and metallicities listed in Table 2. We use these rescaled \( \nu'_{\text{max}} \) and \( \Delta \nu' \) values to compute rescaled \( \langle \nu' \rangle \) and \( \langle \Delta \nu' \rangle \) for each star and each pipeline, using the solar reference values appropriate for each pipeline (see Table 1). Our recommended radius and mass coefficients, \( \langle k_R \rangle \) and \( \langle k_M \rangle \), are those computed using the average parameters \( \langle \nu'_{\text{max}} \rangle \) and \( \langle \Delta \nu' \rangle \), and the APOKASC-2 solar reference values are modified so that our radii are on the Gaia parallactic scale (see Section 4): \( \nu_{\text{max}}, \langle \nu' \rangle, \langle \Delta \nu' \rangle, \langle k_R \rangle \), and \( \langle k_M \rangle \) for both RGB stars and RC stars, which may be considered typical of the uncertainties in our sample. We also include typical fractional uncertainties in these parameters from K2 GAP DR2, APOKASC-2 (Pinsonneault et al. 2018), and another independent analysis of the Kepler data (Yu et al. 2018). The typical \( \Delta \nu' \) uncertainty for K2 GAP DR3 is somewhat larger than it was for K2 GAP DR2, due to the previously mentioned difference in how the sigma clipping is performed in the averaging procedure used for the two data releases. The resulting precisions in RGB masses, which are deterministic in asteroseismic age precisions, are about a factor of two larger than those of Kepler, corresponding to uncertainties of about 20\%–30\% in age.

We provide all of the results returned by every pipeline in Table 6. Included in this table are machine-learning evolutionary states based on \( \langle \Delta \nu' \rangle \) and \( \langle \nu'_{\text{max}} \rangle \), as well as evolutionary states based on individual pipeline values, which are taken to be \( \Delta \nu' \) and \( \nu_{\text{max}} \).31 We also include the EPIC IDs for stars that had no measured asteroseismic parameters from any pipeline, but that were targeted as part of K2 GAP, so that users may investigate asteroseismic selection functions as needed; we quantify K2 GAP DR3 completeness as a function of mass and radius in Section 4.1. The K2 GAP DR3 sample that we refer to in what follows is a subset of the totality of the targeted stars, and consists only of the stars with a valid \( \langle \nu'_{\text{max}} \rangle \). There are 19,417 such stars, 18,821 of which also have a valid \( \langle \Delta \nu' \rangle \) and therefore \( \langle k_R \rangle \) and \( \langle k_M \rangle \). Stars with both \( \langle \nu'_{\text{max}} \rangle \) and \( \langle \Delta \nu' \rangle \) are assigned an evolutionary state, resulting in 12,978 RGB stars and 5843 RC stars. The numbers of stars with asteroseismic detections broken down by campaign and pipeline are listed in Table 7. The Kiel diagram for the K2 GAP DR3 sample is shown in Figure 2, and its distribution on the sky is shown in Figure 1; the sample is also shown in Galactocentric coordinates in Figure 3.

4. Validation of Asteroseismic Values in K2 GAP DR3

4.1. Injection Tests

In the previous section, we detailed the dependence of asteroseismic results across pipelines. However, there are likely additional systematics due to the length of the K2 light curves compared to, e.g., Kepler light curves. Indeed, Hekker et al. (2012) revealed nonnegligible variations in the completeness, precision, and accuracy of red giant asteroseismic parameters due to the length of the time series (i.e., the time baseline). In order to test the completeness, precision, and accuracy of the different asteroseismic modeling pipelines for K2-like data, we generated synthetic data for which we knew the “true” \( \nu_{\text{max}} \) and \( \Delta \nu \) from Kepler, and performed blind injection recovery tests.

We first created a grid of magnitude-\( \nu_{\text{max}} \) space from the distribution of Kepler stars using APOKASC-2 (Pinsonneault et al. 2018), the faint giant sample of Mathur et al. (2016), and the M-giant sample of Stello et al. (2014) in order to select Kepler stars evenly across this parameter space. From each bin, where possible, we generated K2-like light curves based on 80 day segments of Kepler light curves via two methods. First, we attempted to select from each bin three Kepler stars with at least five quarters of data each, from which we created 15 synthetic K2 light curves (selecting five different 80 day sections from three stars). Second, we attempted to generate 15 synthetic K2 light curves from 15 different Kepler stars using a single 80 day section of each of their light curves. In practice, however, not all bins had enough stars to create 30 synthetic K2 light curves via these two methods. Each of the synthetic K2 light curves was created using KASOC v1 Q1–Q4 light curves (Handberg & Lund 2014), linearly interpolating the Kepler flux onto the cadence of a star in K2 C3 in order to mimic the spectral window of actual C3 data and the frequency resolution of K2. We then increased the white noise level for each of the synthetic K2 light curves according to the following procedure. First, the white noise as a function of magnitude was computed for the entire grid of Kepler stars as well as the 10,291 non-GAP C3 targets with EVEREST long-cadence light curves. The white noise for each star was computed by taking the standard deviation of its light curve, filtered to remove variability slower than ~150 \( \mu \text{Hz} \). For both of these samples, the 20th percentile of the white noise levels as a function of magnitude were fitted using third-degree polynomials. The white noise levels of each synthetic K2 light curve were increased by the ratio of the Kepler-to-K2 white noise if that ratio was less than unity at the Kepler star’s magnitude. In practice, this resulted in increasing the white noise levels of stars fainter than \( Kp = 14 \), by 10\%, on average, and by no more than 20\%.

We show in Figure 4(a) the S/N of the synthetic sample.32 We compute the S/N of the synthetic K2 data in a way that takes into account both the expected maximum mode amplitude and the granulation background level at \( \nu_{\text{max}} \). To do so, we adopt the approach from Campante et al. (2016), by

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30 Since A2Z \( \Delta \nu \) values do not contribute to \( \langle \Delta \nu' \rangle \), no \( \Delta \nu_{\text{A2Z}} \) values are populated in Table 2, and the \( \langle k_R \rangle_{\text{A2Z}} \) and \( \langle k_M \rangle_{\text{A2Z}} \) values in Table 4 are calculated using the raw \( \Delta \nu \) and rescaled \( \nu_{\text{max}} \) values.

31 The A2Z evolutionary states are based on raw \( \Delta \nu \) and rescaled \( \nu_{\text{max}} \). Also, for the small number of cases for which there were multiple observations of the same star across different campaigns, we adopted the evolutionary state from the campaign with the smallest evolutionary state uncertainty according to the machine-learning approach.

32 Note that this is the S/N in power, not amplitude.
Table 4

Radius and Mass Coefficients

| EPIC ID       | 〈κ_R〉 | 〈κ_M〉 | 〈κ_R, A2Z〉 | 〈κ_R, BAM〉 | 〈κ_R, BHM〉 | 〈κ_R, CAN〉 | 〈κ_R, COR〉 | 〈κ_R, SYD〉 | 〈κ_M, A2Z〉 | 〈κ_M, BAM〉 | 〈κ_M, BHM〉 | 〈κ_M, CAN〉 | 〈κ_M, COR〉 | 〈κ_M, SYD〉 |
|--------------|--------|--------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 21306475     | 13.406 | 1.086  | 1.331       | 12.815      |             |             |             |             |             |             |             |             |             |             |
| 21307958     | 10.541 | 0.818  | 1.060       | 10.323      | 10.298      | 1.901       | 1.912       | 1.573       | 1.515       | 2.438       | 1.362       |             |             |             |
| 21304854     | 10.232 | 0.480  | 1.073       | 10.323      | 10.927      | 0.594       | 0.562       | 1.439       | 1.019       | 1.100       |             |             |             |             |
| 21315825     | 9.194  | 0.193  | 1.661       | 10.323      | 10.927      | 0.594       | 0.562       | 1.439       | 1.019       | 1.100       |             |             |             |             |
| 21318976     | 11.201 | 1.015  | 1.343       | 11.392      | 1.298       | 1.573       | 2.438       | 1.362       | 1.847       | 0.359       | 0.605       | 0.324       |             |             |

Note. 〈κ_R〉 and 〈κ_M〉, and their uncertainties, are computed based on 〈\Delta R⟩ and 〈\Delta M⟩, according to Equations (6) and (8). 〈κ_R〉 and 〈κ_M〉 values have an evolutionary state-dependent correction to align asteroseismic radii with the Gaia radii, per Section 4. The pipeline-specific radius and mass coefficients, 〈κ_R˚〉 and 〈κ_M˚〉, are computed with the pipeline-specific asteroseismic parameters 〈ΔR˚⟩ and 〈ΔM˚⟩. See Section 3 for details.

(This table is available in its entirety in machine-readable form.)
assuming three modes per order, ignoring observation integration time effects, and assuming a noise level according to the observed star-to-star white noise level at high frequencies in the spectra. For the maximum mode amplitude, we adopt the model $M_{4,3}$ from Corsaro et al. (2013). The points are colored by the provenance of the Kepler data, in which there are potentially multiple synthetic stars per KIC ID because of the division of the Kepler light curves into 80 day sections. In total, there are 57 synthetic stars from the M-giant catalog (Stello et al. 2014); 891 synthetic stars from the faint giant catalog (Mathur et al. 2016); and 1691 synthetic stars from the APOKASC-2 catalog (Pinsonneault et al. 2018). The dashed lines demarcate the boundaries of the grid we used to draw the synthetic light curves in $v_{\text{max}}$ space. We also show the distribution in magnitude space in Figure 4(b), with the vertical lines demarcating the magnitude bins used to populate the synthetic sample.

The analysis of these synthetic K2 data via the pipelines proceeded blindly (i.e., the synthetic data were treated as real data), and the resulting asteroseismic parameters were processed using an iteration of the averaging procedure described in Section 3.2. The average results are denoted in the following figures as “ALL,” and any pipeline-specific results for synthetic K2 data are only shown if they meet the same criteria as the real data (i.e., having at least two pipelines return results).

In Figure 5, we show the accuracy of the recovery for each of the asteroseismic pipelines, based on the ground truth Kepler asteroseismic values. For this exercise, each pipeline analyzed the Kepler light curves to generate ground truth labels. For the purposes of this plot and those that follow, uncertainties on the binned median are computed by inflating the standard uncertainty on the binned mean by a factor of $\frac{\sigma}{\sqrt{N}}$ (Kenney & Keeping 1962).

