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THE RADIAL VELOCITY EXPERIMENT (RAVE): FIFTH DATA RELEASE

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Data Release 5 (DR5) of the Radial Velocity Experiment (RAVE) is the fifth data release from a magnitude-limited (9 < I < 12) survey of stars randomly selected in the Southern Hemisphere. The RAVE medium-resolution spectra (R ~ 7500) covering the Ca-triplet region (8410–8795 Å) span the complete time frame from the start of RAVE observations in 2003 to their completion in 2013. Radial velocities from 520,781 spectra of 457,588 unique stars are presented, of which 255,922 stellar observations have parallaxes and proper motions from the Tycho-Gaia astrometric solution in Gaia DR1. For our main DR5 catalog, stellar parameters (effective temperature, surface gravity, and overall metallicity) are computed using the RAVE DR4 stellar pipeline, but calibrated using recent K2 Campaign 1 seismic velocities and Gaia benchmark stars, as well as results obtained from high-resolution studies. Also included are temperatures from the Infrared Flux Method, and we provide a catalog of red giant stars in the dereddened color (J − Ks)0 interval (0.50, 0.85) for which the gravities were calibrated based only on seismology. Further data products for subsamples of the RAVE stars include individual abundances for Mg, Al, Si, Ca, Ti, Fe, and Ni, and distances found using isochrones. Each RAVE spectrum is complemented by an error spectrum, which has been used to determine uncertainties on the parameters. The data can be accessed via the RAVE Web site or the VizieR database.

Key words: catalogs – Galaxy: abundances – Galaxy: kinematics and dynamics – Galaxy: stellar content – stars: abundances – surveys

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ABSTRACT

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1. INTRODUCTION

The kinematics and spatial distributions of Milky Way stars help define the Galaxy we live in, and allow us to trace parts of the formation of the Milky Way. In this regard, large spectroscopic surveys that provide measurements of fundamental structural and dynamical parameters for a statistical sample of Galactic stars have been extremely successful in advancing the understanding of our Galaxy. Recent and ongoing spectroscopic surveys of the Milky Way include the RAdial Velocity Experiment (RAVE, Steinmetz et al. 2006), the Sloan Extension for Galactic Understanding and Exploration (Yanny et al. 2009), the APO Galactic Evolution Experiment (APOGEE, Eisenstein et al. 2011), the LAMOST Experiment for Galactic Understanding and Exploration (LAMOST, Zhao et al. 2012), the Gaia-ESO Survey (Gilmore et al. 2012), and the GALactic Archaeology with HERMES (GALAH, De Silva et al. 2015). These surveys were made possible by the emergence of wide-field multi-object spectroscopy fiber systems, technology that especially took off in the 1990s. Each survey has its own unique aspect, and together they form complementary samples in terms of capabilities and sky coverage.

Of the above mentioned surveys, RAVE was the first, designed to provide stellar parameters to complement missions that focus on astrometric information. The four previous data releases—DR1 (Steinmetz et al. 2006), DR2 (Zwitter et al. 2008), DR3 (Siebert et al. 2011), and DR4 (Kordopatis et al. 2013a)—have been the foundation for a number of studies that have advanced our understanding of especially the disk of the Milky Way (see review by Kordopatis 2014). For example, in recent years a wave-like pattern in the stellar velocity distribution was uncovered (Williams et al. 2013) and the total mass of the Milky Way was measured using the RAVE extreme-velocity stars (Piffl et al. 2014b), as was the local dark matter density (Bienaymé et al. 2014; Piffl et al. 2014a). Moreover, chemokinematic signatures of the dynamical effect of mergers on the Galactic disk (Minchev et al. 2014), and signatures of radial migration were detected (Kordopatis et al. 2013b; Wojno et al. 2016a). Stars tidally stripped from globular clusters were also identified (Kunder et al. 2014; Anguiano et al. 2015, 2016). RAVE further allowed for the creation of pseudo-3D maps of the diffuse interstellar band at 8620 Å (Kos et al. 2014) and for high-velocity stars to be studied (Hawkins et al. 2015).

RAVE Data Release 5 (DR5) includes not only the final RAVE observations taken in 2013, but also earlier discarded observations recovered from previous years, resulting in an additional ~30,000 RAVE spectra. This is the first RAVE data release in which an error spectrum was generated for each RAVE observation, so we can provide realistic uncertainties and probability distribution functions for the derived radial velocities and stellar parameters. We have performed a recalibration of stellar metallicities, especially improving stars of supersolar metallicity. Using the Gaia benchmark stars (Jofré et al. 2014; Heiter et al. 2015) as well as 72 RAVE stars with Kepler-2 asteroseismic log g parameters (Valentini et al. 2017, hereafter V17), the RAVE log g values have been recalibrated, resulting in more accurate gravities especially for the giant stars in RAVE. The distance pipeline (Binney et al. 2014) has been improved and extended to process more accurately stars with low metallicities ([M/H] < −0.9 dex). Finally, by combining optical photometry from APASS (Munari et al. 2014) with 2MASS (Skrutskie et al. 2006) we have derived temperatures from the infrared flux method (IRFM; Casagrande et al. 2010).

Possibly the most distinct feature of DR5 is the extent to which it complements the first significant data release from Gaia. The successful completion of the Hipparcos mission and publication of the catalog (ESA 1997) demonstrated that space astrometry is a powerful technique to measure accurate distances to astronomical objects. Already in RAVE-DR1 (Steinmetz et al. 2006), we looked forward to the results from the ESA cornerstone mission Gaia, because this space-based mission’s astrometry of Milky Way stars will have ~100 times better astrometric accuracies than its predecessor, Hipparcos. Although Gaia has been launched and data collection is ongoing, a long enough time baseline has to have elapsed for sufficient accuracy of a global reduction of observations (e.g., five years for Gaia to yield positions, parallaxes, and annual proper motions at an accuracy level of 5–25 mas, Michalik et al. 2014). To expedite the use of the first Gaia astrometry results, the approximate positions at the earlier epoch (around 1991) provided by the Tycho-2 Catalogue (Hög et al. 2000) can be used to disentangle the ambiguity between parallax and proper motion in a shorter stretch of Gaia observations. These Tycho-Gaia astrometric solution (TGAS) stars therefore have positions, parallaxes, and proper motions before the global astrometry from Gaia can be released. There are 215,590 unique RAVE stars in TGAS, so for these stars we now have space-based parallaxes and proper motions from Gaia DR1 in addition to stellar parameters, radial velocities, and in many cases chemical abundances. The Tycho-2 stars observed by RAVE in a homogeneous and well-defined manner can be combined with the released TGAS stars to exploit the larger volume of stars for which astrometry with milliarcsecond accuracy exists, for an extraordinary return in scientific results. We note that in a companion paper, a data-driven reanalysis of the RAVE spectra using The Cannon model has been carried out (Casey et al. 2016, hereafter C16), which presents the derivation of $T_{\text{eff}}$, surface gravity log g, and [Fe/H], as well as chemical abundances of giants of up to seven elements (O, Mg, Al, Si, Ca, Fe, Ni).

In Section 2, the selection function of the RAVE DR5 stars is presented—further details can be found in Wojno et al. (2016b, hereafter W16). The RAVE observations and reductions are summarized in Section 3. An explanation of how the error spectra were obtained is found in Section 4, and Section 5 summarizes the derivation of radial velocities from the spectra. In Section 6, the procedure used to extract atmospheric parameters from the spectrum is described and the external verification of the DR5 $T_{\text{eff}}$, log g, and [M/H] values is discussed in Section 7. The dedicated pipelines to extract elemental abundances and distances are described in Sections 8 and 9, respectively—DR5 gives radial velocities for all RAVE stars but elemental abundances and distances are given for subsamples of RAVE stars that have signal-to-noise ratio (S/N) > 20 and the most well-defined stellar parameters. Temperatures from the IRFM are presented in Section 10. In Section 11 we present gravities for the red giants based on asteroseismology by the method of V17. A comparison of the stellar parameters in the RAVE DR5 main catalog to other stellar parameters for RAVE stars (e.g., those from C16) is provided in Section 12. The final sections, Sections 13 and 14, provide a summary of the difference between DR4 and DR5, and an overview of DR5, respectively.
2. SURVEY SELECTION FUNCTION

Rigorous exploitation of DR5 requires knowledge of RAVE’s selection function, which was recently described by W16. Here we provide only a summary.

The stars for the RAVE input catalog were selected from their I-band magnitudes, focusing on bright stars \(9 < I < 12\) in the Southern Hemisphere, but the catalog does contain some stars that are either brighter or fainter, in part because stars were selected by extrapolating data from other sources, such as Tycho-2 and SuperCOSMOS before DENIS was available in 2006 (see Section 2 of the DR4 paper by Kordopatis et al. 2013a for details). As the survey progressed, the targets in the input catalog were grouped into four I-band magnitude bins: 9.0–10.0, 10.0–10.75, 10.75–11.5, and 11.5–12.0, which helped mitigate problems of fiber cross-talk. This led to a segmented distribution of RAVE stars in I-band magnitudes, but the distributions in other passbands are closely matched by Gaussians (see, e.g., Figure 11 in Munari et al. 2014). For example, in the B-band, the stars observed by RAVE have a nicely Gaussian distribution, peaking at \(B = 12.62\) with \(\sigma = 1.11\) mag.

The initial target selection was based only on the apparent I-band magnitude, but a color criterion \((J - K_s) \geq 0.5\) was later imposed in regions close to the Galactic plane (Galactic latitude \(|b| < 25^\circ\)) to bias the survey toward giants. Therefore, the probability, \(S\), of a star being observed by the RAVE survey is

\[
S \propto S_{\text{select}}(l, b, I, J - K_s),
\]

where \(l\) is Galactic longitude. W16 determine the function \(S_{\text{select}}\) both on a field-by-field basis, so time-dependent effects can be captured, and with Hierarchical Equal-Area iso-Latitude Pixelisation (HEALPix) (e.g., Górski et al. 2005), which divides the sky into equal-area pixels, as regularly distributed as possible. The sky is divided into 12,288 pixels \(N_{\text{side}} = 32\), which results in a pixel area of \(\approx 3.36\) deg\(^2\), and we consider only the selection function evaluated with HEALPix for quality control and variability tests, because RAVE fields overlap on the sky.

The parent RAVE sample is constructed by first discarding all repeat observations, keeping only the observation with the highest S/N. Then observations that were not conducted as part of the typical observing strategy (e.g., calibration fields) were removed. Finally, all stars with \(|b| < 25^\circ\) that were observed despite violating the color criterion \((J - K_s) \geq 0.5\) were dismissed. After applying these cuts, we are left with 448,948 stars, or 98% of all stars targeted by RAVE. These define the RAVE DR5 core sample (survey footprint). The core sample is complemented by targeted observations (e.g., open clusters), mainly for calibration and testing.

The number of RAVE stars \(N_{\text{RAVE}}\) in each HEALPix pixel is then counted as a function of \(I_{\text{MASS}}\). We apply the same criteria to two photometric all-sky surveys, 2MASS and Tycho-2, to discover how many stars could, in principle, have been observed. After these catalogs were purged of spurious measurements, we obtain \(N_{\text{2MASS}}\) and \(N_{\text{TYCHO2}}\) and can compute the completeness of RAVE as a function of magnitude for both 2MASS and Tycho-2 as \(N_{\text{RAVE}}/N_{\text{2MASS}}\) and \(N_{\text{RAVE}}/N_{\text{TYCHO2}}\).

Figure 1 shows the DR5 completeness with respect to Tycho-2 as a function of magnitude. It is evident that RAVE avoids the Galactic plane, and we find that the coverage on the sky is highly anisotropic, with a significant drop-off in completeness at the fainter magnitudes. A similar result is seen for \(N_{\text{RAVE}}/N_{\text{2MASS}}\) (W16). However, in \(N_{\text{RAVE}}/N_{\text{2MASS}}\), there is a significantly higher completeness at low Galactic latitudes \((|b| < 25^\circ)\) for the fainter magnitude bins.

Because stars that passed the photometric cuts were randomly selected for observation, RAVE DR5 is free of kinematic bias. Hence, the contents of DR5 (see Table 1) are representative of the Milky Way for the specific magnitude interval. A number of peculiar and rare objects are included. The morphological flags of Matijevič et al. (2012) allow one to identify the normal single stars (90%–95%), and those that are unusual—the peculiar stars include various types of spectroscopic binary and chromospherically active stars. The stars falling within the footprint of the RAVE selection function described in W16 are provided in https://www.rave-survey.org/project/documentation/dr5/rave_completeness_php/.

3. SPECTRA AND THEIR REDUCTION

The RAVE spectra were taken using the multi-object spectrograph 6dF (6 degree field) on the 1.2 m UK Schmidt Telescope of the Australian Astronomical Observatory (AAO). A total of 150 fibers could be allocated in one pointing, and the covered spectral region (8410–8795 Å) at an effective resolution of \(R = \lambda/\Delta\lambda \sim 7500\) was chosen as analogous to the
wavelength range of Gaia’s Radial Velocity Spectrometer (see Sections 2 and 3 of the DR1 paper by Steinmetz et al. 2006 for details).

The RAVE reductions are described in detail in DR1 Section 4 and upgrades to the process are outlined in DR3 Section 2. In DR5 further improvements have been made to the Spectral Parameters And Radial Velocity (SPARV) pipeline, the DR3 pipeline that carries out the continuum normalization, masks bad pixels, and provides RAVE radial velocities. The most significant is that instead of the reductions being carried out on a field-by-field basis, single fiber processing was implemented. Therefore, if there were spectra within a RAVE field that simply could not be processed, instead of the whole field failing and being omitted from the final RAVE catalog, only the problematic spectra are removed. This is one reason why DR5 has more stars than the previous RAVE data releases.

The DR5 reduction pipeline is able to processes the problematic DR1 spectra, and it produces error spectra. An overhaul of bookkeeping and process control led to identification of multiple copies of the same observation and of spectra with corrupted FITS headers. Some RAVE IDs have changed from DR4, and some stars released in DR4 could not be processed by the DR5 pipeline. The vast majority of these stars have low signal-to-noise ratios ($S/N < 10$). Details are provided in Appendix A; less than 0.1% of RAVE spectra were affected by bookkeeping inconsistencies.