We show the trends in the K2 asteroseismic values as functions of both $v_{\text{max}}$ and $\Delta\nu$. There are also biases when the trends are averaged over all of $v_{\text{max}}$ and $\Delta\nu$, which can be seen by the fact that the trends for some pipelines in Figure 5 are systematically offset below the one-to-one line. This suggests that there are nonnegligible systematics in asteroseismic pipeline recovery that are a function of the baseline, which would result in too-small radii and masses compared to Kepler asteroseismology (see the below comparison between mass distributions in K2 and Kepler). The time baseline seems to have the smallest impact on $\Delta\nu$, since several pipelines report nearly identical $\Delta\nu$ with Kepler as with K2 data (though some pipelines show substantial disagreement). $v_{\text{max}}$, however, suffers from significant biases relating to the time baseline: excursions of 2\%-3\% and zero-point biases of 1\%-2\% are observed. There are also indications that some pipelines may have S/N-dependent biases, which manifest as trends in fractional agreement between Kepler and synthetic K2 values as a function of S/N in Figure 6. Note that the S/N shown in this figure is not the same S/N that is shown in Figure 4(a): the S/N in Figure 6 represents the relative S/N at fixed $v_{\text{max}}$, and is computed by dividing out the median trend from Figure 4(a).

Although we will be calibrating our K2 data based on independent estimates of radius in Section 4.2, these biases are important to note, and are being investigated in the context of Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014; Stello et al. 2021). It should also be noted that additional biases could be introduced in the asteroseismic analysis, based on the preparation of the pixel-level data and the details of processing the light curves into power spectra (e.g., choices of frequency filter). Based on internal consistency checks against K2SFF light curves (Vanderburg & Johnson 2014), such effects are smaller than the time baseline biases shown here (<1%).

As well as testing the $v_{\text{max}}$, $\Delta\nu$, S/N, and time baseline-dependent biases in the pipeline results, we can test the internal consistency of the uncertainties using the synthetic K2 data. Since we have results from precise Kepler data, we can compare these to the less precise, simulated K2 data for the same stars, and evaluate whether the pipeline results are internally consistent to within their reported uncertainties. To do so, the observed distribution of the fractional deviation between the K2 and Kepler measurements (“true” in Figure 7) is compared to the expected distribution (“reported” in Figure 7), created by drawing Gaussian random variables assuming the reported K2 uncertainty for each simulated K2 star. If the reported uncertainties should be self-consistent, then the two distributions would be identical. If the pipeline should tend to overestimate uncertainties, however, the “reported” distribution would be skewed toward higher uncertainties compared to the “true” distribution, and vice versa. The internal consistency is globally good for most pipelines. This plot also indicates the relative precision of the pipelines, with the dashed line indicating $\sigma_{\Delta\nu} = 0.01$ and $\sigma_{v_{\text{max}}} = 0.03$, which are representative values for the internal uncertainties for the pipelines. For $\Delta\nu$, there is perhaps a tendency for the pipelines that provide results for fewer stars (and hence that are perhaps more strict in accepting which measurements are valid) to show smaller deviations between the “true” and “reported” values. By the same token, the more values that a pipeline accepts as

|               | APOKASC-2 | RGB or RGB/AGB | K2 GAP DR2 | K2 GAP DR3 | APOKASC-2 | Y18 | K2 GAP DR2 | K2 GAP DR3 |
|---------------|-----------|----------------|------------|------------|-----------|-----|------------|------------|
| $\sigma_{\text{max}}$ | 0.9       | 1.0            | 1.7        | 1.3        | 1.3       | 2.1 | 2.4        | 2.2        |
| $\sigma_{\Delta\nu}$ | 0.4       | 0.3            | 1.7        | 1.1        | 1.1       | 1.1 | 2.3        | 1.8        |
| $\sigma_{R}$   | 1.3       | 1.1            | 3.3        | 2.9        | 2.7       | 3.3 | 5.0        | 4.7        |
| $\sigma_{M}$   | 3.4       | 3.1            | 7.7        | 6.7        | 6.2       | 8.4 | 10.5       | 11         |

Note. “APOKASC-2” indicates the median fractional uncertainties from the analysis of Pinsonneault et al. (2018), while “Y18” refers to the analysis of Yu et al. (2018). The K2 GAP DR2 uncertainties are taken from Table 7 of Zinn et al. (2020).
Table 6

Raw Asteroseismic $\nu_{\text{max}}$ and $\Delta\nu$ Values, with Evolutionary States

| ID       | EPIC ID         | Campaign | Priority | $\nu_{\text{max, A2Z}}$ | $\nu_{\text{max, BAM}}$ | $\nu_{\text{max, CAN}}$ | $\nu_{\text{max, SYD}}$ | $\Delta\nu_{\text{A2Z}}$ | $\Delta\nu_{\text{BAM}}$ | $\Delta\nu_{\text{CAN}}$ | $\Delta\nu_{\text{SYD}}$ | $\sigma_{\Delta\nu_{\text{A2Z}}}$ | $\sigma_{\Delta\nu_{\text{BAM}}}$ | $\sigma_{\Delta\nu_{\text{CAN}}}$ | $\sigma_{\Delta\nu_{\text{SYD}}}$ |
|----------|-----------------|----------|----------|-------------------------|-------------------------|-------------------------|-------------------------|--------------------------|--------------------------|-------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 210306475 | 210306475       | 4        | 903      | RGB RGB RGB RC          | RGB RC                  | RGB RC                  | RGB RC                  | 28.550                   | 2.25                     | 3.620                   | 0.010                      | 30.135                      | 0.733                       | 0.157                       | 26.900                    |
| 210307958 | 210307958       | 4        | 2771     | RGB RC                  | RC RC                   | RGB RC                  | RGB RC                  | 27.940                   | 2.47                     | 3.890                   | 0.290                      | 30.165                      | 0.713                       | 0.124                       | 29.260                    |
| 210314854 | 210314854       | 4        | 1651     | RGB RGB RGB RC RGB RGB | RGB RC                  | RGB RC                  | RGB RC                  | 24.800                   | 1.88                     | 3.270                   | 0.040                      | 25.080                      | 0.841                       | 0.076                       | 24.900                    |
| 210315825 | 210315825       | 4        | 1051     | RGB RGB RGB RGB RGB RGB | RGB RC                  | RGB RC                  | RGB RC                  | 24.800                   | 1.88                     | 3.270                   | 0.040                      | 25.080                      | 0.841                       | 0.076                       | 24.900                    |

Note. The “raw” asteroseismic parameters returned by a given pipeline, along with their uncertainties, without the rescaling described in Section 3 being applied. Evolutionary states are also given for stars with both $\langle \nu_{\text{max}} \rangle$ and $\langle \Delta\nu \rangle$ values (EV), as well for individual pipeline values (A2Z EV, BAM EV, etc.); see the text for details. If classified, a star’s evolutionary state is assigned as “RGB,” “RGB/AGB,” or “RC.” “Priority” refers to the K2 GAP target priority for a given K2 campaign, which is discussed in Section 2 (a smaller numerical value corresponds to a higher priority); serendipitous targets do not have a populated priority entry. “ID” is a unique combination of the EPIC ID and the campaign from which the measurements come (some stars were observed during multiple campaigns).

(This table is available in its entirety in machine-readable form.)
Table 7
Numbers of Stars with Raw Asteroseismic Values ($\nu_{\text{max}}$, $\Delta \nu$), Rescaled Asteroseismic Values ($\nu'_{\text{max}}$, $\Delta \nu'$), and Radius and Mass Coefficients ($R_k'$, $M_k'$), as a Function of Pipeline and Campaign

| Pipeline | $\nu_{\text{max}}$ | $\nu'_{\text{max}}$ | $\Delta \nu$ | $\Delta \nu'$ | $R_k'$ | $M_k'$ |
|----------|-------------------|-------------------|-------------|-------------|--------|--------|
| A2Z      | 672               | 541               | 672         | 0           | 541    | 541    |
| A2Z      | 2326              | 993               | 1932        | 0           | 833    | 833    |
| A2Z      | 1418              | 834               | 1042        | 0           | 636    | 636    |
| A2Z      | 1966              | 1272              | 1536        | 0           | 1116   | 1116   |
| A2Z      | 3088              | 2088              | 2398        | 0           | 1761   | 1761   |
| A2Z      | 1086              | 1311              | 1086        | 0           | 1215   | 1215   |
| A2Z      | 993               | 835               | 293         | 0           | 224    | 224    |
| A2Z      | 1254              | 718               | 959         | 0           | 581    | 581    |
| A2Z      | 1660              | 832               | 1213        | 0           | 629    | 629    |
| A2Z      | 1359              | 670               | 1058        | 0           | 540    | 540    |
| A2Z      | 1717              | 866               | 1280        | 0           | 678    | 678    |
| A2Z      | 2393              | 1578              | 1924        | 0           | 1304   | 1304   |
| A2Z      | 1571              | 799               | 1138        | 0           | 621    | 621    |
| A2Z      | 3777              | 2598              | 2906        | 0           | 2055   | 2055   |
| A2Z      | 2685              | 1621              | 2025        | 0           | 1388   | 1388   |
| A2Z      | 1913              | 1173              | 1458        | 0           | 1016   | 1016   |
| A2Z      | 423               | 230               | 323         | 0           | 221    | 221    |
| Total A2Z| 30301             | 17291             | 23243       | 0           | 13827  | 13827  |
| A2Z      | 948               | 698               | 757         | 457         | 457    | 457    |
| C2       | 2591              | 1030              | 361         | 264         | 264    | 264    |
| CAN      | 1105              | 778               | 582         | 482         | 482    | 482    |
| C2       | 1116              | 816               | 494         | 433         | 433    | 433    |
| C3       | 1261              | 817               | 1003        | 739         | 739    | 739    |
| C3       | 1304              | 810               | 610         | 610         | 610    | 610    |
| C3       | 1000              | 612               | 874         | 515         | 515    | 515    |
| C3       | 1181              | 854               | 1104        | 753         | 753    | 753    |
| C3       | 1975              | 1548              | 1851        | 1326        | 1326   | 1326   |
| C3       | 1261              | 817               | 1003        | 739         | 739    | 739    |
| C3       | 3032              | 2497              | 2817        | 2250        | 2250   | 2250   |
| C3       | 1814              | 1581              | 1633        | 1336        | 1336   | 1336   |
| C3       | 780               | 1039              | 733         | 884         | 884    | 884    |
| C3       | 297               | 235               | 260         | 191         | 191    | 191    |
| Total BHM| 28791             | 18049             | 23297       | 16014       | 16014  | 16014  |
| C3       | 1105              | 778               | 582         | 482         | 482    | 482    |
| C3       | 1609              | 948               | 616         | 503         | 503    | 503    |
| C3       | 1116              | 816               | 494         | 433         | 433    | 433    |
| C3       | 1897              | 1204              | 968         | 793         | 793    | 793    |
| C3       | 2530              | 2030              | 1559        | 1458        | 1458   | 1458   |
| C3       | 1956              | 1514              | 1455        | 1273        | 1273   | 1273   |
| C3       | 1564              | 1083              | 1048        | 879         | 879    | 879    |
| C3       | 935               | 713               | 785         | 606         | 606    | 606    |
| C3       | 1234              | 840               | 1093        | 679         | 679    | 679    |
| C3       | 1000              | 612               | 874         | 515         | 515    | 515    |
| C3       | 1181              | 854               | 1104        | 753         | 753    | 753    |
| C3       | 1975              | 1548              | 1851        | 1326        | 1326   | 1326   |
| C3       | 958               | 755               | 854         | 677         | 677    | 677    |
| C3       | 3032              | 2497              | 2817        | 2250        | 2250   | 2250   |
| C3       | 1814              | 1581              | 1633        | 1336        | 1336   | 1336   |
| C3       | 780               | 1039              | 733         | 884         | 884    | 884    |
| C3       | 297               | 235               | 260         | 191         | 191    | 191    |
| Total CAN| 24983             | 17386             | 18726       | 13650       | 13650  | 13650  |
| C3       | 777               | 681               | 777         | 610         | 610    | 610    |
| C3       | 1635              | 960               | 1635        | 930         | 930    | 930    |
| C3       | 1022              | 757               | 1022        | 699         | 699    | 699    |
| C3       | 1803              | 1233              | 1803        | 1177        | 1177   | 1177   |
| C3       | 2526              | 1953              | 2526        | 1774        | 1774   | 1774   |

Table 7 (Continued)
being valid, the more results deviating strongly from the truth are reported.

The above exercise tests the internal consistency of the uncertainties reported by each pipeline, but, by comparing the reported uncertainties to the scatter in the pipeline values for each star, \( \sigma_\nu \) and \( \sigma_\Delta \nu \), we can better establish the accuracy of the pipeline uncertainties. Indeed, even if a pipeline consistently assigns uncertainties to \( \nu_{\text{max}} \) and \( \Delta \nu \), these uncertainties do not necessarily correspond to the true uncertainties—i.e., including systematic uncertainties—in the physical parameters: each pipeline’s methodology is for its own system, and measures \( \nu_{\text{max}} \) and \( \Delta \nu \) in slightly different ways. This can be seen to the extent that the scaling factors for each pipeline, \( X_{\nu_{\text{max}}} \) and \( X_{\Delta \nu} \), differ from unity, indicating that the pipelines measure asteroseismic values on scales that differ by up to 1%. Even after correction to the mean scale, the top panels of Figures 8–11 show that there are

### Table 7 (Continued)

|   | \( \nu_{\text{max}} \) | \( \nu'_{\text{max}} \) | \( \Delta \nu \) | \( \Delta \nu' \) | \( \kappa_{\nu} \) | \( \kappa_{\Delta \nu} \) |
|---|----------------|----------------|----------|--------|----------------|----------------|
| C6 | COR 1443 1404 | 1443 1286 | 1286    | 1286 |
| C7 | COR 1561 1162 | 1561 1127 | 1127    | 1127 |
| C8 | COR 955 681 | 955 617 | 617     | 617 |
| C10 | COR 1449 824 | 1449 737 | 737     | 737 |
| C11 | COR 1048 201 | 1048 164 | 164     | 164 |
| C12 | COR 1309 2151 | 1309 740 | 740     | 740 |
| C13 | COR 1879 | 1470 1389 | 1389    | 1389 |
| C14 | COR 1034 755 | 1034 699 | 699     | 699 |
| C15 | COR 2944 2432 | 2944 2342 | 2342    | 2342 |
| C16 | COR 1833 | 1490 1323 | 1323    | 1323 |
| C17 | COR 1368 955 | 1368 617 | 617     | 617 |
| C18 | COR 265 265 | 265 164 | 164     | 164 |
| Total | COR 24851 | 17019 | 15850 | 15850 |
| C1 | SYD 558 490 | 472 418 | 418     | 418 |
| C2 | SYD 1290 684 | 486 397 | 397     | 397 |
| C3 | SYD 1066 | 752 588 | 588     | 588 |
| C4 | SYD 2151 | 1270 670 | 670     | 670 |
| C5 | SYD 2627 | 2001 1515 | 1515    | 1515 |
| C6 | SYD 2232 | 1472 743 | 743     | 743 |
| C7 | SYD 1678 | 1088 481 | 481     | 481 |
| C8 | SYD 937 | 681 518 | 518     | 518 |
| C10 | SYD 1138 | 715 385 | 385     | 385 |
| C11 | SYD 1583 | 699 378 | 378     | 378 |
| C12 | SYD 1097 | 751 511 | 511     | 511 |
| C13 | SYD 2007 | 1519 1103 | 1103    | 1103 |
| C14 | SYD 1079 | 768 586 | 586     | 586 |
| C15 | SYD 3128 | 2492 1819 | 1819    | 1819 |
| C16 | SYD 1886 | 1598 1184 | 1184    | 1184 |
| C17 | SYD 598 | 1091 629 | 629     | 629 |
| C18 | SYD 266 | 232 183 | 183     | 183 |
| Total | SYD 25321 | 16688 | 11080 | 11080 |

---

**Figure 2.** Kiel diagram of K2 GAP DR3, with stars colored red (blue) if they are classified as RGB stars (RC stars). The purple curves delineate the 38% and 68% contours for RC stars, to enhance clarity of the RGB bump (indicated by the arrow). The surface gravity is calculated using the EPIC temperature in combination with \( \nu_{\text{max}} \) according to Equation (1). The spread in temperature of the red clump is caused in part by its intrinsic width—set by population-level variations in metallicity, mass, and age—and also by the EPIC temperature uncertainty, which is indicated by the typical error bar indicated in the lower right.

**Figure 3.** The distribution of K2 GAP DR3 stars (i.e., GAP targets with \( \nu_{\text{max}} \), as defined in Section 3.2), shown in Galactocentric coordinates. The Sun’s position of \((X, Y, Z) = (-8.18, 0, 0.021 \text{ kpc})\) is marked as the black star, and is taken from a combination of the distance to Sgr A’ (Gravity Collaboration et al. 2019; X) and the Gaia DR2 Galactic disk velocity distribution symmetry analysis from Bennett & Bovy (2019; Z). The inner (outer) contour represents the 68th (99th) percentile of the plotted stars. Within these contours, the logarithmic density of the stars is indicated according to the color bar. Dashed circles indicate distances of 1, 5, and 10 kpc.
residual fractional deviations between the rescaled pipeline values and the mean values across pipelines, \( \nu_{\text{max}} \) and \( \nu_{\text{max}} \) as a function of \( \nu_{\text{max}} \) and \( \Delta \nu \). By adopting the scatter in asteroseismic values across the pipelines for our uncertainties in K2 GAP DR3, we take into account the uncertainties resulting from these differences in pipeline methodologies. We show comparisons between the internal uncertainties for each pipeline and the K2 GAP DR3 uncertainties in the right panels of Figures 8–11. The region above (below) the dotted lines is the regime where the pipeline-reported uncertainties are larger (smaller) than the K2 GAP DR3 adopted uncertainties. As found in DR2, the pipelines often agree on \( \Delta \nu \) and \( \nu_{\text{max}} \) better than would be expected from their internal uncertainties.

The uncertainties \( \sigma_{\nu_{\text{max}}} \) and \( \sigma_{\Delta \nu} \) do not explicitly take into account the reported measurement/statistical uncertainties of the pipelines, but, by virtue of \( \sigma_{\nu_{\text{max}}} \) and \( \sigma_{\Delta \nu} \) being defined based on the pipeline-to-pipeline scatter, they capture both systematic uncertainties in the pipeline methods and statistical measurement uncertainties: large bias in the pipeline results would tend to increase the pipeline-to-pipeline scatter, as would large measurement uncertainties. Even if we assume that the reported pipeline measurement uncertainties represent the true uncertainties, which is to varying degrees an inaccurate assumption (cf., Figure 7), it is not clear how the statistical uncertainties in the pipeline measurements should be combined in order to yield a purely statistical uncertainty in \( \nu_{\text{max}} \) and \( \Delta \nu \), which are averages of the pipeline measurements. This is because the pipelines will have some degree of correlation between their measurements, owing to all of the pipelines analyzing the same power spectrum for a given star (i.e., there is only one realization of the data). In order to estimate a purely statistical uncertainty on \( \nu_{\text{max}} \) and \( \Delta \nu \), we conservatively assume that all of the pipeline measurements are completely correlated, and compute the uncertainties on \( \nu_{\text{max}} \) and \( \Delta \nu \), which we report in Table 2 as \( \sigma_{\nu_{\text{max}}} \) and \( \sigma_{\Delta \nu} \). These latter uncertainties are larger than our adopted empirical uncertainties in this work, \( \sigma_{\nu_{\text{max}}} \) and \( \sigma_{\Delta \nu} \), by factors of \( \sim 2.2 \) and \( \sim 1.5 \), respectively. Assuming a correlation of 0.1 between all of the pipelines reduces the differences to \( \sim 1.2 \) and 0.95. Because the reported pipeline uncertainties are to varying degrees unreliable (Figure 7), and because of the unknown correlations between different pipeline measurements, these uncertainties are not used in this analysis, but are rather provided as a conservative indication of a purely statistical uncertainty compared to our adopted empirical uncertainties, \( \sigma_{\nu_{\text{max}}} \) and \( \sigma_{\Delta \nu} \).