4. ERROR SPECTRA

The wavelength range of the RAVE spectra is dominated by strong spectral lines: for a majority of stars, the dominant absorption features are due to the infrared calcium triplet (CaT), which in hot stars gives way to the Paschen series of hydrogen. Also present are weaker metallic lines for the solar-type stars and molecular bands for the coolest stars. Within an absorption trough the flux is small, so shot noise is more significant in the middle of a line than in the adjacent continuum. Error levels increase also at wavelengths of airglow sky emission lines, which have to be subtracted during reductions. As a consequence, a single number, usually reported as $S/N$, is not an adequate quantification of the observational errors associated with a given spectrum.

For this reason, DR5 provides error spectra that comprise uncertainties (“errors”) for each pixel of the spectrum. RAVE spectra generally have a high $S/N$ in the continuum (its median value is $S/N \sim 40$), and there shot noise dominates the errors. Denoting the number of counts accumulated in the spectrum before sky subtraction by $N_0$, the corresponding number after sky subtraction by $N_i$, and the effective gain by $g$, the shot noise is $N = \sqrt{gN_i}$ and the signal is $S = gN_i$. The appearance of $N_i$ rather than $N_0$ in the relation for $N$ reflects the fact that noise is enhanced near night-sky emission lines. As a consequence the $S/N$ is decreased both within profiles of strong stellar absorption lines (where $N_i$ is small) and near sky emission lines. The gain $g$ is determined using the count versus magnitude relation (see Equation (1) from Zwitter et al. 2008). Its value ($g = 0.416e^{-}/ADU$) reflects systematic effects on a pixel-to-pixel scale that lower the effective gain to this level.

Telluric absorptions are negligible in the RAVE wavelength range (Munari 1999). RAVE observations from Siding Spring generally show a sky signal with a low continuum level, even when observed close to the Moon. The main contributors to the sky spectrum are therefore airglow emission lines, which belong to three series: OH transitions $6-2$ at $\lambda < 8651 \, \text{Å}$, OH transitions $7-3$ at $\lambda > 8758 \, \text{Å}$, and $\text{O}_2$ bands at $8610 \, \lambda < 8710 \, \text{Å}$. Wavelengths of OH lines are listed in the file linelists/$\text{sky}$lines.dat, which is part of the IRAF reduction package, while the physics of their origin is nicely summarized at http://www.iafe.uba.ar/aeronomia/airglow.html. One needs to be careful when analyzing stellar lines with superimposed airglow lines. Apart from increasing the noise levels, these lines may not be perfectly subtracted, because they can be variable on angular scales of degrees and on timescales of minutes, whereas the telescope’s field of view is $6\dgr 7$ and the exposure time was typically 50 minutes.

Evaluation of individual reduction steps (see Zwitter et al. 2008) shows that fiber cross-talk and scattered light have only a small influence on error levels. In particular, a typical level of fiber cross-talk residuals is 0.0014$/f$, where $f$ is the ratio between flux of an object in an adjacent fiber and flux of the object in question. Fiber cross-talk suffers from moderate systematic effects (variable point-spread function profiles across the wavelength range), but even at the edges of the spectral range these effects do not exceed a level of 1%. Scattered light typically contributes $\sim 5\%$ of the flux level of the spectral tracing. So its effect on noise estimation is not important, and we were not able to identify any systematics. Finally, RAVE observes in the near-IR and uses a thinned CCD chip, so an accurate subtraction of interference fringes is needed. Tests show that fringe patterns for the same night and for the same focal plate typically stay constant to within 1% of the flat-field flux level. As a result scattered light and fringing only moderately increase the final noise levels. Together, scattered light and fringing are estimated to contribute a relative error of $\sim 0.8\%$, which is added in quadrature to the prevailing contribution of shot noise discussed above.

Finally we note that fluxes and therefore noise levels for individual pixels of a given spectrum are not independent of each other, but are correlated because of a limited resolving power of RAVE spectra. So the final noise spectrum was smoothed with a window with a width of 3 pixels in the wavelength direction, which corresponds to the FWHM for a resolving power of RAVE spectra.

For each pixel in a RAVE spectrum, we invoke a Gaussian with a mean and standard deviation as measured from the same pixel of the corresponding error spectrum. A new spectrum is therefore generated that can be roughly interpreted as an alternative measurement of the star (although note that the error spectrum does not take every possible measurement uncertainty into account as discussed above). We then can redetermine our radial velocity for these resampled data, and it will differ slightly from that obtained from the actual observed spectrum. Repeating this resampling process and monitoring the resulting estimates of radial velocity, we get a distribution of the radial velocity from which we can then infer an uncertainty.

The raw errors as derived in the error spectra are propagated into both the radial velocities and stellar parameters presented here. This process allows a better assessment of the uncertainties, especially of stars with low $S/N$ or hot stars, where the CaT is not as prominent. Figure 2 shows the mean radial velocity from the resulting estimates of radial velocity of 100 resampled spectra for low $S/N$ stars. For most RAVE...
stars, the errors in radial velocity are consistent with a Gaussian (see middle panel), but for the more problematic hot stars, or those with low S/N, this is clearly not the case.

Each RAVE spectrum was resampled from its error spectrum 10 times. Whereas our tests indicate that a larger number of resamplings (~60) would be ideal for the more problematic spectra, 10 resamplings were chosen as a compromise between computing time and the relatively small number of RAVE spectra with low S/N and hot stars that would benefit from additional resamplings. For ~97.5% of the RAVE sample, there is 1σ or less difference in the radial velocity and radial velocity dispersions when resampling the spectrum 10 or 100 times. In DR5, we provide both the formal error in radial velocity, which is a measure of how well the cross-correlation of the RAVE spectrum against a template spectrum was matched, and the standard deviation and median absolute deviation (MAD) in heliocentric radial velocity from a spectrum resampled 10 times.

5. RADIAL VELOCITIES

The DR5 radial velocities are derived in an identical manner to those in DR4. The process of velocity determination is explained by Siebert et al. (2011). Templates are used to measure the radial velocities (RVs) in a two-step process. First, using a subset of 10 template spectra, a preliminary estimate of the RV is obtained, which has a typical accuracy better than 5 km s\(^{-1}\). A new template is then constructed using the full template database described in Zwitter et al. (2008), from which the final, more precise RV is obtained. This has a typical accuracy better than 2 km s\(^{-1}\).

The internal error in RV, \(\sigma(\text{RV})\), comes from the \texttt{xcsao} task within IRAF, and therefore describes the error on the determination of the maximum of the correlation function. It was noticed that for some stars, particularly those with \(\sigma(\text{RV}) > 10\) km s\(^{-1}\), \(\sigma(\text{RV})\) was underestimated. The inclusion of error spectra in DR5 largely remedies this problem, and the standard deviation and MAD provide independent measures of the RV uncertainties (see Figure 2). Uncertainties derived from the error spectra are especially useful for stars that have low S/N or high temperatures. Figure 3 shows the errors from the resampled spectra compared to the internal errors. For the majority of RAVE stars, the uncertainty in RV is dominated by the cross-correlation between the RAVE spectrum and the RV template, and not by the array of uncertainties (“errors”) for each pixel of the RAVE spectrum.

Repeated RV measurements have been used to characterize the uncertainty in the RVs. There are 43,918 stars that have been observed more than once; the majority (82%) of these stars have two measurements, and six RAVE stars were observed 13 times. The histogram of the RV scatter between the repeat measurements peaks at 0.5 km s\(^{-1}\), and has a long tail at larger scatter. This extended scatter is due both to variability from stellar binaries and to problematic measurements. If stars are selected that have radial velocities derived with high confidence, e.g., stars with \(|\text{correctionRV}| < 10\) km s\(^{-1}\), \(\sigma(\text{RV}) < 8\) km s\(^{-1}\), and \(\text{correlationCoef} > 10\) (see Kordopatis et al. 2013a), then the scatter of the repeat measurements peaks at 0.17 km s\(^{-1}\) and the tail is reduced by 90%.

The zero-point in RV has already been evaluated in the previous data releases. The exercise is repeated here, with the inclusion of a comparison to APOGEE and \textit{Gaia}-ESO, and the summary of the comparisons to different samples is given in Table 2. Our comparison sample comprises the data from the Geneva–Copenhagen survey (GCS, Nordström et al. 2004) as
well as high-resolution echelle follow-up observations of RAVE targets at the ANU 2.3 m telescope, the Asiago Observatory, the Apache Point Observatory (Ruchti et al. 2011), and Observatoire de Haute Provence using the instruments Elodie and Sophie. Sigma-clipping is used to remove contamination by spectroscopic binaries or problematic measurements, and the mean \( \Delta(RV) \) given is \( \Delta(RV) = RV_{R5} - RV_{eff} \). As seen previously, the agreement in zero-point between RAVE and the external sources is better than 1 km s\(^{-1}\).

### 6. STELLAR PARAMETERS AND ABUNDANCES

#### 6.1. Atmospheric Parameter Determinations

RAVE DR5 stellar atmospheric parameters—\( T_{\text{eff}}, \log g, \) and [M/H]—have been determined using the same stellar parameter pipeline as in DR4. The details can be found in Kordopatis et al. (2011) and the DR4 paper (Kordopatis et al. 2013a), but a summary is provided here.

The pipeline is based on the combination of a decision tree, DEGAS (Bijaoui et al. 2012), to renormalize the spectra iteratively and obtain stellar parameter estimations for the low S/N spectra, and a projection algorithm MATISSE (Recio-Blanco et al. 2006) to derive the parameters for stars having high S/N. The threshold above which MATISSE is preferred to DEGAS is based on tests performed with synthetic spectra (see Kordopatis et al. 2011) and has been set to S/N = 30 pixel\(^{-1}\).

The learning phase of the pipeline is carried out using synthetic spectra computed with the Turbospectrum code (Álvarez & Plez 1998) combined with MARCS model atmospheres (Gustafsson et al. 2008) assuming local thermodynamic equilibrium (LTE) and hydrostatic equilibrium. The cores of the CaT lines are masked in order to avoid issues such as non-LTE effects in the observed spectra, which could affect our parameter determination.

The stellar parameters covered by the grid are between 3000 and 8000 K for \( T_{\text{eff}}, 0 \) and 5.5 for \( \log g, \) and \(-5 \) to +1 dex in metallicity. Varying \( \alpha \)-abundances ([\( \alpha/Fe \)]) as a function of metallicity are also included in the learning grid, but are not a free parameter. The line list was calibrated on the Sun and Arcturus (Kordopatis et al. 2011).

The pipeline is run on the continuum-normalized, radial velocity-corrected RAVE spectra using a soft conditional constraint based on the 2MASS \( J - K_s \) colors of each star. This restricted the solution space and minimized the spectral degeneracies that exist in the wavelength range of the CaT (Kordopatis et al. 2011). Once a first set of parameters is obtained for a given observation, we select pseudo-continuum windows to renormalize the input spectrum based on the pseudo-continuum shape of the synthetic spectrum that has the parameters determined by the code, and the pipeline is run again on the modified input. This step is repeated 10 times, which is usually enough for convergence of the continuum shape to be reached and hence to obtain a final set of parameters (see, however, next paragraph).

Once the spectra have been parameterized, the pipeline provides one of the five quality flags for each spectrum:33

1. “0”: The analysis was carried out as desired. The renormalization process converged, as did MATISSE (for high S/N spectra) or DEGAS (for low S/N spectra).
2. “1”: Although the spectrum has a sufficiently high S/N to use the projection algorithm, the MATISSE algorithm did not converge. Stellar parameters for stars with this flag are not reliable. Approximately 6% of stars are affected by this.
3. “2”: The spectrum has a sufficiently high S/N to use the projection algorithm, but MATISSE oscillates between two solutions. The reported parameters are the mean of these two solutions. In general the oscillation happens for a set of parameters that are nearby in parameter space, and computing the mean is a sensible thing to do. However, this is not always the case, for example if the spectrum contains artifacts. Then the mean may not provide accurate stellar parameters. Spectra with a flag of “2” could be used for analyses, but with caution.
4. “3”: MATISSE gives a solution that is extrapolated from the parameter range of the learning grid, and the solution is forced to be the one from DEGAS. For spectra having artifacts but high S/N overall, this is a sensible thing to do, because DEGAS is less sensitive to such discrepancies. However, for the few hot stars that have been observed by RAVE, adopting this approach is not correct. A flag of “3” and \( T_{\text{eff}} > 7750 \) K is very likely to indicate that this is a hot star with \( T_{\text{eff}} > 8000 \) K and hence that the parameters associated with that spectrum are not reliable.
5. “4”: This flag will appear only for low S/N stars. For metal-poor giants, the spectral lines available are neither strong enough nor numerous enough to have DEGAS successfully parameterize the star. Tests on synthetic spectra have shown that to derive reliable parameters the settings used to explore the branches of the decision tree need to be changed from the parameters adopted for the rest of the parameter space. A flag “4” therefore marks this change in the setting for bookkeeping purposes, and the spectra associated with this flag should be safe for any analysis.

The several tests performed for DR4 as well as the subsequent science papers have indicated that the stellar parameter pipeline is globally robust and reliable. However, being based on synthetic spectra that may not match the real stellar spectra over the entire parameter range, the direct outputs of the pipeline need to be calibrated on reference stars in order to minimize possible offsets.