We next estimate the completeness of each pipeline’s results by comparing the number of recovered stars to the total number of synthetic stars. The completeness fraction, where 1.0 indicates a perfect recovery rate, is shown as a function of \( \nu_{\text{max}} \), \( \Delta \nu \), radius, and mass in Figures 12–15. The synthetic sample was created with a range of S/Ns, and with magnitude-dependent noise consistent with K2 data, but the distribution of the synthetic sample is not, in detail, representative of the K2 GAP DR3 sample. For this reason, the completeness curves plotted in Figures 12–15 are indicative but not definitive of the completeness of the respective parameters in K2 GAP DR3. Note also that the completeness is defined with respect to Kepler results, so this completeness is, strictly speaking, an estimate of the completeness of recovering the K2 data with respect to Kepler, and not necessarily an absolute completeness estimate, which must await a future analysis using Gaia as a reference (e.g., by following the Kepler observation completeness analysis from Wolniewicz et al. 2021).

We see that the completeness curves are peaked in the middle of the parameter space for \( \nu_{\text{max}} \) and \( \Delta \nu \), with lower completeness at the high and low values of \( \nu_{\text{max}} \) and \( \Delta \nu \). This is understood to be related to the frequency resolution: detection of both \( \Delta \nu \) and \( \nu_{\text{max}} \) is limited on the lower end by the time baseline, and on the upper end by the sampling rate of the K2 observations. It is even more difficult to recover \( \nu_{\text{max}} \) and \( \Delta \nu \) at low values because of another effect: there are fewer modes that are excited at low \( \nu_{\text{max}} \), and they can be difficult to distinguish from noise, especially at the frequency resolution of K2. This latter effect is the reason why there is a marked decrease in completeness for \( \nu_{\text{max}} \lesssim 10 \mu \text{Hz} \). This incompleteness has been noted in previous data releases (Stello et al. 2017; Zinn et al. 2020), but we are able to robustly quantify it here for the first time: although it varies by pipeline, at least \( \sim 20\% \) of stars with \( \nu_{\text{max}} \lesssim 10 \mu \text{Hz} \) are not detected.

The completeness fractions in radius and mass space are not one-to-one mappings from \( \nu_{\text{max}} \) and \( \Delta \nu \), since, for a given surface gravity \( \nu_{\text{max}} \), there is a spread in mass (\( \Delta \nu \)). For this reason, we consider the radius and mass completeness curves separately from the \( \nu_{\text{max}} \) and \( \Delta \nu \) cases. The completeness of radius suffers from a drop-off in recovery with increasing radius, due to incompleteness of \( \nu_{\text{max}} \) and \( \Delta \nu \) at lower frequencies. Given the lack of a strong correlation between
radius and age for the giant branch (since the majority of a red giant’s lifetime is spent on the main sequence, as opposed to climbing the giant branch), the drop-off in recovery with increasing radius does not require a selection function correction in age space, but it does have implications for a selection function correction as a function of distance. The completeness curves are much less peaked in mass space. This is of particular interest for Galactic archeology applications of K2 GAP DR3: were completeness a strong function of mass, it would require special treatment in the selection function. There is a tendency for low-mass stars to be underrepresented in some pipelines, for $M \lesssim 1.2 M_\odot$. This may be relevant for detailed studies, since this will map onto an underrepresentation of older stars. Regarding the completeness of the underlying K2 GAP sample itself, typically 97% of the proposed targets in any given campaign were observed, with the targets following simple color–magnitude cuts (S. Sharma et al. 2021, in preparation).

Figure 5. Binned medians and uncertainties on the median of the fractional difference between Kepler and synthetic K2 $\nu_{\text{max}}$ (top) and $\Delta \nu$ (bottom) values for each pipeline contributing results to K2 GAP DR3, according to the legend. The deviations from the dashed line indicate that the pipeline returns K2 values that are on a different scale than the pipeline’s Kepler results (labeled as $\nu_{\text{max,K2}}$ and $\nu_{\text{max,Kp}}$, (top) and $\Delta \nu_{\text{K2}}$ and $\Delta \nu_{\text{Kp}}$, (bottom), respectively).

Figure 6. Fractional difference between Kepler and synthetic K2 values, for each pipeline according to the legend, as a function of the synthetic K2 $S/N$. The differences are shown as binned medians and uncertainties on the medians. Trends as a function of $S/N$ would indicate that a pipeline’s asteroseismic values are noise-dependent.

Figure 16(a) is indicative of the mass distribution for those stars in the K2 GAP DR3 sample with both $\nu_{\text{max}}$ and $\langle \Delta \nu \rangle$, where the ordinate is an asteroseismic proxy for mass proposed by Huber et al. (2010) that scales like $M^{0.25}$, given the asteroseismic scaling relations (Equations (3) and (4)). For reference, Figure 16(b) shows the Kepler sample from Yu et al. (2018). Comparing the Kepler and K2 samples, we find a good correspondence, with a couple of differences worth noting. First, the right edge of the clump is better defined in the Kepler data, by virtue of having greater precision and more high-mass secondary RC stars. The Kepler sample also extends to higher frequencies than K2 GAP DR3, presumably as a result of better
noise properties in Kepler compared to K2. However, K2 has double the fraction of low-frequency ($<20 \mu$Hz) oscillators than Kepler, in spite of the tendency to not recover stars in this frequency regime with K2-like time baselines (Figure 12). Note that the overall shift in mass between the Yu et al. (2018) and K2 GAP DR3 samples is consistent with the time baseline systematics in $\nu_{\text{max}}$ (Figure 5), such that the SYD Kepler $\nu_{\text{max}}$ values would be expected to be larger by $\sim$1% than the K2 $\nu_{\text{max}}$ values.

As with Figure 16(a), Figure 17 shows the K2 GAP DR3 stars in the mass proxy versus $\nu_{\text{max}}$ space, but for each pipeline, and separately for raw pipeline results ($\nu_{\text{max}}$, $\Delta \nu$; left panels) and rescaled pipeline values ($\nu_{\text{max}}'$, $\Delta \nu'$; right panels). The structures of the distributions in this space are generally similar across pipelines, though there are differences in detail. For instance, we see that there are some pipeline-dependent differences in the recovery of low-mass RC stars and the recovery of low-frequency stars. There are also differences between the raw and rescaled values, the most salient of which are that (1) raw values have more scatter in the ordinate (due to the requirement for more than one pipeline to return results in order to define the rescaled values, which tends to favor stars with more precise asteroseismic values); and (2) there tend to be fewer low-frequency and high-frequency rescaled values (a selection effect of it being less likely for multiple pipelines to return values for stars affected by K2’s white noise and time baseline). The diagonal ridge on the left side of the RC distribution is due to the requirement that stars with $\Delta \nu < 3.2$ be assigned an RGB evolutionary state (see Section 3.2). However, we see that this choice does not cut out true RC stars, which are found in the locus where the density of the blue points saturates.

4.2. Asteroseismic Calibration with Gaia

In Section 3, we indicated that it is important to use appropriate solar reference values in accordance with the asteroseismic pipeline that is being used. The K2 GAP DR3 values are averages across pipelines, so the question arises as to what solar reference value scale is appropriate. One proposal
would be to adopt the solar reference values from APOKASC-2 (Pinsonneault et al. 2018), $\nu_{\max,\odot} = 3076 \mu$Hz and $\Delta\nu_{\odot} = 135.146 \mu$Hz, given that APOKASC-2 values are also averages across pipelines. Although we follow a very similar methodology of placing the pipeline values on a common scale, it differs in some regards (e.g., sigma clipping and not weighting pipeline values by their uncertainties during the averaging process). We include results from BAM as well, which was not a pipeline that was considered in Pinsonneault et al. (2018). For this reason, we cannot assume that $\langle \nu_{\max}' \rangle$ and $(\Delta \nu')$ are on the same scale as defined by Pinsonneault et al. (2018) just because we use the solar reference values from the cluster calibration procedure in Pinsonneault et al. (2018). It is also possible that the difference between Kepler versus K2 observation durations results in systematically different parameter measurements (see Section 4.1).

With this in mind, in what follows we calibrate the K2 GAP DR3 $\langle \nu_{\max}' \rangle$ values by using a nonunity, scalar $f_{\nu_{\max}'}$ (Section 3); or, equivalently, by rescaling the APOKASC-2 $\nu_{\max,\odot}$ value. Our Gaia calibration sample is the subset of stars
in the K2 GAP DR3 sample with \( \langle \nu'_{\text{max}} \rangle \) and \( \langle \Delta \nu' \rangle \) that have APOGEE DR16 (Ahumada et al. 2020) temperatures and metallicities, and Gaia parallaxes and proper motions from Gaia Data Release 2 (Gaia Collaboration et al. 2018; Lindegren et al. 2018).

With the known zero-point offset in Gaia parallax (e.g., Lindegren et al. 2018; Khan et al. 2019; Zinn et al. 2019a) in mind, we appeal to the methodology described in Schönrich et al. (2019), which infers distances in Gaia-based bulk stellar motions. This method can be sensitive to the selection function of the stellar population, and so we take care to model the selection function of the GAP targets according to Schönrich & Aumer (2017). The resulting parallax zero-points show a scatter of \( \sim 10 \mu \text{as} \) across the campaigns, comparable to the positional variation found by Chan & Bovy (2020) and Khan et al. (2019).

We perform the calibration using a subset of the Gaia–APOGEE–K2 overlap, knowing that there are certain known systematics that could bias the calibration. First, we limit the impact of parallax zero-points by only working with stars with raw Gaia parallaxes of \( \pi > 0.4 \) mas, parallax uncertainties of less than 10\%, and Gaia G-band magnitudes \(< 13 \) mag, out of an abundance of caution, in light of the indications of parallax- and magnitude-dependent offsets (Schönrich et al. 2019; Zinn et al. 2019a). We also reject metal-poor stars \([\text{Fe/H}] < -1 \) from subsequent analysis, since there are also indications that asteroseismic scaling relation systematics could exist in the metal-poor regime (Zinn et al. 2019b; Epstein et al. 2014;
though see also Kallinger et al. 2018). We further reject stars that are highly evolved \((R > 3.0R_\odot)\), in order to avoid potential systematics in the asteroseismic scale in the luminous regime (Mosser et al. 2013; Stello et al. 2014; Kallinger et al. 2018; Zinn et al. 2019b). Finally, we reject from consideration 12 RGB and 2 RC stars that have asteroseismic and Gaia radius disagreements by more than 3\(\sigma\), leaving 841 RGB and 214 RC stars for calibration. Since this sample includes APOGEE spectroscopic abundances, we also modify the \(f_{\Delta\nu}\) for our calibration sample, by adjusting the metallicity that goes into computing \(f_{\Delta\nu}\) to account for nonsolar \(\alpha\) abundances according to the Salari et al. (1993) prescription.