#### 6.2. Metallicity Calibrations

In DR4, the calibration of metallicity proved to be the most critical and important one. Using a set of reference stars for

| Sample | \( N_{\text{obs}} \) | \( \langle \Delta RV \rangle \) | \( \sigma_{\Delta RV} \) (\( \alpha_{\text{Fe}}, \alpha_{\text{Mg}} \)) |
|--------|----------------|-----------------|---------------------|
| GCS    | 1020           | 0.31            | 1.76 (3, 113)       |
| Chubak | 97             | -0.07           | 1.28 (3, 2)         |
| Ruchti | 443            | 0.79            | 1.79 (3, 34)        |
| Asiago | 47             | -0.22           | 2.98 (3, 0)         |
| ANU 2.3 m | 197       | -0.58           | 3.13 (3, 16)        |
| OHP Elodie | 13        | -0.49           | 2.45 (3, 2)         |
| OHP Sophie | 48        | 0.83            | 1.58 (3, 4)         |
| APOGEE | 1121           | -0.11           | 1.87 (3, 144)       |
| Gaia-Eso | 106         | -0.14           | 1.68 (3, 15)        |

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33 The flags are unchanged as compared to DR4.
which metallicity determinations were available in the literature (usually derived from high-resolution spectra), a second-order polynomial correction, based on surface gravity and raw metallicity, was applied in DR4. This corrected the metallicity offsets with the external data sets of Pasquini et al. (2004), Pancino et al. (2010), Cayrel et al. (2004), Ruchti et al. (2011), and the PASTEL database (Soubiran et al. 2010). For DR5, we relied on the same approach. However, we added reference stars to the set used in DR4, with the focus on expanding our calibrating sample toward the high-metallicity end to better calibrate the tails of the distribution function. This calibration is based on the crossmatch of RAVE targets with the catalogs of Worley et al. (2012) and Adibekyan et al. (2013), as well as the Gaia benchmark stellar spectra. The metallicity of the Gaia benchmark stars is taken from Jofré et al. (2014), where a library of Gaia benchmark stellar spectra was specially prepared to match RAVE data in terms of wavelength coverage, resolution, and spectral spacing. This was done following the procedure described in Blanco-Cuaresma et al. (2014). Our calibration has already been successfully used in Kordopatis et al. (2015), Wojno et al. (2016a), and Antoja et al. (2015). The calibration relation for DR5 is

\[
[M/H] = [M/H]_p - (-0.276 + 0.044 \log g_p - 0.002 \log g_p^2 + 0.248 [M/H]_p - 0.007 [M/H]_p \log g_p + 0.078 [M/H]_p^2),
\]

where \([M/H]\) is the calibrated metallicity, and \([M/H]_p\) and \(\log g_p\) are, respectively, the uncalibrated (raw output from the pipeline) metallicity and surface gravity. The effect of the calibration on the raw output can be seen in the top panel of Figure 4. The bottom panel shows that in the range \((-2, 0)\) the
DR5 and DR4 values are very similar. Above \([\text{M/H}] \approx 0\), the DR5 metallicities are higher than the DR4 ones and are in better agreement with the chemical abundance pipeline presented below (Section 8). We note that after metallicity calibration we do not rerun the pipeline to see if other stellar parameters change with this new metallicity.

### 6.3. Surface Gravity Calibrations

Measuring the surface gravity spectroscopically, and in particular from medium-resolution spectra around the IR CaT, is challenging. Nevertheless, the DR4 pipeline proved to perform in a relatively reliable manner, so no calibration was performed on \(\log g\). The uncertainties in the DR4 \(\log g\) values are of the order of \(\sim 0.2 - 0.3\) dex, with any offsets being mainly confined to the giant stars. In particular, an offset in \(\log g\) of \(\sim 0.15\) was detected for the red clump stars.

For the main DR5 catalog, the surface gravities are calibrated using both the asteroseismic \(\log g\) values of 72 giants from V17 and the \(\text{Gaia}\) benchmark dwarfs and giants (Heiter et al. 2015). Although the calibration presented in V17 focuses only on giant stars and should therefore perform better for these stars (see Section 11), the global DR5 \(\log g\) calibration is valid for all stars for which the stellar parameter pipeline provides \(T_{\text{eff}}, \log g, \) and [M/H].

Biases in \(\log g\) depended mostly on \(\log g\), so for the surface gravity calibration, we computed the offset between the pipeline output and the reference values, as a function of the pipeline output, and a low-order polynomial fitted to the residuals (see V17 for a more quantitative assessment). This quadratic expression defines our surface gravity calibration:

\[
\log g_{\text{DR5}} = \log g_{\text{p}} - (-0.515 + 0.026 \log g_{\text{p}} + 0.023 \log (g_{\text{p}}^2)).
\]

The calibration above affects mostly the giants but also allows a smooth transition of the calibration for the dwarfs. The red clump is now at \(\sim 2.5\) dex, consistent with isochrones for thin disk stars of metallicity \([\text{M/H}] = -0.1\) and age 7.5 Gyr (see Section 6.5). This calibration has the effect of increasing the minimum published \(\log g\) from 0 (as set by the learning grid) to \(\sim 0.5\). The maximum reachable \(\log g\) is \(\sim 5.2\) (instead of 5.5, as in DR4). Tests carried out with the Galaxia model (Sharma et al. 2011), where the RAVE selection function has been applied (W16), show that the calibration improves \(\log g\) even at these boundaries. We do caution, however, that special care should be taken for stars with \(\log g \gtrsim 0.75\) or \(\log g \lesssim 5\).

### 6.4. Effective Temperature Calibrations

Munari et al. (2014) showed that the DR4 effective temperatures for warm stars (\(T_{\text{eff}} \gtrsim 6000\) K) are underestimated by \(\sim 250\) K. This offset is evident when plotting the residuals against the reference (photometric) \(T_{\text{eff}}\), but is barely discernible when plotting them against the pipeline \(T_{\text{eff}}\). Consequently, it is difficult to correct for this effect. The calibration that we carry out changes \(T_{\text{eff},p}\) only modestly, and does not fully compensate for the (fortunately small) offsets (see Figure 6). The adopted calibration for effective
temperatures is
\[ T_{\text{eff,DRS}} = T_{\text{eff,p}} + (285 - 0.073T_{\text{eff,p}} + 40 \log g_p). \] (4)

6.5. Summary of the Calibrations

Figures 7 and 8 show, as functions of metallicity and effective temperature respectively, the residuals between the calibrated values and the set of reference stars that have been used. We show the log g comparison (first rows of Figures 7 and 8) for all sets of stars, and not only the stars in V17 and Jofré et al. (2014), which in the end were the only samples used to define the calibration. Although the derivations of log g in V17 and Jofré et al. (2014) are independent of each other, the shifts in log g between the two samples are small, so there is no concern that we could end up with nonphysical combinations of parameters.

Overall there are no obvious trends as a function of any stellar parameter, except the already mentioned mild trend in \( T_{\text{eff}} \) for the stars having \( 4 < \log g < 5 \) (seen in the middle row, last column of Figure 8). The absence of any strong bias in the parameters is also confirmed in the next sections, with additional comparisons with APOGEE, Gaia-ESO, and LAMOST stars (Section 7).

The effect of the calibrations on the \((T_{\text{eff}}, \log g)\) diagram is shown in Figure 9. The calibrations bring the distribution of stars into better agreement with the predictions of isochrones for the old thin disk and thick disk (yellow and red, respectively).

6.6. Estimation of the Atmospheric Parameter Errors and Robustness of the Pipeline

Using the error spectrum of each observation, 10 resampled spectra were computed for the entire database (see also Section 4). The SPARV algorithm was run on these spectra, the radial velocity estimated, and the spectra shifted to the rest frame. Subsequently, the pipeline of Kordopatis et al. (2013a) was run on these radial velocity-corrected spectra.

The dispersion of the derived parameters among the resampled spectra of each observation gives us an indication of the individual errors on \( T_{\text{eff}}, \log g, \) and \([M/H]\) and of the robustness of the pipeline. That said, because the noise is being introduced twice (once during the initial observation and once when resampling), the results should be considered as an overestimation of the errors (since we are dealing with an overall lower S/N).

Figure 10 shows the dispersion of each parameter determined from the spectra collected in 2006. We show both the simple standard deviation and the MAD estimator, which is more robust to outliers. The distribution of the internal errors (normalized to the peak of the black histogram) as given in Tables 1 and 2 of Kordopatis et al. (2013a) is also plotted. Figure 10 shows that the internal errors are consistent with the parameter dispersion we obtain from the resampled spectra, though the uncertainties calculated from the error spectra have a tail extending to larger error values. Therefore, for some stars, the true errors are considerably larger than those produced by the pipeline. This is not unexpected, as it reflects the degeneracies that hamper the IR CaT region, and also the fact...
that the resampled spectra have a lower S/N than the true observations, since the noise is introduced a second time.

The published DR5 parameters, however, are not the raw output of the pipeline, but are calibrated values. Since this calibration takes into account the output $T_{\text{eff}}$, $\log g$, and [M/H], it is also valuable to test the dispersion of the calibrated values. This is shown in Figure 11 for the same set of stars. As before, no large differences are introduced, indicative again of a valid calibration and reliable stellar parameter pipeline.

6.7. Completeness of Stellar Parameters

It is of value to consider the completeness of DR5 with respect to derived stellar parameters. To evaluate this, the stars that satisfy the following criteria are selected: S/N $\geq$ 20, $|\text{correctionRV}| < 10$ km s$^{-1}$, $\sigma(\text{RV}) < 8$ km s$^{-1}$, and $\text{correlationCoeff} > 10$ (see Kordopatis et al. 2013a).

The resulting distributions are shown in Figure 12. Whereas the magnitude bin 10.0 $< I_{\text{MASS}} < 10.8$ has the highest number of stars with spectral parameters, distances, and chemical abundances, the fractional completeness compared to 2MASS (bottom left panel) peaks in the magnitude bin 9.0 $< I_{\text{MASS}} < 10.0$. In this bin, we find that we determine stellar parameters for approximately 50% of 2MASS stars in the RAVE fields. We further estimate distances for 40% of stars, and chemical abundances for $\sim$20%. This fraction drops off significantly at fainter magnitudes.
Similarly, for the brighter bins we obtain stellar parameters for $\sim 55\%$ of Tycho-2 stars, distances for $\sim 45\%$ of stars, and similar trends in the completeness fraction of chemical abundances.

7. EXTERNAL VERIFICATION

Stars observed specifically for understanding the stellar parameters of RAVE, as well as stars observed that fortuitously overlap with high-resolution studies, are compiled to further assess the validity of the RAVE stellar parameter pipeline. As discussed above, calibrating the RAVE stellar parameter pipeline is not straightforward, and although a global calibration over the diverse RAVE stellar sample has been applied, the accuracy of the atmospheric parameters depends also on the stellar population probed. Therefore, for the specific samples investigated in this section, Table 4 summarizes the results of the external comparisons split into (i) hot, metal-poor dwarfs, (ii) hot, metal-rich dwarfs, (iii) cool, metal-poor dwarfs, (iv) cool, metal-rich dwarfs, (v) cool, metal-poor giants, and (vi) cool, metal-rich giants. The boundary between “metal-poor” and “metal-rich” occurs at $\mathrm{[M/H]} = -0.5$, and that between “hot” and “cool” lies at $T_{\text{eff}} = 5500$ K. The giants and dwarfs are divided at $\log g = 3.5$ dex. From here on, only the calibrated RAVE stellar parameters are used.

7.1. Cluster Stars

In the 2011B, 2012, and 2013 RAVE observing semesters, stars in various open and globular clusters were targeted with the goal of using the cluster stars as independent checks on the reliability of RAVE stellar parameters and their errors. RAVE stars observed within the targeted clusters that have also been studied externally from high-resolution spectroscopy are compiled, so a quantitative comparison of the RAVE stellar parameters can be made.

Table 3 lists clusters and their properties for which RAVE observations could be matched to high-resolution studies. The properties of open clusters come from the Milky Way global survey of star clusters (Kharchenko et al. 2013) and the properties of globular clusters come from the Harris catalog (Harris 1996, 2010 update). The number of RAVE stars that were crossmatched and the literature sources are also listed.

Figure 13 shows a comparison between the high-resolution cluster studies and the RAVE cluster stars. From this inhomogeneous sample of 75 overlap RAVE cluster stars with an $\text{AlgoConv} \neq 1$, the formal uncertainties in $T_{\text{eff}}$, $\log g$, and $\mathrm{[M/H]}$ are 300 K, 0.6 dex, and 0.04 dex, respectively, but decrease by a factor of almost two when only stars with
| Cluster ID | Alternative Name | R.A.  | Decl.  | Ang. Rad. (deg) | RV_{Heli} [Fe/H] | Dist. (kpc) | Age (Gyr) | Semester Targeted | Total # RAVE (AlgoConv = 0) | Comments |
|------------|------------------|-------|--------|----------------|----------------|-------------|-----------|------------------|--------------------------|----------|
| Pleiades   | Melotte 22, M45  | 03 47 00 | 24 07 00 | 6.2            | 5.5            | −0.036      | 0.13      | 0.14             | 2011B                    | 11 (8)   |
|            |                  |       |        |                |                |             |           |                  |                          | Funayama et al. (2009)     |
| Hyades     | Melotte 25       | 04 26 54 | 15 52 00 | 20             | 39.4           | 0.13        | 0.046     | 0.63             | 2011B                    | 5 (5)    |
|            |                  |       |        |                |                |             |           |                  |                          | Takeda et al. (2013)       |
| IC 4651    |                  | 17 24 49 | −49 56 00 | 0.24           | −31.0          | −0.102      | 0.888     | 1.8              | 2011B                    | 10 (4)   |
|            |                  |       |        |                |                |             |           |                  |                          | Carretta et al. (2014), Pasquini et al. (2004) |
| 47 Tuc GC  | NGC 104          | 00 24 05 | −72 04 53 | 0.42           | −18.0          | −0.72       | 4.5       | 13               | 2012B                    | 23 (12)  |
|            |                  |       |        |                |                |             |           |                  |                          | Cordero et al. (2014), Koch & McWilliam (2008), Carretta et al. (2009) |
| NGC 2477   | M93              | 07 52 10 | −38 31 48 | 0.45           | 7.3            | −0.192      | 1.450     | 0.82             | 2012B                    | 9 (4)    |
|            |                  |       |        |                |                |             |           |                  |                          | Bragaglia et al. (2008), Mishenina et al. (2015) |
| M67        | NGC 2682         | 08 51 18 | 11 48 00 | 1.03           | 33.6           | −0.128      | 0.890     | 3.4              | 2012A + 2013              | 1 (1)    |
|            |                  |       |        |                |                |             |           |                  |                          | Onehag et al. (2014)       |
| Blanco 1   |                  | 00 04 07 | −29 50 00 | 2.35           | 5.5            | 0.012       | 0.250     | 0.06             | 2013                     | 1 (1)    |
|            |                  |       |        |                |                |             |           |                  |                          | Ford et al. (2005)         |
| Omega Cen GC | NGC 5139 | 09 12 03.10 | −64 51 48.6 | 0.12           | 101.6          | −1.14       | 9.6       | 10               | 2013                     | 15 (2)   |
|            |                  |       |        |                |                |             |           |                  |                          | Johnson & Pilachowski (2010) |
| NGC 2632   | Praesepe         | 08 40 24.0 | +19 40 00 | 3.1            | 33.4           | 0.094       | 0.187     | 0.83             | 2012                     | 1 (0)    |
|            |                  |       |        |                |                |             |           |                  |                          | Yang et al. (2015)         |
SN 5 0 are considered (see Table 5). This is a ∼15% improvement on the same RAVE cluster stars in DR4.

7.2. Field Star Surveys

We have matched RAVE stars with the high-resolution studies of Gratton et al. (2000), Carrera et al. (2013), Ishigaki et al. (2013), Roederer et al. (2014), and Schlaufman & Casey (2014), which concentrate on bright, metal-poor stars, the study of Trevisan et al. (2011), which concentrates on old, metal-rich stars, and the studies of Ramírez et al. (2013), Reddy et al. (2003, 2006), Valenti & Fischer (2005), and Bensby et al. (2014), which target FGK stars in the solar neighborhood. Figures 14–16 compare stellar parameters from these studies with the DR5 values. Trends are detectable in log g for both giants and dwarfs. For the giants the same tendency for log g to be overestimated when it log g is small was evident in V17. In Figure 15 a similar, but less pronounced, tendency is evident in the log g values for dwarfs.
7.3. APOGEE

The Apache Point Observatory Galactic Evolution Experiment, part of the Sloan Digital Sky Survey and covering mainly the Northern Hemisphere, has made public near-IR spectra with a resolution of $R \sim 22,500$ for over 150,000 stars (DR12, Holtzman et al. 2015). Stellar parameters are provided only for APOGEE giant stars, and temperatures, gravities, $[\text{Fe/H}]$ metallicities, and radial velocities are reported to be accurate to $\sim 100$ K (internal), $\sim 0.11$ dex (internal), $\leq 0.1$ dex (internal), and $\sim 100$ m s$^{-1}$, respectively (Holtzman et al. 2015; Nidever et al. 2012). Despite the different hemispheres targeted by RAVE and APOGEE, there are $\sim 1100$ APOGEE stars that overlap with RAVE DR5 stars, two-thirds of these having valid APOGEE stellar parameters.

A comparison between the APOGEE and RAVE stellar parameters is shown in Figure 17. The zero-point and standard deviation for different subsets of S/N and AlgoConv are provided in Table 5. There appears to be a $\sim 0.15$ dex zero-point offset in $[\text{Fe/H}]$ between APOGEE and RAVE, as seen most clearly in the high S/N sample, and there is a noticeable break in log g where the cool main-sequence stars and stars along the giant branch begin to overlap. This is a consequence of degeneracies in the CaT region that affect the determination of log g (see Tables 1 and 2 in DR4).

7.4. LAMOST

The Large sky Area Multi-Object Spectroscopic Telescope is an ongoing optical spectroscopic survey with a resolution of $R \sim 1800$, and has gathered spectra for more than 4.2 million objects. About 2.2 million stellar sources, mainly with S/N $> 10$, have stellar parameters. Typical uncertainties are 150 K, 0.25 dex, 0.15 dex, and 5 km s$^{-1}$ for $T_{\text{eff}}$, log g, metallicity, and radial velocity, respectively (Xiang et al. 2014).

The overlap between LAMOST and RAVE comprises almost 3000 stars, including both giants and dwarfs. Figure 18 shows the comparison between the stellar parameters of RAVE and LAMOST. The giants (stars with log g $< 3$) and dwarfs (stars with log g $> 3$) exhibit different trends in log g, and the largest uncertainties in log g occur where these populations overlap in log g. The zero-point and standard deviation for the comparisons between RAVE and LAMOST stellar parameters are provided in Table 4.

7.5. GALAH

The GALAH Survey is a high-resolution ($R \sim 28,000$) spectroscopic survey using the HERMES spectrograph and Two Degree Field fiber positioner on the 3.9 m Anglo-Australian telescope. The first data release provides $T_{\text{eff}}$, log g, [\alpha/Fe], radial velocity, distance modulus, and reddening for 9860 Tycho-2 stars (Martell et al. 2016). There are $\sim 1800$ RAVE stars that overlap with a star observed in GALAH, spanning the complete range in temperature, gravity, and metallicity.

Figure 19 shows the comparison of stellar parameters between the RAVE and Galah overlap stars, and Table 4 quantifies the agreement between these two surveys.

7.6. GAIA-ESO

Gaia-ESO, a public spectroscopic survey observing stars in all major components of the Milky Way using the Very Large Telescope, provides 14,947 unique targets in DR2. The resolution of the stellar spectra ranges from $R \sim 17,000$ to $R \sim 47,000$. There are $\sim 100$ RAVE stars that overlap with a star observed in Gaia-ESO; half of these are situated around the $\eta$ Chamaeleontis Cluster (Mamajek et al. 1999), and a third are in the vicinity of the $\gamma$ Velorum cluster (Jeffries et al. 2014). The overlap sample is small and new internal values are being
Table 4
Estimates of the External Errors in the Stellar Parameters

| Stellar type                          | N      | $\sigma (T_{eff})$ | $\sigma (\log g)$ | $\sigma ([M/H])$ | $\sigma (T_{eff,IRFM})$ |
|---------------------------------------|--------|--------------------|-------------------|------------------|------------------------|
| Dwarfs ($\log g > 3.5$)               |        |                    |                   |                  |                        |
| Hot, all metallicities DR5            | 375    | 442                | 0.39              | 0.41             | 129                    |
| Hot, metal-poor DR5                   | 38     | 253                | 0.48              | 0.95             | 258                    |
| Hot, metal-rich DR5                   | 337    | 453                | 0.38              | 0.95             | 233                    |
| Cool, all metallicities DR5           | 332    | 250                | 0.75              | 0.41             | 187                    |
| Cool, metal-poor DR5                  | 68     | 303                | 0.87              | 0.61             | 301                    |
| Cool, metal-rich DR5                  | 264    | 233                | 0.72              | 0.29             | 146                    |
| Hot, all metallicities RAVE-on        | 510    | 411                | 0.56              | 0.37             | ...                    |
| Hot, metal-poor RAVE-on               | 95     | 498                | 0.94              | 0.55             | ...                    |
| Hot, metal-rich RAVE-on               | 415    | 389                | 0.41              | 0.32             | ...                    |
| Cool, all metallicities RAVE-on       | 267    | 291                | 0.62              | 0.24             | ...                    |
| Cool, metal-poor RAVE-on              | 49     | 417                | 0.75              | 0.32             | ...                    |
| Cool, metal-rich RAVE-on              | 218    | 255                | 0.57              | 0.20             | ...                    |
| Hot, all metallicities RAVE-on        | 260    | 210                | 0.29              | 0.16             | ...                    |
| Hot, metal-poor RAVE-on               | 30     | 260                | 0.39              | 0.16             | ...                    |
| Hot, metal-rich RAVE-on               | 230    | 201                | 0.28              | 0.15             | ...                    |
| Cool, all metallicities RAVE-on       | 185    | 202                | 0.50              | 0.17             | ...                    |
| Cool, metal-poor RAVE-on              | 48     | 256                | 0.70              | 0.21             | ...                    |
| Cool, metal-rich RAVE-on              | 137    | 164                | 0.41              | 0.13             | ...                    |
| Hot, all metallicities RAVE-on        | 314    | 273                | 0.34              | 0.21             | ...                    |
| Hot, metal-poor RAVE-on               | 55     | 354                | 0.61              | 0.36             | ...                    |
| Hot, metal-rich RAVE-on               | 259    | 253                | 0.24              | 0.16             | ...                    |
| Cool, all metallicities RAVE-on       | 187    | 250                | 0.54              | 0.17             | ...                    |
| Cool, metal-poor RAVE-on              | 35     | 303                | 0.65              | 0.21             | ...                    |
| Cool, metal-rich RAVE-on              | 152    | 237                | 0.49              | 0.15             | ...                    |
| Giants ($\log g < 3.5$)               |        |                    |                   |                  |                        |
| All, all metallicities                | 1294   | 156                | 0.48              | 0.17             | 110                    |
| Hot DR5                               | 28     | 240                | 0.45              | 0.30             | 261                    |
| Cool, metal-poor DR5                  | 260    | 211                | 0.58              | 0.20             | 93                     |
| Cool, metal-rich DR5                  | 1006   | 125                | 0.46              | 0.15             | 96                     |
| Hot RAVE-on                           | 1318   | 140                | 0.41              | 0.20             | ...                    |
| Cool, metal-poor RAVE-on              | 5      | 270                | 0.62              | 0.27             | ...                    |
| Cool, metal-rich RAVE-on              | 293    | 195                | 0.55              | 0.27             | ...                    |
| Hot RAVE-on                           | 1020   | 110                | 0.36              | 0.17             | ...                    |
| S/N > 40                              |        |                    |                   |                  |                        |
| Hot DR5                               | 22     | 189                | 0.46              | 0.24             | ...                    |
| Cool, metal-poor DR5                  | 225    | 210                | 0.58              | 0.20             | ...                    |
| Cool, metal-rich DR5                  | 843    | 113                | 0.44              | 0.13             | ...                    |
| Hot RAVE-on                           | 3      | 120                | 0.28              | 0.23             | ...                    |
| Cool, metal-poor RAVE-on              | 248    | 159                | 0.52              | 0.23             | ...                    |
| Cool, metal-rich RAVE-on              | 810    | 88                 | 0.33              | 0.15             | ...                    |
| Giants (asteroseismically calibrated sample) | N       | $\sigma (T_{eff,IRFM})$ | $\sigma (\log g)$ | $\sigma ([Fe/H])$ |
| All, all metallicities                | 332    | 169                | 0.37              | 0.21             | ...                    |
| Hot                                   | 11     | 640                | 0.39              | 0.28             | ...                    |
| Cool, metal-poor                      | 180    | 161                | 0.40              | 0.23             | ...                    |
| Cool, metal-rich                      | 835    | 107                | 0.29              | 0.15             | ...                    |
| S/N > 40                              |        |                    |                   |                  |                        |
| Hot                                   | 5      | 471                | 0.42              | 0.15             | ...                    |
| Cool, metal-poor                      | 154    | 170                | 0.38              | 0.21             | ...                    |
| Cool, metal-rich                      | 701    | 95                 | 0.28              | 0.12             | ...                    |
analyzed currently; still Table 4 quantifies the results between these two surveys.

8. ELEMENTAL ABUNDANCES

The elemental abundances for aluminum, magnesium, nickel, silicon, titanium, and iron are determined for a number of RAVE stars using a dedicated chemical pipeline that relies on a library of equivalent widths encompassing 604 atomic and molecular lines in the RAVE wavelength range. This chemical pipeline was first introduced by Boeche et al. (2011) and then improved upon for the DR4 data release.

Briefly, equivalent widths are computed for a grid of stellar parameter values in the following ranges: \( T_{\text{eff}} \) from 4000 to 7000 K, \( \log g \) from 0.0 to 0.5 dex, [M/H] from \(-2.5\) to \(+0.5\) dex, and five levels of abundances from \(-0.4\) to \(+0.4\) dex relative to the metallicity, in steps of 0.2 dex, using the solar abundances of Grevesse & Sauval (1998). Using the calibrated RAVE effective temperatures, surface gravities, and metallicities (see Section 5), the pipeline searches for the best-fitting model spectrum by minimizing the \( \chi^2 \) between the models and the observations.

The line list and specific aspects of the equivalent width library are given in Boeche et al. (2011) and the full scheme to compute the abundances is given in Section 5 of Kordopatis et al. (2013a). Abundances from the RAVE chemical abundance pipeline are provided only for stars fulfilling the following criteria:

1. \( T_{\text{eff}} \) must be between 4000 and 7000 K.
2. \( S/N > 20 \)
3. Rotational velocity, \( V_{\text{rot}} < 50 \) km s\(^{-1}\).

The highest quality of abundances will be determined for stars that satisfy the following additional constraints:

1. \( \chi^2 < 2000 \), where \( \chi^2 \) quantifies the mismatch between the observed spectrum and the best-matching model.
2. $\text{frac} > 0.7$, where $\text{frac}$ represents the fraction of the observed spectrum that satisfactorily matches the model.

3. $c_1$, $c_2$ and $c_3$ classification flags indicate that the spectrum is “normal” (see Matijević et al. 2012, for details on the classification flags).

4. AlgoConv value indicates the stellar parameter pipeline converged. AlgoConv = 0 indicates the highest quality result.

The precision and accuracy of the resulting elemental abundances are assessed in two ways. First, uncertainties in the elemental abundances are investigated from a sample of 1353 synthetic spectra. The typical dispersions are $\sigma \sim 0.05$ dex for $S/N = 100$ spectra, $\sigma \sim 0.1$ dex for $S/N = 40$ spectra and $\sigma \sim 0.25$ dex for $S/N = 20$ spectra. The exceptions are the element Fe, which has a smaller dispersion by a factor of two, and the element Ti, which has a larger dispersion...
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| Z      | Y    | [M/H] |
|--------|------|-------|
| 0.0010 | 0.249| -2.207|
| 0.0020 | 0.249| -1.906|
| 0.0030 | 0.249| -1.604|
| 0.0040 | 0.250| -1.355|
| 0.00112| 0.250| -1.156|
| 0.00200| 0.252| -0.903|
| 0.00320| 0.254| -0.697|
| 0.00400| 0.256| -0.598|
| 0.00562| 0.259| -0.448|
| 0.00800| 0.263| -0.291|
| 0.01000| 0.266| -0.191|
| 0.01120| 0.268| -0.139|
| 0.01300| 0.272| -0.072|
| 0.01600| 0.277| 0.024 |
| 0.02000| 0.284| 0.127 |
| 0.02500| 0.293| 0.233 |
| 0.03550| 0.312| 0.404 |
| 0.04000| 0.320| 0.465 |
| 0.04470| 0.328| 0.522 |
| 0.05000| 0.338| 0.581 |
| 0.06000| 0.355| 0.680 |

Note. We take and apply a scaled solar composition with \( Y = 0.2485 + 1.78 Z \).

by a factor of 1.5–2 (see Boeche et al. 2011; Kordopatis et al. 2013a, for details).