The Gaia radii are computed following the procedure from Zinn et al. (2017), wherein a bolometric flux, Gaia parallax, and APOGEE effective temperature are combined using the Stefan–Boltzmann law. We use a \(K_s\)-band bolometric correction (González Hernández & Bonifacio 2009) to minimize extinction effects, and employ the three-dimensional dust map of Green et al. (2015), as implemented in mwdust (Bovy et al. 2016).

We see in Figure 18 similar trends as we saw in K2 GAP DR2 (Zinn et al. 2020): there is an overestimation of the asteroseismic radii compared to Gaia at and below \(R \approx 8R_\odot\) among RGB stars.

The strong trend of radius agreement for the RC stars is of astrophysical interest, particularly given constraints on mass loss (e.g., Miglio et al. 2012; Kallinger et al. 2018) that rely on the accuracy of asteroseismic scaling relations for the RC stars. However, as we noted in Zinn et al. 2020, the trend seems to be mostly a function of \(\Delta\nu\), and it may therefore be related to inadequacies in the red clump stellar structure models that underpin theoretical \(f_{\Delta\nu}\) calculations (An et al. 2019). It is beyond the scope of the present work to further examine the cause of the discrepancy, but developments in terms of better understanding this behavior in the RC stars are in preparation.

We calibrate our K2 GAP DR3 asteroseismic values to be on the Gaia parallactic scale by adopting the following:

\[
\Delta \nu_{\text{max}} = \langle R_{\text{Gaia}} / R_{\text{Gaia}0} \rangle = \frac{\sum R_{\text{max}} / \sigma_R}{\sum 1 / \sigma_R},
\]

where \(\sigma_R = \sqrt{\left(\frac{\langle R_{\text{Gaia}} / R_{\text{Gaia}0} \rangle - \langle R_{\text{max}} / R_{\text{Gaia}0} \rangle}{\langle R_{\text{Gaia}0} \rangle}\right)^2 + \left(\frac{\langle R_{\text{max}} / R_{\text{Gaia}0} \rangle}{\langle R_{\text{Gaia}0} \rangle}\right)^2} \).

We do this separately for RGB and RC stars, finding \(f_{\Delta\nu,\text{RGB}} = 1.017 \pm 0.001\) and \(f_{\Delta\nu,\text{RC}} = 1.008 \pm 0.003\). This can be thought of as a rescaling of the solar reference value, \(\nu_{\text{max},\odot}\), though, for convenience, we apply this correction directly to the \(\langle \nu'_{\text{max}} \rangle\), \(\langle \kappa_R \rangle\), and \(\langle \kappa_M \rangle\) values provided in Table 2, and thus when working with \(\langle \nu'_{\text{max}} \rangle\), the K2 GAP DR3 \(\nu_{\text{max},\odot}\) value given in Table 1 should be used, which is the same as that from Pinsonneault et al. (2018). Even after accounting for this \(f_{\Delta\nu}\), the uncertainty in the \(f_{\Delta\nu}\) becomes a systematic uncertainty in the \(\langle \kappa_R \rangle\) and \(\langle \kappa_M \rangle\) scales, viz., 0.1% and 0.3% in \(\langle \kappa_R \rangle\) and \(\langle \kappa_M \rangle\) for RGB stars and 0.3% and 0.9% for RC stars. Note that it is possible that a scalar correction of \(\langle \Delta\nu' \rangle\) is required as well. We therefore conservatively treat the uncertainty in \(f_{\Delta\nu}\) as an uncertainty in a scalar contribution to \(f_{\Delta\nu}^2\), given that our calibration of the asteroseismic radius, which scales as \(f_{\nu_{\text{max}}^{-1}} f_{\Delta\nu}^2\), (Equation 6), is formally a calibration of the quantity \(f_{\nu_{\text{max}}^{-1}} f_{\Delta\nu}^2\). This implies a systematic uncertainty in \(\langle \Delta\nu' \rangle\) of 0.05% and 0.15% for RGB stars and RC stars, respectively. As discussed in Zinn et al. (2019b), there are additional systematics in the asteroseismology–Gaia radius comparison that could amount to about \(\pm 2\%\) in \(f_{\Delta\nu}\), and that are due to intrinsic uncertainties in the bolometric correction scale, the temperature scale, and the spatial correlations in Gaia parallaxes.

On balance, the modest corrections required to bring the asteroseismic data onto the Gaia parallactic scale support previous findings that the asteroseismic scaling relations are

\[
\sum 1 / \sigma_R,
\]

\[
\langle R_{\text{Gaia}} / R_{\text{Gaia}0} \rangle = \frac{\sum R_{\text{max}} / \sigma_R}{\sum 1 / \sigma_R},
\]

\[
\Delta \nu_{\text{max}} = \langle R_{\text{Gaia}} / R_{\text{Gaia}0} \rangle = \frac{\sum R_{\text{max}} / \sigma_R}{\sum 1 / \sigma_R},
\]
accurate to within a few to several percent on the lower giant branch (e.g., Huber et al. 2012; Silva Aguirre et al. 2012; Hall et al. 2019; Khan et al. 2019; Zinn et al. 2019b). With the assurance that the K2 GAP DR3 asteroseismic masses are well calibrated, we now turn to applications of those data to age-abundance patterns.

5. Age-abundance Patterns in K2 GAP DR3

5.1. Notes on GALAH Abundances

Our examination of age-abundance patterns makes use of GALAH DR3 (Buder et al. 2021) abundances for stars targeted as part of the K2-HERMES (Wittenmyer et al. 2018) program. Although our asteroseismic calibration uses APOGEE temperatures and metallicities for deriving asteroseismic radii (Section 4.2), we note that calibration using GALAH spectroscopic parameters instead results in an equivalent $f_{\text{max,n}}$ to within uncertainties. We opt to use GALAH abundances in what follows because (1) there are neutron-capture element lines in the optical unavailable to APOGEE’s infrared bandpass, and (2) GALAH abundances are corrected for non-LTE effects for the elements H, Li, C, O, Na, Mg, Al, Si, K, Ca, Mn, Fe, and Ba. On the latter point, non-LTE spectral analysis seems especially important for bringing into agreement dwarf and giant abundances at fixed metallicities within $\sim 0.05$ dex (Amarsi et al. 2020), though some systematics at the 0.1–0.2 dex level may remain for Al, Ba, and $\alpha$ elements, which are mentioned below.

We note that APOGEE DR16 temperatures and GALAH DR3 temperatures for RGB stars differ by $\approx 30$ K, in the sense that APOGEE temperatures tend to be hotter. This difference is at the same level as the intrinsic uncertainty in the APOGEE temperature scale, which is set by the accuracy of the infrared flux method temperature scale for red giants (e.g., Alonso et al. 1999; González Hernández & Bonifacio 2009). The metallicity scales of the two systems differ by $\approx -0.05$ dex, in the sense that APOGEE is more metal-rich. The combined effect of these small offsets means that the asteroseismic parameter calibration performed with APOGEE temperatures in Section 4 is consistent to within systematic uncertainties of $f_{\text{max,n}}$, and thus the calibrated parameters are suitable for the following analysis using GALAH temperatures.

It should also be noted that scattering on background opacities was not included in the GALAH DR3 non-LTE calculations. Background scattering may affect giant abundances at the 0.01dex level for elements other than C, Mg, Ca, and Mn, which can have larger effects due to background scattering at lower metallicities (e.g., Hayek et al. 2011). Among metal-poor giants, Mg, Ca, and Mn may thus be underestimated by up to 0.05 dex for stars with $[\text{Fe/H}] < -2$ (Amarsi et al. 2020).
5.2. Benchmark Galactic Chemical Evolution Model

We compare our age-abundance patterns to the fiducial abundance models of Kobayashi et al. (2020a, hereafter K20). The models use nucleosynthetic yields from CCSNe, SNe Ia, AGB stars, and neutron star mergers, which are discussed as relevant in the discussion that follows. The K20 models assume a one-zone enrichment model, wherein mixing of the interstellar medium is instantaneous, and there is pristine gas inflow. The infall rate and star formation efficiency are chosen to match the metallicity distribution function of the solar neighborhood. For the solar neighborhood model considered here, there is assumed to be no gas outflow. K20 assume single-degenerate SNe Ia, where the total number of SNe is determined from the O/Fe slope. The fraction of main sequence + white dwarf to RGB + white dwarf progenitors is
Bayesian framework using BSTEP (Sharma et al. 2018), a Bayesian stellar parameter estimator that may incorporate asteroseismic parameters, \( \nu_{\text{max}} \) and \( \Delta \nu \), which essentially constrain the mass of the star and therefore its main sequence lifetime. Further details regarding the BSTEP ages used in this work are available in Sharma et al. (2021) (see also Buder et al. 2021). In what follows, we only use the stars that BSTEP classifies with high confidence as RGB, given uncertainties on RC ages due to mass loss (e.g., Casagrande et al. 2016).

5.4. \([\text{Mg}/\text{H}]\) versus \([\text{Fe}/\text{H}]\) Space

We begin by dividing our sample into high- and low-\( \alpha \) samples, following the high-\( \alpha \) boundary from Weinberg et al. (Weinberg et al. 2019; hereafter, W19):

- for \([\text{Fe}/\text{H}] < 0\): \([\text{Fe}/\text{Mg}] > 0.12 - 0.13|\text{Fe}/\text{H}|\),
- for \([\text{Fe}/\text{H}] > 0\): \([\text{Fe}/\text{Mg}] > 0.12\).

The above division was initially used for stars with APOGEE abundances, but it has subsequently been used successfully to divide GALAH DR2 (Buder et al. 2018) abundances into high- and low-\( \alpha \) populations by Griffith et al. (2019; hereafter, GJW19), who recently interpreted both APOGEE and GALAH DR2 abundance ratios in the context of Galactic chemical evolution. Following the example of GJW19, we also restrict analysis to those stars with effective temperatures between 4500 and 6200 K, which avoids blending in cool stars from molecular lines and highly broadened lines in fully radiative stars.