The number of measured absorption lines for an element, which is also provided in the DR5 data release, is, like S/N, a good indicator of the reliability of the abundance. The higher the number of measured lines, the better the expected precision. The relatively low uncertainty in the Fe abundances reflects the large number of its measurable lines at all stellar parameter values.

A second assessment of the performance of the chemical pipeline is provided by comparing the DR5 abundances in 98 dwarf stars with values given in Soubiran & Girard (2005) and in 203 giant stars with abundances in Ruchti et al. (2011). The dwarfs in Soubiran & Girard (2005) typically have RAVE S/N > 100, and the giants in Ruchti et al. (2011) have RAVE S/N in the range 30–90.

Figures 20 and 21 show the results obtained for the six elements from the RAVE chemical pipeline. In general, there is a slight improvement in the external comparisons from DR4, likely resulting from the improved DR5 calibration for the stellar parameters. The accuracy of the RAVE abundances depends on many variables, which can be interdependent in a nonlinear way, making it nontrivial to provide one value to quantify the accuracy of the RAVE elemental abundances. We also have not taken into account the errors in abundance measurements from high-resolution spectra. Here is a summary of the expected accuracy of the DR5 abundances, element by element.

1. **Magnesium**: The uncertainty is \( \sigma_{\text{Mg}} \sim 0.2 \) dex, slightly worse for stars with S/N < 40.
2. **Aluminum**: This is measured in RAVE spectra from only two isolated lines. Abundance errors are \( \sigma_{\text{Al}} \sim 0.2 \) dex, and slightly worse for stars with S/N < 40.
3. **Silicon**: This is one of the most reliably determined elements, with \( \sigma_{\text{Si}} \sim 0.2 \) dex, and slightly worse for stars with S/N < 40.
4. **Titanium**: The estimates are best for high-S/N, cool giants (\( T_{\text{eff}} \lesssim 5500 \) K and \( \log g < 3 \)). We suggest rejecting Ti abundances for dwarf stars. Uncertainties for cool giants are \( \sigma_{\text{Ti}} \sim 0.2 \) dex, and slightly worse for stars with S/N < 40.
5. **Iron**: A large number of measurable lines are available at all stellar parameter values. The expected errors are \( \sigma_{\text{Fe}} \sim 0.2 \) dex.
6. **Nickel**: Ni estimates should be used for high-S/N, cool stars only (\( T_{\text{eff}} < 5000 \) K). In this regime, \( \sigma_{\text{Ni}} \sim 0.25 \) dex, but it correlates with the number of measured lines (i.e., with S/N).
7. **\( \alpha \)-enhancement**: This is the average of [Mg/Fe] and [Si/Fe], and is a particularly useful measurement at low S/N. The expected uncertainty is \( \sigma_{\alpha} \sim 0.2 \) dex.

The green histogram in Figure 22 shows the distribution of [Fe/H] from the chemical pipeline. This is similar to the black histogram of [Fe/H] values in DR4 but shifted to slightly larger [Fe/H]. The red histogram of [M/H] values in DR5 is slightly narrower than either [Fe/H] histogram and peaks at slightly lower values than the DR5 [Fe/H] histogram.

9. DISTANCES, AGES, AND MASSES

In DR4 we included for the first time distances derived using the Bayesian method developed by Burnett & Binney (2010). This takes as its input the stellar parameters \( T_{\text{eff}}, \log g \), and [M/H] determined from the RAVE spectra, and \( J, H, \) and \( K_s \) magnitudes from 2MASS. This method was extended by Binney et al. (2014), who included dust extinction in the modeling and introduced an improvement in the description of the distance to the stars by providing multi-Gaussian fits to the full probability density function (pdf) in distance modulus. Previous data releases included distance estimates from different sources (Breddels et al. 2010; Zwitter et al. 2010), but the Bayesian pipeline has been shown to be more robust when dealing with atmospheric parameter values with large uncertainties, so it provided the recommended distance estimates for DR4 and the only estimates that we provide with DR5.

We provide distance estimates for all stars except those for which we do not believe we can find reliable distances, which include stars with the following DR5 characteristics:

1. \( \text{AlgoConv} = 1 \) or S/N < 20.
2. \( T_{\text{eff}} < 4000 \) K and \( \log g > 3.5 \) (i.e., cool dwarfs), and
3. \( T_{\text{eff}} > 7400 \) K and [M/H] < −1.2.

The distance pipeline applies the simple Bayesian statement

\[
P(\text{model} | \text{data}) = \frac{P(\text{data} | \text{model})P(\text{model})}{P(\text{data})},
\]

where in our case “data” refers to the inputs described above for a single star, and “model” comprises a star of specified initial mass \( M \), age \( \tau \), metallicity [M/H], and location, observed through a specified line-of-sight extinction. \( P(\text{data} | \text{model}) \) is determined assuming uncorrelated Gaussian uncertainties on all inputs, and using isochrones to find the values of the stellar parameters and absolute magnitudes of the model star. The uncertainties of the stellar parameters are assumed to be the quadratic sum of the quoted internal uncertainties and the external uncertainties calculated from
stars with $S/N > 40$ (Table 4). $P(\text{model})$ is our prior and $P(\text{data})$ is a normalization that we can safely ignore.

The method we use to derive the distances for DR5 is nearly the same as that used by DR4, and we refer readers to Binney et al. (2014) for details. We apply the same priors on stellar location, age, metallicity, and initial mass, and on the line-of-sight extinction to the stars. These are all described in Section 2 of Binney et al. (2014). The isochrone set that we use has been updated to the PARSEC v1.1 set (Bressan et al. 2012), which provide values for 2MASS $J$, $H$, and $K_s$ magnitudes, so we no longer need to obtain 2MASS magnitudes by transforming Johnston–Cousins–Glass magnitudes, as we did when calculating the distances for DR4. Whereas the isochrones used by Binney et al. (2014) went no lower in metallicity than $Z = 0.00220$ ([M/H] = −0.914), the new isochrones extend to $Z = 0.00010$ ([M/H] = −2.207)—see Table 6. The new isochrones have a clear impact on distances to stars at lower metallicities (Figure 23). Experiments on a subset of stars using isochrones more closely spaced in [M/H] found that the inclusion of more isochrones has negligible impact on the derived properties of the stars.

The distance pipeline determines a full pdf, $P(\text{model}|\text{data})$, for all the parameters used to describe the stars and their positions. We characterize this pdf in terms of expectation values and formal uncertainties for $[M/H]$, $\log_{10}(\tau)$, initial mass, and $\log_{10}(A_V)$ (marginalizing over all other properties). For the distance we provide several characterizations of the pdf: expectation values and formal uncertainties for the distance itself ($s$), for the distance modulus ($\mu$), and for the parallax $\varpi$. As pointed out by Binney et al. (2014), it is inevitable that the expectation values (denoted as e.g., $\langle s \rangle$) are such that $\langle s \rangle > s_{\text{med}} > 1/\langle \varpi \rangle$ (where $\log_{10}s_{\text{med}} = 1 + \langle \mu \rangle/5$ and $s$ is in parsecs). In addition we provide multi-Gaussian fits to the pdfs in distance modulus.

As shown in Binney et al. (2014), the pdfs in distance are not always well represented by an expectation value and uncertainty (which are conventionally interpreted as the mean and dispersion of a Gaussian distribution). A number of the pdfs are double- or even triple-peaked (typically because it cannot be definitively determined whether the star is a dwarf or a giant), and approximating this as a single Gaussian is extremely misleading. The multi-Gaussian fits to the pdfs in $\mu$ provide a compact representation of the pdf, and can be written as

$$P(\mu) = \sum_{k=1}^{N} \frac{f_k}{\sqrt{2\pi\sigma_k^2}} \exp\left(-\frac{(\mu - \mu_k)^2}{2\sigma_k^2}\right),$$

where the number of components $N$, the means $\mu_k$, weights $f_k$, and dispersions $\sigma_k$ are determined by the pipeline. DR5 gives these values as $\text{number\_of\_Gaussians}_\text{fit}$ (for $N$), and for $k = 1, 2, 3$ as $\text{mean}_k$, $\text{sig}_k$, and $\text{frac}_k$ (corresponding to $\mu_k$, $\sigma_k$, and $f_k$ respectively).

To determine whether a distance pdf is well represented by a given multi-Gaussian representation in $\mu$ we take bins in distance modulus of width $w_i = 0.2$, which contain a fraction $p_i$ of the total probability taken from the computed pdf and a fraction $P_i$ from the Gaussian representation, and compute the goodness-of-fit statistic

$$F = \sum_i \left( \frac{P_i}{w_i} - \frac{P_i}{w_i} \right)^2 \tilde{\sigma}w_i,$$

where the weighted dispersion

$$\tilde{\sigma}^2 = \sum_{k=1}^{N} f_k \sigma_k^2$$

is a measure of the overall width of the pdf. Our strategy is to represent the pdf with as few Gaussian components as possible, but if the value of $F$ is greater than a threshold value ($F = 0.04$), or the dispersion associated with the model differs by more than 20% from that of the complete pdf, then we conclude that the representation is inadequate, and add another Gaussian component to the representation (to a maximum of three components). For around 45% of the stars, a single Gaussian component proves adequate, while around 51% are fitted with two Gaussians, and only 4% require a third component. The value of $F$ is provided in the database as CHISQ_Binney and we also include a flag (denoted FitFLAG_Binney) that is nonzero if the dispersion of the fitted model differs by more than 20% from that of the computed pdf. Typically the problems flagged are rather minor (as shown in Figure 3 of Binney et al. 2014).

Using the derived distance moduli and extinctions, it is simple to plot an absolute color–magnitude diagram, from which we can check that the pipeline produces broadly sensible results. It was inspection of this plot that led us to filter out dwarfs with $T_{\text{eff}} \leq 4000$ K and hot, metal-poor stars, because they fell in implausible regions of the diagram. We show this plot, constructed from the filtered data, in Figure 24.

To test the output from the pipeline, we compare the derived parallaxes (and uncertainties) with those found by Hipparcos (van Leeuwen 2007) for the ~5000 stars common to the two catalogs. It is important to compare parallax with parallax, because, as noted before, $\langle \varpi \rangle > 1/\langle s \rangle$, so this is the only fair test. We therefore consider the statistic $\Delta$, which we define as

$$\Delta = \frac{\langle \varpi_{\text{DRS}} \rangle - \langle \varpi_H \rangle}{\sqrt{\sigma^2_{\varpi,\text{DRS}} + \sigma^2_{\varpi,H}}}.$$
where \( \varpi_H \) is the quoted Hipparcos parallax and \( \sigma_{\varpi,H} \) the quoted uncertainty, while \( \varpi_{\text{DR5}} \) and \( \sigma_{\varpi,\text{DR5}} \) are the same quantities from the distance pipeline. Ideally, \( \Delta \) would have a mean value of zero and a dispersion of unity.

In Figure 25 we plot a histogram of the values of \( \Delta \) for these stars separated into giants (\( \log g < 3.5 \)), cool dwarfs (\( \log g > 3.5 \) and \( T_{\text{eff}} \leq 5500 \) K), and hot dwarfs (\( \log g > 3.5 \) and \( T_{\text{eff}} > 5500 \) K), as well as for the subset of giants that we associate with the red clump (\( 1.7 < \log g < 2.4 \) and \( 0.55 < J - K_s < 0.8 \)). We have “sigma clipped” the values, such that none of the (very few) stars with \( \Delta > 4 \) contribute to the statistics. The results are all pleasingly close to having zero mean and a dispersion of unity, especially the giants. We tend to slightly overestimate the parallaxes of the hot dwarfs, and slightly underestimate those of the cool dwarfs (corresponding to underestimated distances to the hot dwarfs and overestimated distances to the cool dwarfs. This represents an improvement over the comparable figures for DR4, except for a very slightly worse mean value for the cool dwarfs (and even for these stars, there is an improvement in that the dispersion is now closer to unity).

With the release of the TGAS data it becomes possible to construct a figure such as Figure 25 using the majority of RAVE stars. Thus much more rigorous checks of our distance (parallax) estimates are now possible. When that has been done and systematics calibrated out, we will be able to provide distances to all stars that are more accurate than those based on either DR5 or TGAS alone, by feeding the TGAS data, including parallaxes, into the distance pipeline.

Where stars have been observed more than once by RAVE, we recommended using the distance (and other properties) obtained from the spectrum with the highest signal-to-noise ratio. However, DR5 reports distances from each spectrum.

10. IRFM TEMPERATURES

The IRFM (Blackwell & Shallis 1977; Blackwell et al. 1979) is one of the most accurate techniques for deriving stellar effective temperatures in an almost model-independent way. The basic idea is to measure for each star its bolometric flux and a monochromatic infrared flux. Their ratio is then compared to that obtained for a surface at \( T_{\text{eff}} \), i.e., \( \sigma_{T_{\text{eff}}} \) divided by the theoretical monochromatic flux. The latter quantity is relatively easy to predict for spectral types earlier than \( \sim M0 \), because the near-infrared region is dominated by the continuum, and the monochromatic flux is proportional to \( T_{\text{eff}} \) (Rayleigh–Jeans regime), so dependences on other stellar parameters (such as \([\text{Fe/H}]\) and \( \log g \)) and model atmospheres are minimized (as extensively tested in the literature, e.g., Alonso et al. 1996; Casagrande et al. 2006). The method thus ultimately depends on a proper derivation of stellar fluxes, from which \( T_{\text{eff}} \) can then be derived. Here we adopt an updated version of the IRFM implementation described in Casagrande et al. (2006, 2010), which has been validated against interferometric angular diameters (Casagrande et al. 2014) and combines APASS \( BVgr'iv' \) together with 2MASS \( JHK_s \) to recover the bolometric and infrared flux of each star. The flux outside photometric bands (i.e. the bolometric correction) is derived using a theoretical model flux at given \( T_{\text{eff}} \), \([\text{Fe/H}]\), and \( \log g \). An iterative procedure in \( T_{\text{eff}} \) is adopted to cope with the mildly model-dependent nature of the bolometric correction and of the theoretical surface infrared monochromatic flux. For each star, we interpolate over a grid of synthetic model fluxes, starting with an initial estimate of the stellar effective temperature and fixing \([\text{Fe/H}]\) and \( \log g \) to the RAVE values, until convergence is reached within 1 K in effective temperature.

In a photometric method such as the IRFM, reddening can have a non-negligible impact and must be corrected for. For each target RAVE provides an estimate of \( E(B - V) \) from Schlegel...
et al. (1998). These values, however, are integrated over the line
of sight, and in the literature there are several indications
suggesting that reddening from this map is overestimated,
particularly in regions of high extinction (e.g., Arce & Goodman
1999; Schlafly & Finkbeiner 2011). To mitigate this effect,
we recalibrate the map of Schlegel et al. (1998) using the
intrinsic color of clump stars, identified as number overdensities
in color distribution (and thus independently of the RAVE
spectroscopic parameters). We take the 2MASS stellar catalog,
tessellate the sky with boxes of $10^3 \times 10^2$, and select stars in the
magnitude range of RAVE. Within each box we can easily
identify the overdensity due to clump stars, whose position in
$J - K_s$ color is little affected by their age and metallicity. Thus,
despite the presence of metallicity and age gradients across the
Galaxy (e.g., Boeche et al. 2014; Casagrande et al. 2016),
we can regard the average $J - K_s$ color of clump stars as a standard
crayon. We take the sample of clump stars from Casagrande
et al. (2014), for which reddening is well constrained, and use
their median unreddened ($J - K_s)_0$ against the median measured
at each $n$-tessellation, to derive a value of reddening at each location $E(J - K_s) = (J - K_s)_0 - (J - K_s)_b$. We then compare these values of reddening with the median ones obtained
using the map of Schlegel et al. (1998) over the same
tessellation. The difference between the reddening values we
infer and those from the map is well fitted as function of log$(b)$
up to $\approx 40^\circ$ from the Galactic plane. We use this fit to rescale the
$E(B - V)$ from the map of Schlegel et al. (1998), thus
correcting for its tendency to overestimate reddening, while at the
same time keeping its superior spatial resolution ($\approx$arcmin).
For $|b| \geq 40^\circ$ the extinction is low and well described.

Figure 26 shows a comparison between the DR5 tempera-
tures and those from the IRFM, $T_{\text{eff,IRFM}}$. Stars with
temperatures cooler than $T_{\text{eff}} \sim 5300$ K show a good
agreement between $T_{\text{eff,IRFM}}$ and $T_{\text{eff,DR5}}$, with a scatter of
$\sim 150$ K, which is the typical uncertainty of the RAVE
temperatures. Stars hotter than $T_{\text{eff}} = 5300$ K have an offset
in temperature, in the sense that $T_{\text{eff,IRFM}}$ is approximately
350 K warmer than $T_{\text{eff,DR5}}$ at 5500 K. As the temperature
increases, the temperature offset decreases to $\sim 100$ K at
7000 K. This offset is consistent with what is seen in a
comparison between RAVE and other data sets (see, e.g.,
Table 4 and Figures 14 and 18), thus suggesting that the offset
is unlikely to stem from the IRFM only. From Table 4 it is
evident that the IRFM temperatures for especially the cool
dwarfs are in better agreement with high-resolution studies than
the spectroscopic DR5 temperatures.

Nevertheless, we remark that various reasons might be
responsible for this trend: first, the rescaling of the map of
Schlegel et al. (1998) is based on clump stars, so it is not
surprising that best agreement is found for giant stars. Turnoff
and main-sequence stars are on average closer than intrinsically
brighter giants, so despite the rescaling, $E(B - V)$ will on
average still be overestimated, implying higher effective
temperatures in the IRFM. Also, at the hottest $T_{\text{eff}}$ the
contribution of optical photometry becomes increasingly
important, as do proper control over the standardization, and
absolute calibration of the APASS photometry.

11. ASTEROSEISMICALLY CALIBRATED RED GIANT
CATALOG

Asteroseismic data provide a very accurate way to determine
surface gravities of red giant stars (e.g., Stello et al. 2008; Mosser
et al. 2010; Bedding et al. 2011). When solar-like
pulsations in red giants can be detected, the pulsation
frequencies, such as the average large frequency separation,
$\langle \Delta \nu \rangle$, and the frequency of maximum oscillation power, $\nu_{\text{max}}$,
can be used to obtain the density and surface gravity of the star. Exquisite data sets with which to search for oscillations have arisen in the space-based missions CoRoT and Kepler, and it has already been shown that their long data set in time gives the frequency resolution needed to extract accurate estimates of the basic parameters of individual modes covering several radial orders, such as frequencies, frequency splittings, amplitudes, and damping rates.

Pulsations in red giants have significantly longer periods and larger amplitudes than in solar-type stars, so oscillations may be detected in fainter (more numerous) targets observed with long cadence. Further, the seismic log g values are almost fully independent of the input physics in the stellar evolution models that are used (e.g., Gai et al. 2011). This makes the use of red giants with asteroseismic log g values ideal to check and calibrate surface gravities that are obtained spectroscopically.

V17 present 72 RAVE stars with solar-like oscillations detected by the K2 mission. The finite length and cadence of the observations of a K2 field means there is a limit to our ability to extract properties from solar-like oscillations, and hence for how well \( \Delta \nu \) and \( \nu_{\text{max}} \) can be obtained (e.g., Davies & Miglio 2016). This means that the asteroseismic calibration based on the K2 stars is limited to roughly the range of \( 2.1 < \log g < 3.35 \) dex. For the color interval \( 0.50 < J - K_s < 0.85 \), which was shown to be appropriate for selecting red giant stars in the Kepler field, the spectroscopic gravities present in the RAVE catalog are calibrated against the seismic gravities. This calibration is a function only of RAVE log g, and does not depend on photometric color, metallicity, or S/N. Whereas the reddening maps of Schlegel et al. (1998) indicate that the \( (J - K) \) reddening in the K2 field is negligible, RAVE observes many reddened stars. Therefore, the dereddened color range is kept unchanged, and DR5 includes log g calibrated according to V17 only when the dereddened color \( (J - K_s) \) lies in the interval (0.50, 0.85).

There are 207,050 RAVE stars that fall within \( 0.50 < (J - K_s) < 0.85 \); 200,524 of these have a RAVE log g, enabling the application of an asteroseismic calibration. Because of the RAVE log g uncertainties, misclassifications of red giants can occur, i.e., red giants can have gravities that indicate they are dwarfs or supergiant stars. Therefore each asteroseismically calibrated RAVE star has a flag, Flag050, indicating whether the seismically calibrated log g, log g\(_{\text{seis}}\), and the DR5 log g\(_{\text{DR5}}\) are within 0.5 dex of each other. The flag Flag\(_{\text{M}}\) specifies whether all 20 classification flags of Matijević et al. (2012) point to the star being “normal”, which likely means the star is indeed a typical red giant. Therefore, stars with both Flag050 = 1 and Flag\(_{\text{M}}\) = 1 point to an especially desirable sample of asteroseismically calibrated giants.

Figure 27 shows log g\(_{\text{DR5}}\) compared to the gravities from the RAVE stars observed by the APOGEE, GALAH, and Gaia-ESO surveys, as well as the RAVE cluster and external stars (from Section 7). The scatter about these 906 stars with
S/N > 40, Flag_M = 1, and Algo_Conv = 0 is $\sigma \log g_{\mathrm{ec}} = 0.35$ dex. This is a 12% smaller scatter than when using the RAVE DR5 log $g$ from the main catalog. When additionally imposing the criterion Flag_050 = 1, $\sigma \log g_{\mathrm{ec}} = 0.26$ dex, which is a 25% smaller scatter than when using the RAVE DR5 log $g$. Tables 4 and 5 summarize how $\log g_{\mathrm{ec}}$ compares with external results. The criterion Flag_M = 1 is implemented in these comparisons.

Combining the $\log g_{\mathrm{ec}}$ with the temperatures from the IRFM, the RAVE chemistry (Section 8) and distance pipeline (Section 9) are rerun. Neither the uncertainty in chemical pipeline nor the uncertainty in distance changes when using the more accurate $\log g_{\mathrm{ec}}$ and IRFM temperatures as an input, as seen in Figure 28. The seismically calibrated giants are presented in a separate table, along with the elemental abundances and distances derived.

12. USE OF DIFFERENT RAVE STELLAR PARAMETERS

12.1. DR5 Main Catalog versus RAVE-on

While our official DR parameters are constantly under improvement, other approaches to determining parameters from RAVE spectra have become public. One example is the result from C16, who present the RAVE-on catalog by the data-driven approach The Cannon. In short, this method is based on training the data on a set for which more information is known by independent means (i.e., spectra of the stars in other wavelength domains, asteroseismic observations, etc.). The disadvantage, however, is that the performance of the results relies fully on the training set. For example, as seen in C16, if the training set does not contain metal-poor stars, the derived metallicities from survey stars will lack a metal-poor population as well. The RAVE training sample used in C16 was inhomogeneous, using RAVE overlap stars from APOGEE, Fulbright et al. (2010), and Ruchti et al. (2011) for the giants, and RAVE overlap stars from LAMOST and the fourth RAVE data release for the main-sequence stars. Unlike for the giants, the training sample for the main-sequence stars did not have known elemental abundances, so no elemental abundances could be derived for main-sequence stars.

The main RAVE DR5 catalog, on the other hand, is based on stellar physics—the use of a grid of synthetic spectra over a large parameter space is utilized to derive stellar parameters. Therefore for each star there is a physical justification ensuring the coherence of the obtained stellar parameters. This leads to cases in which no feasible match to a theoretical spectrum can be made, and so unlike in The Cannon, there are instances in which the algorithm does not converge. Also, stellar parameters are obtained along the gridlines of the synthetic spectra, leading to pixelization of the values, different visually to the smooth interpolation of The Cannon.

Figure 29 shows the metallicities and Mg elemental abundances of thin-disk, thick-disk, and halo RAVE stars for the RAVE DR5 and RAVE-on stars. The maximum distance above the plane ($\sigma_{\max}$), rotational velocity, and eccentricity were used to separate these components as described by Boeche et al. (2013). These parameters were computed by integrating the orbits of the RAVE stars using galpy (Bovy 2015), where the input parameters were the radial velocities and distances presented here, as well as the TGAS proper motions. We opted to not use the TGAS parallaxes to determine distances, because this is nontrivial (Bailer-Jones 2015; Astramadja & Bailer-Jones 2016).

Figure 29 illustrates the narrower chemical sequences of RAVE-on, due in part to smaller formal uncertainties in [Mg/Fe] and [Fe/H], and the smooth interpolation of the stellar parameters (i.e., no pixelization). It can also be seen that RAVE DR5 has a larger sample of stars with elemental abundances, and a more physical distribution for stars with [Fe/H] < −1 dex. This is due to the difficulty of obtaining main-sequence stars needed to train The Cannon (C16).
Table 4 quantifies the agreement from external stars of the $T_{\text{eff}}$, log g, and [Fe/H] presented in RAVE-on and in RAVE DR5. C16 performed external validation of the RAVE-on stellar parameters on cool stars (F, G, and K stars), and here we extend this. There is no significant difference in the precision when comparing the RAVE-on and RAVE DR5 stellar parameters to those from high-resolution stars. RAVE-on lacks metal-poor stars in the training sample, leading to a worse agreement for stars with [Fe/H] metallicities more metal-poor than $-1$ dex. It also is on a different metallicity scale than RAVE DR5, on average 0.15 dex more metal-poor than RAVE DR5. There are more RAVE stars with derived stellar parameters—$T_{\text{eff}}$, log g, and [Fe/H]—in RAVE-on, and more stars with elemental abundances in RAVE DR5.

12.2. DR5 Main Catalog $T_{\text{eff}}$ versus IRFM $T_{\text{eff}}$

The IRFM temperatures and those from the main DR5 are similar, as shown in Figure 26, and as discussed in Section 10. However, there is better agreement between RAVE stars observed from high-resolution studies and $T_{\text{eff,IRFM}}$ (see Table 4). Moreover, $T_{\text{eff,IRFM}}$ is available for 95% of the RAVE stars, and is independent of S/N. Temperatures from the IRFM are critical for the RAVE stars that were released in DR1, because during the first year of RAVE operations, no blocking filter was used to isolate the spectral range required, and as a result, the spectra collected were contaminated by the second order. Hence, although the determination of radial velocities is still straightforward, stellar parameters cannot be reliably determined from the spectra. IRFM temperatures are further especially valuable for stars with temperatures lower than 4000 K and for stars hotter than 8000 K, because the main DR5 catalog is only able to determine temperatures for stars in the range 4000–8000 K.

12.3. DR5 Main Catalog log g versus log $g_{\text{sc}}$

A direct asteroseismic calibration can be carried out for RAVE stars with colors in the range $0.50 < (J - K_s) < 0.85$, as described by V17. This calibration uses the raw DR5 log g as a starting point, and therefore any problems in the derivation of the raw DR5 log g are also carried over to log $g_{\text{sc}}$. Figure 27 shows how log $g_{\text{sc}}$ compares to log $g_{\text{DR5}}$ for external stars observed with high resolution. log $g_{\text{sc}}$ agrees with external estimates ~12% better than log $g_{\text{DR5}}$. However, we note the linear relation between log $g_{\text{sc}}$ and gravities from the literature, suggesting that minor biases are present in log $g_{\text{sc}}$, in a sense that log g values less than 2.3 dex are underestimated and log g values greater than 2.8 dex are overestimated. This can be minimized by selecting stars with Flag50 = 1. There is no correlation between literature log g and log $g_{\text{DR5}}$.