We believe there is some contamination from genuinely \( \alpha \)-poor stars that, by virtue of their abundance uncertainties, scatter into the high-\( \alpha \) selection (and vice versa). For this reason, we require each star’s 2D uncertainty ellipse to have more than 95% of its density on one side or the other of the high-\( \alpha \)/low-\( \alpha \) division line. In order to construct the 2D uncertainty ellipse, we assume a uniform correlation between \([\text{Fe}/\text{H}]\) and [Mg/Fe]. The Pearson correlation coefficient between \([\text{Fe}/\text{H}]\) and [Mg/Fe] is observed to be \( \sim -0.4 \), though the precise value adopted does not significantly affect our results. We also require stars to have \([\text{Fe}/\text{H}] > -1\) at 95% confidence, since the metal-poor stellar population is likely populated by accretion (e.g., Belokurov et al. 2018; Haywood et al. 2018), rather than in situ formation, as the K20 models assume. The resulting division of the GALAH abundances is demonstrated in Figure 19, where each star is colored by its age. The high-\( \alpha \)/low-\( \alpha \) division line is shown in black. The gray curve represents the raw K20 \([\text{Fe}/\text{H}]\)–[Mg/Fe] trend, which has been shifted by a scalar offset in \([\text{Fe}/\text{H}]\) and a scalar offset in [Mg/Fe] to reflect the same solar abundance scale used by GALAH DR3—see Table A2 of Buder et al. (2021).35 The segmented blue curve represents the K20 \([\text{Fe}/\text{H}]\)–[Mg/Fe] trend, rescaled by an additive offset in Mg such that the median predicted [Mg/Fe] agrees with the median observed [Mg/Fe]. The band around the curve corresponds to a 1σ uncertainty in the Asplund et al. (2009) solar abundances, which are used in the K20 models for abundance normalization.35

The sample consists of 396 high-\( \alpha \) stars and 208 low-\( \alpha \) stars, with typical uncertainties of 20%–30% in age.36 The ages for

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34 Where possible, we adopt the “composite” abundance normalizations listed in Table A2 of Buder et al. (2021) and, otherwise, the average of a given element’s line-by-line normalizations.

35 The exception is O, whose solar abundance is taken to be \( A_(O) = 8.76 \pm 0.02 \) (Steffen et al. 2015).
The transparency of the binned weighted means of the data emphasizes where uncertainties in the solar abundances from Asplund et al. 2009

The Galactic chemical evolution model from K20 is shown before (gray dotted curve) and after (blue segmented curve) an additive correction to [Mg/Fe] to enforce agreement with the median [Mg/Fe] of the observed stars. The region around the blue segmented curve reflects the 1σ uncertainty in the K20 abundance normalization, taken to be the uncertainties in the solar abundances from Asplund et al. (2009). The transparency of the binned weighted means of the data emphasizes where the K20 models track the high-α stars ([Fe/H] ≤ −0.3 and τ ≥ 8 Gyr) and the low-α stars ([Fe/H] ≥ −0.3 and τ ≤ 8 Gyr).

We show in Figures 21–29 abundance ratios ([X/Fe] versus [Fe/H] or [X/Mg] versus [Mg/H]) and age-abundance patterns/enrichment histories ([X/Fe] versus stellar age or [X/Mg] versus stellar age) for different nucleosynthetic families of elements. A running weighted average of the data is shown as colored error bars connected by lines, with green indicating the low-α population and orange indicating the high-α population. Not plotted are stars with flagged GALAH DR3 abundance measurements in [Fe/H] or in [X/Fe]. As mentioned above, the extent to which the low-α (green curves) pattern is above the high-α (orange curves) pattern in [X/Mg]–[Mg/H] space is generally indicative of a nucleosynthetic production site.

Regarding how to compare the K20 models with the data in these figures, we note that at young and intermediate ages, the K20 models may be best interpreted as a low-α population, while they represent a high-α population at old ages. Because the K20 models are one-zone models, there is a one-to-one mapping of age to abundance, which is not necessarily the case in the data. To guide the eye, we therefore highlight in Figure 19 and subsequent figures where the data should be compared to the models: bold curves indicate solidly old/metal-poor high-α stars or young/metal-rich low-α stars.

36 These are the number of stars with Mg and Fe measurements, which are necessary to define the high-α and low-α stars. Note that not all of these stars have abundance measurements for every element that we consider in what follows.
which are comparable to the K20-modeled populations shown in blue, whereas light curves indicate apparent young high-α or old low-α populations that are not directly comparable to the K20 models. To evaluate the agreement of the models with the data for older, high-α stars, we make reference here and in what follows to a single weighted average of the high-α abundances (which can be seen as a single orange error bar in the following figures), since the width of the high-α age distribution is dominated by uncertainties, and has a central value of \( \approx 9 \) Gyr.

Table 8

K2 GAP DR3 Ages with GALAH Spectroscopy

| EPIC ID     | object_id | \( \tau \) Gyr | \( \sigma_\tau \) Gyr | [Fe/H] | \( \sigma_{[Fe/H]} \) | [Mg/Fe] | \( \sigma_{[Mg/Fe]} \) | \( T_{\text{eff}} \) K | \( \sigma_{T_{\text{eff}}} \) K | \( \alpha_{\text{hi}} \) |
|------------|-----------|-----------------|------------------------|--------|---------------------|---------|---------------------|-------------------|-------------------|----------------|
| 220387110  | 161007003801220 | 7.7              | 1.8                    | -0.2   | 0.1                 | 0.2     | 0.1                 | 4691              | 91                | ...            |
| 220352927  | 161007003801158 | 11.1             | 1.5                    | -1.3   | 0.1                 | 0.1     | 0.1                 | 4883              | 124               | ...            |
| 220420379  | 161007003801285 | 5.2              | 2.9                    | -0.6   | 0.1                 | 0.3     | 0.2                 | 4705              | 136               | ...            |
| 220329169  | 161007003801110 | 4.1              | 0.7                    | -0.3   | 0.1                 | 0.1     | 0.1                 | 4864              | 95                | ...            |
| 220425435  | 161007003801301 | 9.2              | 2.7                    | -1.6   | 0.2                 | 0.1     | 0.2                 | 5060              | 174               | ...            |
| 220377647  | 161007003801390 | 4.2              | 0.9                    | -0.4   | 0.1                 | 0.2     | 0.1                 | 4995              | 116               | ...            |
| 220382480  | 161007003801378 | 10.8             | 1.7                    | -0.7   | 0.2                 | 0.2     | 0.2                 | 5085              | 190               | ...            |
| 220392564  | 161007003801360 | 6.6              | 2.5                    | -0.9   | 0.1                 | 0.3     | 0.2                 | 4791              | 137               | ...            |
| 220408286  | 161007003801353 | 6.0              | 4.0                    | -0.2   | 0.1                 | 0.1     | 0.1                 | 4770              | 111               | ...            |
| 220272081  | 16100604401209   | 9.1              | 3.0                    | -0.6   | 0.1                 | 0.4     | 0.1                 | 4559              | 87                | 1              |

Note. Ages, GALAH metallicities, [Mg/Fe], and effective temperatures for the subset of the K2 GAP DR3 sample with GALAH data. object_id is the GALAH observation ID, which may be used to crossmatch with the GALAH catalogs. \( \alpha_{\text{hi}} \) is 1 (0) if the star has GALAH abundances indicative of a high-α (low-α) star at 2σ confidence; if the classification is ambiguous, the entry is blank (see the text for details). A full version of this table is available in the online journal.

(\( \text{This table is available in its entirety in machine-readable form.} \))

5.5. \( \alpha \) Elements: O, Mg, Si, Ca, and Ti

Looking at O in Figure 21, it is clear that, after a global correction, the observed abundance ratios for \([\text{Fe/H}] > -1\) are in excellent agreement with the K20 model predictions. That the metallicity dependence of the O enrichment agrees with the observations is a built-in feature of the models: the K20 models are adjusted by tuning the total number of supernovae to agree with the observed O abundance metallicity dependence in the literature (K20). With age information in hand, however, we
can independently test the models. We see that the agreement is
good when looking at the low-\(\alpha\) \([\text{O}/\text{Mg}]\) trend as a function of
time up to \(\tau \sim 8\) Gyr, tracking Mg production, as an \(\alpha\) element
would. We see that the high-\(\alpha\) \([\text{O}/\text{Fe}]\) enrichment history is in
tension with the model predictions at 9 Gyr (orange error bar
versus blue curve). Given the agreement of the high-\(\alpha\)
population \([\text{O}/\text{Fe}]\) as a function of \([\text{Fe}/\text{H}]\), the disagreement
of \([\text{O}/\text{Fe}]\) for the high-\(\alpha\) population in age space suggests an
offset in the observed and predicted high-\(\alpha\) ages. A natural
solution would be to appeal to \(\alpha\)-enhanced stellar model
opacities. Indeed, Warfield et al. (2021) have demonstrated that
the increase in stellar opacities due to nonsolar \(\alpha\) abundances
can increase low-mass (old) stellar ages by ≈10%, by decreasing core temperature and extending a red giant’s main sequence lifetime. For the majority of the elements considered in what follows of Section 5, an increase in the high-α ages of that magnitude would improve the agreement between the data and the models. The global offset required to match the O abundances at high metallicities (blue curves versus gray dashed curves) could be due to the GALAH α element abundances O, Mg, and Si having residual offsets of 0.1 dex, in the sense that giants have larger [α/Fe] compared to dwarfs even after non-LTE corrections (Amarsi et al. 2020).

Both Ca and Si in Figure 21 show good agreement between the predicted and the observed enrichment history: the predicted enrichment history at ages τ ≲ 8 Gyr tracks the
observed trend (green curve) in [Mg/H] and [Fe/H] space. The models also predict [Si/Fe] at 9 Gyr consistent with the observed abundances of the old high-α population (orange error bar).