13. DIFFERENCES BETWEEN DR4 AND DR5

RAVE DR5 differs from DR4 in a number of ways, as listed below.

1. The DR5 RAVE sample is larger than DR4 by ~30,000 stars. This is due in part to the inclusion of the 2013 data, but mainly to the improvement of the DR5 reduction pipeline, which now processes data on a fiber-by-fiber basis instead of a field-by-field basis.

2. The DR1 data are now ready to be ingested through the same reduction pipeline, improving the homogeneity of the DR5 radial velocities compared to those in DR4.

3. The error spectra now available for all RAVE stars have yielded more accurate uncertainties on the RAVE radial velocities and stellar parameters, especially for low-S/N and hot stars. We plan to extend the analysis of error spectra to the chemical elements in a future release.

4. A new calibration of $T_{\text{eff}}$, log g, and [M/H] has been applied, increasing the accuracy of the stellar parameters by up to 15%. This calibration is employed mainly because there are now RAVE stars with log g values determined asteroseismically (V17). The metal-rich tail of the RAVE stars has also been re-investigated, by increasing the number of calibration stars in the supersolar metallicity regime. Hence the updated DR5 stellar parameters mainly improve the gravities of the giants and the supersolar [M/H] stars. Figure 30 shows how the atmospheric parameters in DR5 differ from those in DR4.

5. A sample of RAVE giants is provided for which the V16 asteroseismic calibration can be applied. These log g parameters are the most accurate, but can only be applied to stars that fall within 0.50 < $(J - K_s) < 0.85$.

6. Although the chemical pipeline is the same as the one employed in DR4, the stellar parameters fed into this pipeline are better calibrated, and hence the resulting elemental abundances are slightly changed. The [Fe/H] and $[\text{X}/\text{Fe}]$ abundances are shifted by ~0.1 dex to be more metal-rich than in DR4.

7. The distance pipeline has been improved, especially for the metal-poor stars. In DR5, we list individual distances per spectrum and not per star; for stars that have been observed more than once (indicated by the Rep_Flag), we recommend use of the distance from the spectrum with the highest S/N.

8. For the first time, photometry from APASS and WISE can be matched with RAVE stars. This development opens new ways to do science with the database. For example, Figure 31 shows the RAVE giants in a 2MASS–WISE color–color plot. The most metal-poor giants observed by RAVE ([Fe/H] < $-2$ dex) are overplotted in red. These metal-poor stars have been identified by projecting all RAVE spectra on a low-dimensional manifold using the t-Distributed Stochastic Neighbor Embedding (t-SNE) and then reanalyzing the metallicity, via the CaT lines, of all RAVE stars in the manifold that is mostly populated by very metal-poor stars (G. Matijević et al. 2017, in preparation). It is evident that they occupy a distinct WISE color range. The comprehensive RAVE data set may be used as a test bed to define cuts in color space to select metal-poor candidates, which can then be applied to fainter samples than RAVE probed or to regions RAVE has not surveyed (e.g., Schlaufman & Casey 2014).

9. The inclusion of APASS photometry also allows for the determination of IRFM temperatures, which are provided for more than 95% of the RAVE sample.

14. CONCLUSIONS

The RAVE DR5 presents radial velocities for 457,589 individual stars in the brightness range $9 < I < 12$ mag.
Table 7
Main DR5 Catalog Description

| Col. | Format | Units | NULL | Label | Explanations |
|------|--------|-------|------|-------|--------------|
| 1    | char   | ...   | N    | RAVE_OBS_ID | Target designation |
| 2    | char   | ...   | N    | HEALPix | Hierarchical Equal-Area iso-Latitude Pixelisation value (Note 1) |
| 3    | char   | ...   | N    | RAVEID | RAVE target designation |
| 4    | double | deg   | N    | RAdeg | Right ascension |
| 5    | double | deg   | N    | Ddeg | Declination |
| 6    | double | deg   | N    | Glon | Galactic longitude |
| 7    | double | deg   | N    | Glat | Galactic latitude |
| 8    | float  | km $^{-1}$ | N   | HRV | Heliocentric radial velocity |
| 9    | float  | km $^{-1}$ | N   | eHRV | HRV error |
| 10   | float  | km $^{-1}$ | N   | StdDev_HRV | Standard deviation in HRV from 10 resampled spectra |
| 11   | float  | km $^{-1}$ | N   | MAD_HRV | Median absolute deviation in HRV from 10 resampled spectra |
| 12   | float  | STN_SPARV | Y   | Signal-to-noise ratio calculated by SPARV (Note 2) |
| 13   | float  | ...   | Y    | S/N_K | Signal-to-noise value (Note 2) |
| 14   | float  | K     | Y    | Teff_K | Effective temperature (Note 2) |
| 15   | float  | K     | Y    | Teff_N_K | Calibrated effective temperature (Note 2) |
| 16   | float  | K     | Y    | eTeff_K | Error effective temperature (Note 2) |
| 17   | float  | K     | N    | MAD_Teff_K | Median absolute deviation in Teff_K from 10 resampled spectra |
| 18   | float  | K     | N    | StdDev_Teff_K | Standard deviation in Teff_K from 10 resampled spectra |
| 19   | float  | dex   | Y    | logg_K | Log gravity (Note 2) |
| 20   | float  | dex   | Y    | logg_N_K | Calibrated log gravity (Note 2) |
| 21   | float  | dex   | Y    | elogg_K | Error log gravity (Note 2) |
| 22   | float  | dex   | N    | MAD_logg_K | Median absolute deviation in logg_K from 10 resampled spectra |
| 23   | float  | dex   | N    | StdDev_logg_K | Standard deviation in logg_K from 10 resampled spectra |
| 24   | float  | dex   | Y    | Met_K | Metallicity [M/H] (Note 2) |
| 25   | float  | dex   | Y    | eMet_K | Error metallicity [M/H] (Note 2) |
| 26   | float  | dex   | N    | MAD_Met_K | Median absolute deviation in Met_K from 10 resampled spectra |
| 27   | float  | dex   | N    | StdDev_Met_K | Standard deviation in Met_K from 10 resampled spectra |
| 28   | float  | ...   | Y    | CHISQ_K | $\chi^2$ of the stellar parameter pipeline (Note 2) |
| 29   | float  | ...   | Y    | Algo_Conv_K | Quality flag for stellar parameter pipeline [0...4] (Note 2, Note 4) |
| 30   | float  | K     | Y    | Teff_IR | Temperature from infrared flux method |
| 31   | float  | K     | Y    | eTeff_IR | Internal error on Teff_IR |
| 32   | char   | ...   | N    | IR_direct | infrared flux method flag (Note 5) |
| 33   | float  | dex   | Y    | Mg | Abundance of Mg [Mg/H] |
| 34   | float  | dex   | Y    | eMg | Error abundance [Mg/H] |
| 35   | int    | ...   | Y    | Mg_N | Number of spectral lines used for calculation of abundance |
| 36   | float  | dex   | Y    | Al | Abundance of Al [Al/H] |
| 37   | int    | ...   | Y    | Al_N | Number of spectral lines used for calculation of abundance |
| 38   | float  | dex   | Y    | Si | Abundance of Si [Si/H] |
| 39   | int    | ...   | Y    | Si_N | Number of spectral lines used for calculation of abundance |
| 40   | float  | dex   | Y    | Ti | Abundance of Ti [Ti/H] |
| 41   | int    | ...   | Y    | Ti_N | Number of spectral lines used for calculation of abundance |
| 42   | float  | dex   | Y    | Fe | Abundance of Fe [Fe/H] |
| 43   | int    | ...   | Y    | Fe_N | Number of spectral lines used for calculation of abundance |
| 44   | float  | dex   | Y    | Ni | Abundance of Ni [Ni/H] |
| 45   | int    | ...   | Y    | Ni_N | Number of spectral lines used for calculation of abundance |
| 46   | float  | dex   | Y    | Alpha_c | Alpha-enhancement from chemical pipeline (Note 2) |
| 47   | float  | ...   | Y    | CHISQ_c | $\chi^2$ of the chemical pipeline (Note 2) |
| 48   | float  | ...   | Y    | frac_c | Fraction of spectrum used for calculation of abundances (Note 2) |
| 49   | float  | mag   | Y    | AV_Schlegel | Total extinction in V-band from Schlegel et al. (1998) |
| 50   | float  | kpc   | Y    | distance | Spectrophotometric distance (Binney et al. 2014) |
| 51   | float  | kpc   | Y    | edistance | Error on distance (Binney et al. 2014) |
| 52   | float  | mag   | Y    | log_Av | Log Av extinction (Binney et al. 2014) |
| 53   | float  | mag   | Y    | elog_Av | Error on log_Av (Binney et al. 2014) |
| 54   | float  | mas   | Y    | parallax | Spectrophotometric parallax (Binney et al. 2014) |
| 55   | float  | mas   | Y    | eparallax | Error on parallax (Binney et al. 2014) |
| 56   | float  | mag   | Y    | DistanceModulus_Binney | Distance modulus (Binney et al. 2014) |
| 57   | float  | mag   | Y    | eDistanceModulus_Binney | Distance modulus (Binney et al. 2014) |
| 58   | int    | ...   | Y    | Fit_Flag_Binney | See final paragraph Section 3 of Binney et al. (2014) |
| 59   | float  | ...   | Y    | FitQuality_Binney | Given by symbol “F” in Equation (15) of Binney et al. (2014) |
| 60   | int    | ...   | Y    | N_Gauss_fit | Number of components required for multi-Gaussian distance modulus fit |
| 61   | int    | ...   | Y    | Gauss_mean_1 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 62   | float  | ...   | Y    | Gauss_sigma_1 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 63   | float  | ...   | Y    | Gauss_frac_1 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
Table 7  
(Continued)

| Col. | Format | Units | NULL | Label | Explanations |
|------|--------|-------|------|-------|--------------|
| 64   | float  | ...   | Y    | Gauss_mean_2 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 65   | float  | ...   | Y    | Gauss_sigma_2 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 66   | float  | ...   | Y    | Gauss_frac_2 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 67   | float  | ...   | Y    | Gauss_mean_3 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 68   | float  | ...   | Y    | Gauss_sigma_3 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 69   | float  | ...   | Y    | Gauss_frac_3 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 70   | char   |       | Y    | c1     | n.th minimum distance (Note 6) |
| 71   | char   |       | Y    | c2     | n.th minimum distance (Note 6) |
| 72   | char   |       | Y    | c3     | n.th minimum distance (Note 6) |
| 73   | char   |       | Y    | c4     | n.th minimum distance (Note 6) |
| 74   | char   |       | Y    | c5     | n.th minimum distance (Note 6) |
| 75   | char   |       | Y    | c6     | n.th minimum distance (Note 6) |
| 76   | char   |       | Y    | c7     | n.th minimum distance (Note 6) |
| 77   | char   |       | Y    | c8     | n.th minimum distance (Note 6) |
| 78   | char   |       | Y    | c9     | n.th minimum distance (Note 6) |
| 79   | char   |       | Y    | c10    | n.th minimum distance (Note 6) |
| 80   | char   |       | Y    | c11    | n.th minimum distance (Note 6) |
| 81   | char   |       | Y    | c12    | n.th minimum distance (Note 6) |
| 82   | char   |       | Y    | c13    | n.th minimum distance (Note 6) |
| 83   | char   |       | Y    | c14    | n.th minimum distance (Note 6) |
| 84   | char   |       | Y    | c15    | n.th minimum distance (Note 6) |
| 85   | char   |       | Y    | c16    | n.th minimum distance (Note 6) |
| 86   | char   |       | Y    | c17    | n.th minimum distance (Note 6) |
| 87   | char   |       | Y    | c18    | n.th minimum distance (Note 6) |
| 88   | char   |       | Y    | c19    | n.th minimum distance (Note 6) |
| 89   | char   |       | Y    | c20    | n.th minimum distance (Note 6) |
| 90   | int    |       | -    |        | 0: single observation, 1: more than one observation |
| 91   | int    |       | -    |        | 0: not a targeted observation, 1: targeted observation |
| 92   | int    |       | -    |        | 0: outside RAVE selection function footprint, 1: inside footprint |
| 93   | char   |       | -    | Y      | ID_TGAS_source | TGAS target designation |
| 94   | char   |       | -    | Y      | MatchFlag_TGAS | Crossmatch quality flag (Note 7) |
| 95   | float  | deg   | Y    | RA_TGAS | TGAS right ascension (J2015) |
| 96   | float  | deg   | Y    | DE_TGAS | TGAS declination (J2015) |
| 97   | float  | mas yr⁻¹ | Y    | pmRA_TGAS | Proper motion RA from TGAS—ô cos(δ) |
| 98   | float  | mas yr⁻¹ | Y    | pmRA_error_TGAS | Standard error of proper motion in RA from TGAS |
| 99   | float  | mas yr⁻¹ | Y    | pmDE_TGAS | Proper motion in DE from TGAS—δ |
| 100  | float  | mas yr⁻¹ | Y    | pmDE_error_TGAS | Standard error of proper motion in DE from TGAS |
| 101  | float  | mas     | Y    | parallax_TGAS | Parallax from TGAS |
| 102  | float  | mas     | Y    | parallax_error_TGAS | Standard error of parallax from TGAS |
| 103  | float  | mag     | Y    | phot_g_mean_mag_TGAS | G-band mean magnitude from TGAS |
| 104  | float  | e/μs    | Y    | phot_g_mean_flux_TGAS | G-band mean flux from TGAS |
| 105  | float  | e/μs    | Y    | phot_g_mean_flux_error_TGAS | Error on G-band mean flux from TGAS |
| 106  | char   | -       | Y    | ID_Hipparcos | Hipparcos target designation |
| 107  | char   | -       | Y    | ID_TYCHO2 | Tycho-2 target designation |
| 108  | float  | arcsec  | Y    | Dist_TYCHO2 | Center distance to target catalog |
| 109  | char   | ...     | Y    | MatchFlag_TYCHO2 | Crossmatch quality flag (Note 6) |
| 110  | float  | mag     | Y    | BTmag_TYCHO2 | B_T magnitude from Tycho-2 |
| 111  | float  | mag     | Y    | eBTmag_TYCHO2 | Error on B_T mag from Tycho-2 |
| 112  | float  | mag     | Y    | VTmag_TYCHO2 | V_T magnitude from Tycho-2 |
| 113  | float  | mag     | Y    | eVTmag_TYCHO2 | Error V_T magnitude from Tycho-2 |
| 114  | float  | mas yr⁻¹ | Y    | pmRA_TYCHO2 | Proper motion RA from Tycho-2 |
| 115  | float  | mas yr⁻¹ | Y    | epmA_RA_TYCHO2 | Error proper motion RA from Tycho-2 |
| 116  | float  | mas yr⁻¹ | Y    | pmDE_TYCHO2 | Proper motion DE from Tycho-2 |
| 117  | float  | mas yr⁻¹ | Y    | epmA_DE_TYCHO2 | Error proper motion DE from Tycho-2 |
| 118  | char   | ...     | Y    | ID_UCAC4 | UCAC4 target designation |
| 119  | float  | arcsec  | Y    | Dist_UCAC4 | Center distance to target catalog |
| 120  | char   | ...     | Y    | MatchFlag_UCAC4 | Crossmatch quality flag (Note 7) |
| 121  | float  | mas yr⁻¹ | Y    | pmRA_UCAC4 | Proper motion RA from UCAC4 |
| 122  | float  | mas yr⁻¹ | Y    | epmA_UCAC4 | Error proper motion RA from UCAC4 |
| 123  | float  | mas yr⁻¹ | Y    | pmDE_UCAC4 | Proper motion DE from UCAC4 |
| 124  | float  | mas yr⁻¹ | Y    | epmA_DE_UCAC4 | Error proper motion DE from UCAC4 |
| 125  | char   | ...     | Y    | ID_PPMXL | PPMXL target designation |
| 126  | float  | arcsec  | Y    | Dist_PPMXL | Center distance to target catalog |
Table 7
(Continued)