We consider Ti to be an α element, based on the findings in GJW19 that its production seems to be dominated by CCSNe contributions. Indeed, both the low-α and high-α curves share a similar [Ti/Mg] in Figure 21. At older ages, however, the observed high-α [Ti/Fe] abundances are in tension with the model predictions for 9 Gyr, which could be improved via older ages from the aforementioned α-enhanced stellar model opacities. Note that there is a large zero-point offset between the raw model abundances and the observed abundances (the offset to bring the raw model abundances into agreement with the observations is the difference between the gray dashed curves and the blue segmented curves), which is a generic feature of nucleosynthetic Ti yield predictions, and may be remedied by two- or three-dimensional supernovae models (K20).

5.6. Light Odd-Z Elements: Na, Al, and K

Production of odd-Z elements is thought to depend upon progenitor metallicity, because their assumed production during explosive nucleosynthesis in CCSNe depends crucially upon the neutron excess prior to the supernova, which itself is dependent upon CNO cycle efficiency and therefore initial metal content (e.g., Truran & Arnett 1971). The predictions of the nucleosynthetic models for these elements, therefore, are that (1) they should follow a CCSNe enrichment history (either a decreasing [X/Fe] with younger stellar ages or, equivalently, a constant [X/Mg] with stellar age); and (2) they should be less abundant with decreasing metallicity. In Figure 22, we show...
the light odd-Z elements’ abundance ratios and age-abundance patterns in order to test these predictions.

The DR3 GALAH [Na/Mg] abundance ratios show a positive metallicity trend, consistent with findings from GJW19 using GALAH DR2, and broadly consistent with the predicted metallicity slope from the K20 models. The enrichment history predictions appear to be consistent with the observations, across all of the ages probed (keeping in mind the lack of resolution in age space for the high-α stars, which, to within uncertainties, are drawn from a single age of ≈9 Gyr).

The strong negative metallicity gradient seen by GJW19 in [K/Mg] is less pronounced with non-LTE corrections to
GALAH DR3, and is in good agreement with the K20 models in [Fe/H] space. The absolute abundances from K20 for K, however, are well below the observed values (the gray dashed curve is below the plotted region), and this offset may be alleviated by appealing to, e.g., rotating stellar models (K20, and references therein). The predicted abundances at old stellar age are consistent with those observed among high-α at 9 Gyr.

The non-LTE GALAH DR3 corrections to Al reveal a strong metallicity trend, with [Al/Mg] not being found in the GALAH DR2 abundances, corroborating the positive trend found in the APOGEE abundances (GIW19). We confirm GIW19’s interpretation of Al being produced largely during CCSNe production, given the relatively small separation between the high- and low-α tracks (orange and green curves in [Mg/H] space) compared to, e.g., Na. These observations are both consistent with the theoretical predictions of significant metallicity-dependent Al production during explosive C burning (Truran & Arnett 1971). The observed and predicted enrichment histories are in disagreement. As with O, older high-α ages, resulting from α-enhanced stellar model opacities, could improve agreement at old ages. This adjustment would also bring Na and K into even better agreement at old ages. As with K, the absolute yields are severely underpredicted. This may very well be due to an overprediction of the abundances on the observational side: even after non-LTE corrections, the GALAH Al abundances for giants are larger than the abundances for dwarfs by 0.2 dex (Amarsi et al. 2020).

5.7. Iron-peak Elements

Following GIW19’s typology of iron-peak elements, we categorize the elements just beyond iron as cliff elements, which seem to have distinct properties from other iron-peak elements. First, we consider the odd-Z iron-peak elements, then the even-Z elements, and then, finally, the iron-peak cliff elements.

5.7.1. Odd-Z Iron-peak Elements: V, Mn, and Co

In this section, we discuss the odd-Z iron-peak element abundance patterns and enrichment histories, as shown in Figure 23. First, we confirm with GALAH DR3 the metallicity trends at high metallicities in V and Mn abundances, as noted by W19 and GIW19 using APOGEE and GALAH DR2 abundances, respectively. This metallicity-dependent effect is most pronounced in Mn, and is in excellent agreement with the model predictions of the trend, which are the result of Mn production occurring during deflagrations in the single-degenerate scenario (Kobayashi et al. 2020b). That the non-LTE Mn abundances from GALAH DR3 still show a metallicity dependence is in contrast to the decrease in metallicity dependence from LTE to non-LTE found in Battistini & Bensby (2016). The observed low-α V pattern agrees well with the K20-predicted [V/Mg] enrichment history, including at older ages, where the observed high-α abundances at 9 Gyr broadly agree with the predicted abundances. Nevertheless, the model abundances are uniformly vastly underpredicted compared to the observations before rescaling is applied (the gray dashed curves). This underprediction could be remedied, however, by using the yields from multidimensional supernovae yield predictions (K20).

The observed and predicted metallicity dependences for Mn are in very good agreement. The K20 models also reproduce well the enrichment history of [Mn/Mg] and [Mn/Fe] in the low-α regime. For the old high-α populations, however, both the [Mn/Mg] and [Mn/Fe] enrichment histories could be improved with older high-α ages resulting from α-enhanced stellar model opacities (thereby shifting the orange error bar at 9 Gyr to older ages in the Mn enrichment history panels of Figure 23).

The Co enrichment history agrees well in [Co/Mg] space at old ages, though K20 predicts too-fast enrichment in the younger low-α population (the slope of the blue segmented curve versus the slope of the green curve). As with V, the models significantly underpredict the global abundances for Co.

5.7.2. Even-Z Iron-peak Elements: Cr and Ni

To better reproduce the [Cr/Fe] enrichment history and the [Cr/Fe]–[Fe/H] ratios as seen in Figure 24, overall [Cr/Fe] production could be made to be less, such as in the double-degenerate scenario (the green dotted curve of Figure 18 in K20). Note, however, that such low [Cr/Fe] results in higher [α/Fe] and lower [Mn/Fe] and [Ni/Fe] than observed. Otherwise, the observed enrichment history is flatter than that predicted in [Fe/H] space, but is in better agreement with the models for [Mg/H] space. The disagreement between observed and predicted high-α [Cr/Mg] cannot be redressed only with the aforementioned appeals to older high-α ages resulting from α-enhanced stellar model opacities, which would increase the tension in high-α [Cr/Fe]. Rather, this would need to be coupled with a significant decrease in the production of Cr at early times.

Like Cr, the observed age-abundance pattern of Ni in [Fe/H] space seen in Figure 24 is flatter than predicted. Though there is broad agreement between the [Ni/Fe] and [Ni/Mg] high-α enrichment history, it could be improved by an increase (as opposed to a decrease, as for Cr) in Ni at early times, combined with older high-α ages resulting from α-enhanced stellar model opacities, as mentioned earlier. There is also an offset between the raw model abundances (the gray dashed curves) and the observed abundances, though the offset is in the opposite direction to that of Cr. Note that the metallicity dependence is in good agreement with the model predictions in [Ni/Fe]–[Fe/H] space, in contrast to Cr.

5.7.3. Iron-peak Cliff Elements: Sc, Cu, and Zn

Looking at Figure 25, the observed and predicted [Zn/Fe] versus [Fe/H] and age-abundance trends are in good agreement. The small separation in [Zn/Mg] of the low- and high-α sequences corroborates the CCSNe-dominated production assumed in the K20 models as well as the interpretations of the Zn abundance ratios in GIW19 that Zn is mostly a CCSNe element.

The enrichment histories predicted by the K20 models for Cu show strong increases in both [Cu/Mg] and [Cu/Fe] for younger stellar ages, which are in disagreement with the slight trend in the other direction among the low-α population (the green curves in Figure 25) in both [Fe/H] and [Mg/H] space. Slightly higher high-α ages in the data would help to reconcile the observed and predicted [Cu/Fe].
The Sc age-abundance patterns in Figure 25 show the same behavior as Cu: the models predict an age-dependent trend in the opposite direction to that of the observed trends in [Fe/H] and [Mg/H] space, and the observed high-α population is offset in age compared to the models.

Taken together, the Cu and Sc trends are suggestive of different nucleosynthetic histories compared to Zn. The predicted increase in the Cu and Sc yields is theoretically expected, due to the metallicity dependence of Cu and Sc yields, since both elements are odd-Z (see Section 5.6). Indeed, the data show this increase in [Cu/Fe], and at least a flat trend in [Sc/Fe] with [Fe/H] among the low-α population. The observed age trend (a flat or increasing abundance with increasing age among low-α stars) is therefore not straightforwardly related to metallicity-dependent yields, and is an interesting constraint on production of these elements; a similar enrichment history is also seen in the odd-Z element Al (see Section 5.6).

5.8. Neutron-capture Elements

Neutron-capture elements can be produced in one of two primary channels: the s-process and r-process channels, which occur in neutron-poor and neutron-rich environments (for a review, see Truran et al. 2002).

There is evidence of two different kinds of r-process production: a “weak” process that creates elements $A \lesssim 130-140$ (e.g., Honda et al. 2004) and the main r-process for elements with $A \gtrsim 130-140$ (Truran et al. 2002). The main r-process production site has been proposed to decompressing neutron-rich ejecta from a neutron star–neutron star (NS–NS) merger (Lattimer & Schramm 1974; Lattimer et al. 1977; Rosswog et al. 1999). However, the delay-time distribution of NS–NS mergers is difficult to reconcile with that needed to reproduce observed r-process enrichment histories, both at early and late times (e.g., Hotokezaka et al. 2018; Haynes & Kobayashi 2019). Other r-process channels involving neutrino-driven winds during neutron or magnetar birth may be plausible alternatives (e.g., Qian & Woosley 1996; Hoffman et al. 1997).

As with the r-process, there seem to be weak and main kinds of s-process. The weak s-process occurs during core He burning of $M > 25M_\odot$ stars (Peters 1968; Lamb et al. 1977; Raiteri et al. 1993), and works by way of neutron production from the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction, creating free neutrons that can then build elements up to $A \approx 90$ (Truran et al. 2002). The main s-process occurs during the AGB phase of low- and intermediate-mass stars ($M \sim 1-3M_\odot$; Schwarzschild & Härn 1967), acting through the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction, and forming elements with $A \gtrsim 90$.

With K2 GAP DR3 age estimates and GALAH DR3 abundances, we are in a position to test assumed production mechanisms of neutron-capture elements by means of comparisons to the K20 models.

Electron-capture supernovae (ECSNe) are included as sources of neutron-capture elements in the K20 models, the effects of which are to form first-peak s-process elements Sr, Y, Zr, Mo, and Ru via nuclear equilibrium processes, as well as weak r-process production from Nd to In (Wanajo et al. 2011). ECSNe are assumed in the K20 models to occur in the relatively narrow mass range of $\sim 8.8-9M_\odot$; increases of an order of magnitude to the ECSN rate have been assumed in the literature, and so this may be a tunable parameter in order to increase bulk yields (see K20 and references therein). The largest contributors to r-process production in the K20 models, however, are magneto-rotational supernovae (MRSNe), which have been theorized as being CCSNe of massive stars with large magnetic fields and/or strong rotations, which develop accretion disks and jets that can be conducive to r-process production (e.g., Symbalisty et al. 1985; Cameron 2003; Nishimura et al. 2017). An NS–NS merger r-process contribution is also included in the K20 models, though its contribution is subdominant compared to that of MRSNe.

5.8.1. Weak s-process Elements: Rb, Y, and Zr

Shown in Figure 26 are the age-abundance ratios of elements thought to be formed through the “weak” s-process.37

The agreement between the observed and predicted age-abundance patterns of [Rb/Mg] and [Rb/Fe] is very good, across both high- and low-α populations. Although there is an overprediction in the abundances for the high-α stars at 9 Gyr, the agreement between the K20 models and data are good for [Zr/Mg] and [Zr/Fe] as well.

The K20 age–[Y/Mg] pattern does not reach an equilibrium value, indicating a metallicity dependence on the s-process production of Y. This metallicity dependence is also borne out in the data, save for a zero-point offset in [Y/Mg]. The predicted enrichment history is in good agreement in both [Y/Mg] and [Y/Fe] space. The agreement between the observed and predicted Y enrichment histories represents another endorsement of dating stars with Y abundances (e.g., Nissen 2015).

5.8.2. Weak r-process Element: Mo

Although GALAH can measure Ru, the number of stars with good Ru measurements is small, and so we only consider Mo as being representative of elements produced as part of the so-called “weak” r-process.

The K20 models underpredict Mo compared to GALAH (gray curve versus error bars in Figure 27), which is inconsistent with the inferred overproduction compared to high-resolution Mo abundance measurements in the literature (K20). Nevertheless, the predicted history of Mo enrichment is consistent with the observed [Mo/Fe] and [Mo/Mg] age-abundance patterns (the blue curve compared to the error bars).

5.8.3. Main s-process Elements: Ba, La, Ce, and Nd

Ba, shown in Figure 28, is thought to be primarily produced by the s-process at the metallicities considered here ([Fe/H] > −2; Gilroy et al. 1988; Arlandini et al. 1999; Burris et al. 2000). [Ba/Mg] is predicted to reach a plateau in young stars, according to the K20 models, but the data disfavor a plateau and rather suggest a continually increasing ratio with younger ages, like [Y/Mg].

D’Orazi et al. (2009) have observed a similar unexpected increase in [Ba/Fe] at young stellar ages, based on open cluster measurements. They proposed that increased production in low-mass stars would explain the observations, which could possibly be related to enhanced mixing in the helium-burning shell thought to be the site of s-process production in low- and

37 In detail, the K20 models predict that Y and Zr are in fact produced mostly in low- and intermediate-mass AGB stars as part of what we label here the main s-process.
intermediate-mass AGB stars. Similar behavior has also been seen in more recent studies (Mishenina et al. 2013; Magrini et al. 2018; Casamiquela et al. 2021). It is unlikely that this enrichment history is explicable by an astrophysical, metallicity-dependent yield, since [Ba/Fe] decreases with increasing [Fe/H], which demonstrates the advantage of analyzing nucleosynthetic yields with age information.

Our results therefore corroborate a mass-dependent Ba yield interpretation, though it is possible that the GALAH DR3 Ba abundances themselves could be responsible: a trend in Ba with stellar mass would mimic this effect. One candidate for such a systematic may be the choice of the microturbulence parameter, given the sensitivity of one of the GALAH Ba lines, Ba II, to that parameter (Dobrovolskas et al. 2012). The GALAH DR3 Ba abundances are calculated by assuming that RGB stars with the same effective temperature, surface gravity, and [Fe/H] have the same microturbulence velocity. This is not necessarily the case, and such assumptions could lead to artificial shifts in the measured Ba abundance with, e.g., mass/age. Regarding the zero-point offset in the Ba abundances compared to the K20 models under no rescaling (the gray dashed lines), the RGB Ba abundances are systematically larger than the dwarf abundances by 0.2 dex. Were the RGB Ba abundances placed on the dwarf scale, then, there would be an even larger global offset between the observations and models than is shown here. On the model side, K20 noted offsets compared to other Ba abundances in the literature, noting that they could be remedied by imposing a smaller mixing region during the AGB dredge-up. Based on our findings, the models may improve the agreement with the observations more specifically, with a mass-dependent increase in the mixing region.

The predicted and observed enrichment histories of La, Ce, and Nd are in good agreement, as seen in Figure 28. The exception to this agreement is Ce among high-α stars, which is low compared to the predictions, even after considering a ≈10% increase in the observed ages, potentially indicating the need for less Ce production in the K20 models at early times.

5.8.4. Main r-process Elements: Sm and Eu

We show in Figure 29 the abundances of the two main r-process elements available in GALAH DR3, Sm and Eu. Given the relatively few stars in GALAH DR3 with measured Sm abundances, it is difficult to determine the precise agreement with the K20 models as a function of age. It does, however, appear that the high-α abundances at old ages are broadly consistent with the predicted enrichment histories, though they could be further improved with older high-α ages resulting from α-enhanced stellar opacities.

Eu is mostly produced via the r-process (Arlandini et al. 1999; Battistini & Bensby 2016), and, according to the K20 models, the primary site of r-process production is MRSNe (see Figure 32 in K20), where the rate of MRSNe is chosen to be 3% of massive CCSNe (hypernovae) with mass $M > 25 M_{\odot}$, in order to reproduce the [Eu/Fe]−[Fe/H] trend in the solar neighborhood.

The K20 models are in good agreement with both the GALAH abundance ratios and the asteroseismic age-abundance patterns in [Eu/Fe], when comparing the models to low-α stars (the green curves) at intermediate and young ages ($\tau \lesssim 8$ Gyr) and when comparing the models to high-α stars (the orange error bars at 9 Gyr in the Eu enrichment history panels of Figure 29) at older ages. Consistent with studies of metal-poor systems with significant r-process enrichment (e.g., Barklem et al. 2005; Hansen et al. 2018), Lin et al. (2020) have corroborated the short time-delay of Eu production sites by using isochronal stellar ages of subgiants combined with GALAH DR2 abundances. In this context, the agreement of the observed K2 GAP DR3–GALAH DR3 Eu enrichment history with that of the MNSRe-dominated K20 Eu models gives further credence to a significant contribution to r-process elements from a prompt source—e.g., late-time collapsar accretion disk outflows associated with MRSNe (Symbalisty et al. 1985; Cameron 2003; Nicholl et al. 2013; Vlasov et al. 2014; Siegel et al. 2019).

6. Conclusions

The K2 GAP DR3 sample, as the largest asteroseismic sample published to date, which probes a range of Galactic environments, represents an important tool for Galactic archeology and stellar physics. With 18,821 total radius and mass coefficients for RGB and RC stars having been delivered as part of this final data release, below are our main results.

1. We calibrated our asteroseismic values to be on the Gaia parallactic scale. The radius and mass coefficients—$\kappa_R$ and $\kappa_M$—that are released in K2 GAP DR3 need only be multiplied by a temperature-dependent factor according to the user’s preferred temperatures in order to yield radii and masses. The typical uncertainties in these coefficients are 2.9% (stat.) ± 0.1% (syst.) and 6.7% (stat.) ± 0.3% (syst.) in $\kappa_R$ and $\kappa_M$ for RGB stars and 4.7% (stat.) ± 0.3% (syst.) and 11% (stat.) ± 0.9% (syst.) for RC stars. All of the stars with $\kappa_R$ and $\kappa_M$ are classified as RGB or RC stars, according to a machine-learning approach.

2. Using injection tests, we estimate that our completeness in radius peaks for stars with $R \sim 10 R_\odot$, where our recovery rate is around 80%. There is a sharp decline in completeness at smaller radii, and a more gradual decline in completeness at larger radii. We estimate a nearly uniform completeness in mass space of ~60%.

3. Injection tests suggest systematics of 1%–3% may arise due to the shorter time baseline of K2 compared to Kepler, taking the form of both zero-point biases and trends as a function of $v_{\text{max}}$, $\Delta \nu$, and $S/N$. These findings should be informative for future studies using short time baseline TESS light curves, which would presumably suffer from similar, if not more severe, systematics.

4. We derived ages with typical precisions of 20% for a subset of the K2 GAP DR3 sample, based on GALAH metallicities and effective temperatures. In combination with the GALAH abundances, we compared the observed age-abundance patterns with those predicted by Kobayashi et al. (2020a) as an independent check on the abundance evolution of low- and high-α stars. We corroborate recent inferences regarding the nucleosynthesis of α, light, iron-peak, and neutron-capture elements based on abundance ratios alone (e.g., Griffith et al. 2019). Following similar indications from the Lin et al. (2020) analysis of GALAH DR2 subgiants with isochronal ages, we find evidence for significant production of Eu at early times, consistent with CCSNe as the predominant site of r-process production. Our findings also suggest mass-dependent Ba yields, in support of indications from D’Orazi et al. (2009).
Studies of Galactic chemical evolution stand to benefit enormously from a continued focus on considering ages, and not just stellar abundances themselves, as we have shown here. Indeed, ages are of crucial importance in interpreting chemokinematic relations (Minchev et al. 2019)—particularly ages with the levels of precision reported here (e.g., Martig et al. 2014). As the largest asteroseismic data set in the literature, K2 GAP DR3 will prove useful not only for Galactic studies, but also for testing stellar models using the sample’s evolutionary state classifications together with its accurate and precise asteroseismic masses and radii.

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Software: asfgrid (Sharma & Stello 2016), corner (Foreman-Mackey 2016), emcee (Foreman-Mackey et al. 2013), NumPy (Walt 2011), pandas (McKinney 2010), Matplotlib (Hunter 2007), IPython (Pérez & Granger 2007), SciPy (Virtanen et al. 2020).

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