| Col. | Format | Units | NULL | Label | Explanations |
|------|--------|-------|------|-------|--------------|
| 127  | char   |       | Y    | MatchFlag_PPMXL | Crossmatch quality flag (Note 7) |
| 128  | float  | mas yr | Y    | pmRA_PPMXL | Proper motion RA from PPMXL |
| 129  | float  | mas yr | Y    | epmRA_PPMXL | Error proper motion RA from PPMXL |
| 130  | float  | mas yr | Y    | pmDE_PPMXL | Proper motion DE from PPMXL |
| 131  | float  | mas yr | Y    | epmDE_PPMXL | Error proper motion DE from PPMXL |
| 132  | char   |       | Y    | ID_2MASS | 2MASS target designation |
| 133  | float  | arcsec | Y    | Dist_2MASS | Center distance to target catalog |
| 134  | char   |       | Y    | MatchFlag_2MASS | Crossmatch quality flag (Note 7) |
| 135  | double | mag   | Y    | Jmag_2MASS | J magnitude |
| 136  | double | mag   | Y    | eJmag_2MASS | Error J magnitude |
| 137  | double | mag   | Y    | Hmag_2MASS | H magnitude |
| 138  | double | mag   | Y    | eHmag_2MASS | Error H magnitude |
| 139  | double | mag   | Y    | Kmag_2MASS | K magnitude |
| 140  | double | mag   | Y    | eKmag_2MASS | Error K magnitude |
| 141  | char   |       | Y    | ID_ALLWISE | WISE target designation |
| 142  | double | arcsec | Y    | Dist_ALLWISE | Center distance to target catalog |
| 143  | char   |       | Y    | MatchFlag_ALLWISE | Crossmatch quality flag (Note 7) |
| 144  | double | mag   | Y    | W1mag_ALLWISE | W1 magnitude |
| 145  | double | mag   | Y    | eW1mag_ALLWISE | Error W1 magnitude |
| 146  | double | mag   | Y    | W2mag_ALLWISE | W2 magnitude |
| 147  | double | mag   | Y    | eW2mag_ALLWISE | Error W2 magnitude |
| 148  | double | mag   | Y    | W3mag_ALLWISE | W3 magnitude |
| 149  | double | mag   | Y    | eW3mag_ALLWISE | Error W3 magnitude |
| 150  | double | mag   | Y    | W4mag_ALLWISE | W4 magnitude |
| 151  | double | mag   | Y    | eW4mag_ALLWISE | Error W4 magnitude |
| 152  | char   |       | Y    | cc_flags_ALLWISE | Prioritized artifacts affecting the source in each band |
| 153  | int    |       | Y    | ext_flg_ALLWISE | Probability source morphology is not consistent with single PSF |
| 154  | char   |       | Y    | var_flg_ALLWISE | Probability that flux varied in any band greater than amount expected from unc.s |
| 155  | char   |       | Y    | ph_qual_ALLWISE | Photometric quality of each band (A = highest, U = upper limit) |
| 156  | double | arcsec | Y    | Dist_APASSDR9 | Center distance to target catalog |
| 157  | char   |       | Y    | MatchFlag_APASSDR9 | Crossmatch quality flag (Note 7) |
| 158  | double | mag   | Y    | Bmag_APASSDR9 | B magnitude |
| 159  | double | mag   | Y    | eBmag_APASSDR9 | Error B magnitude |
| 160  | double | mag   | Y    | Vmag_APASSDR9 | V magnitude |
| 161  | double | mag   | Y    | eVmag_APASSDR9 | Error V magnitude |
| 162  | double | mag   | Y    | gpmag_APASSDR9 | g' magnitude |
| 163  | double | mag   | Y    | egpmag_APASSDR9 | Error g' magnitude |
| 164  | double | mag   | Y    | rpmag_APASSDR9 | r' magnitude |
| 165  | double | mag   | Y    | erpmag_APASSDR9 | Error r' magnitude |
| 166  | double | mag   | Y    | ipmag_APASSDR9 | i' magnitude |
| 167  | double | mag   | Y    | eipmag_APASSDR9 | Error i' magnitude |
| 168  | char   |       | Y    | ID_DENIS | DENIS target designation |
| 169  | double | arcsec | Y    | Dist_DENIS | Center distance to target catalog |
| 170  | char   |       | Y    | MatchFlag_DENIS | Crossmatch quality flag (Note 7) |
| 171  | double | mag   | Y    | Imag_DENIS | I magnitude |
| 172  | double | mag   | Y    | eImag_DENIS | Error I magnitude |
| 173  | double | mag   | Y    | Jmag_DENIS | J magnitude |
| 174  | double | mag   | Y    | eJmag_DENIS | Error J magnitude |
| 175  | double | mag   | Y    | Kmag_DENIS | K magnitude |
| 176  | double | mag   | Y    | eKmag_DENIS | Error K magnitude |
| 177  | char   |       | Y    | ID_USNOB1 | USNOB1 target designation |
| 178  | double | arcsec | Y    | Dist_USNOB1 | Center distance to target catalog |
| 179  | char   |       | Y    | MatchFlag_USNOB1 | Crossmatch quality flag (Note 7) |
| 180  | double | mag   | Y    | B1mag_USNOB1 | B1 magnitude |
| 181  | double | mag   | Y    | R1mag_USNOB1 | R1 magnitude |
| 182  | double | mag   | Y    | B2mag_USNOB1 | B2 magnitude |
| 183  | double | mag   | Y    | R2mag_USNOB1 | R2 magnitude |
| 184  | double | mag   | Y    | Imag_USNOB1 | I magnitude |
| 185  | int    | mas yr | Y    | pmRA_USNOB1 | Proper motion RA from USNOB1 |
| 186  | int    | mas yr | Y    | epmRA_USNOB1 | Error proper motion RA from USNOB1 |
| 187  | int    | mas yr | Y    | pmDE_USNOB1 | Proper motion DE from USNOB1 |
| 188  | int    | mas yr | Y    | epmDE_USNOB1 | Error proper motion DE from USNOB1 |
| 189  | int    |       | Y    | Obsdate | Observation date yyyy-mm-dd |
obtained from spectra with a resolution of 7500 covering the CaT regime. This catalog can be accessed via doi.org/10.17876/rave/dr.5/001 and CDS/VizieR. The typical S/N of a RAVE star is 40 and the typical uncertainty in radial velocity is <2 km s\(^{-1}\). Stellar parameters are derived from the DR4 stellar parameter pipeline, based on the algorithms of MATISSE and DEGAS, but an updated calibration improves the accuracy of the DR5 stellar parameters by up to 15%. This pipeline is valid for stars with temperatures between 4000 K and 8000 K. The uncertainties in \(T_{\text{eff}}\), \(\log g\), and \([M/H]\) are approximately 250 K, 0.4 dex, and 0.2 dex, respectively, but vary with stellar population and S/N. The best stellar parameters have \(\text{Algo}\_\text{Conv} = 0\), S/N > 40, and \(c1 = n\), \(c2 = n\), and \(c3 = n\). An error spectrum has been computed for each observed spectrum, and it is then used to assess the uncertainties in the radial velocities and stellar parameters.

Temperatures from the IRFM are derived for >95% of all RAVE stars, and the asteroisometrically calibrated \(\log g\) is provided for a subsample of stars that can be calibrated asteroisometrically (~45% of the RAVE sample). The RAVE stars in the asteroisometrically calibrated sample are given in doi.org/10.17876/rave/dr.5/002 and described in Table 8 of Appendix B. As in Matijević et al. (2012), binarity and morphological flags are given for each spectrum. Photometric information and proper motions are compiled for each star.

The abundances of Al, Si, Ti, Fe, Mg, and Ni are provided for approximately two-thirds of the RAVE stars. These are generally good to ~0.2 dex, but their accuracy varies with S/N, and for some elements also with the stellar population. Distances, ages, masses, and the interstellar extinctions are computed using the methods presented in Binney et al. (2014), but upgraded, especially for the more metal-poor stars.

The astrometry and parallaxes from the first Gaia data combined with the RAVE DR5 radial velocities ensure that uncertainties of 10 km s\(^{-1}\) in space velocities for 70% of the RAVE-TGAS stars can be derived. Further, because Gaia astrometry provides completely new constraints on distances and tangential velocities, we can now use the RAVE pipelines to derive yet more accurate stellar parameters and distances for the TGAS stars, and even improve the parameters and distances of RAVE stars that are not in TGAS. The RAVE stars that have TGAS counterparts are provided in doi.org/10.17876/rave/dr.5/004.

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**APPENDIX A**

**APPENDIX BOOKKEEPING**

In total, there are 2505 RAVE DR4 stars that are not in this data release. These fall into five categories:

1. Doubled field—identical field was published twice under a different name

20060123_0456m20 is doubled with 20060126_0456m20
Table 8

Description of the Asteroseismically Calibrated Red Giant Catalog

| Col. | Format | Units | NULL | Label            | Explanations                                                                 |
|------|--------|-------|------|------------------|-----------------------------------------------------------------------------|
| 1    | char(32) | ...   | N    | RAVE_OBS_ID     | Target designation                                                          |
| 2    | float   | Y     | logg_SC | Log gravity calibrated asteroseismically (V16) |
| 3    | float   | Y     | elogg_SC | Error on logg_MV (V16) |
| 4    | int     | Y     | Flag050 | Difference between logg_MV and logg_K is less than 0.5 dex. | 1 = true 0 = false |
| 5    | int     | Y     | Flag075 | Difference between logg_MV and logg_K is less than 0.75 dex. | 1 = true 0 = false |
| 6    | int     | Y     | Flag_M | Normal star, meaning c1~c20 are all “n”. | 1 = true 0 = false |
| 7    | float   | Y     | Teff_IR | Temperature from infrared flux method |
| 8    | float   | Y     | Mg    | Abundance of Mg [Mg/H] |
| 9    | int     | Y     | Mg_N  | Number of spectral lines used for calculation of abundance |
| 10   | float   | Y     | Al    | Abundance of Al [Al/H] |
| 11   | int     | Y     | Al_N  | Number of spectral lines used for calculation of abundance |
| 12   | float   | Y     | Si    | Abundance of Si [Si/H] |
| 13   | int     | Y     | Si_N  | Number of spectral lines used for calculation of abundance |
| 14   | float   | Y     | Ti    | Abundance of Ti [Ti/H] |
| 15   | int     | Y     | Ti_N  | Number of spectral lines used for calculation of abundance |
| 16   | float   | Y     | Fe    | Abundance of Fe [Fe/H] |
| 17   | int     | Y     | Fe_N  | Number of spectral lines used for calculation of abundance |
| 18   | float   | Y     | Ni    | Abundance of Ni [Ni/H] |
| 19   | int     | Y     | Ni_N  | Number of spectral lines used for calculation of abundance |
| 20   | float   | Y     | Alpha_c | Alpha-enhancement from chemical pipeline |
| 21   | float   | Y     | CHIQ_c | Sum of the chemical pipeline |
| 22   | float   | Y     | frac_c | Fraction of spectrum used for calculation of abundances |
| 23   | float   | mag   | AV_Schlegel | Total extinction in V-band from Schlegel et al. (1998) |
| 24   | float   | kpc   | distance | Spectrophotometric distance (Binney et al. 2014) |
| 25   | float   | kpc   | e_distance | Error on distance (Binney et al. 2014) |
| 26   | float   | mag   | log_Av  | Log Av extinction (Binney et al. 2014) |
| 27   | float   | mag   | elog_Av | Error on log_Av (Binney et al. 2014) |
| 28   | float   | mas   | parallax | Spectrophotometric parallax (Binney et al. 2014) |
| 29   | float   | mas   | e_parallax | Error on parallax (Binney et al. 2014) |
| 30   | float   | mag   | DistanceModulus_Binney | Distance modulus (Binney et al. 2014) |
| 31   | float   | mag   | eDistanceModulus_Binney | Distance modulus (Binney et al. 2014) |
| 32   | float   | ...   | Y     | FitQUALITY_Binney | Given by symbol “F” in Equation (15) of Binney et al. (2014) |
| 33   | float   | ...   | Y     | FitFLAG_Binney | See final paragraph Section 3 of Binney et al. (2014) |
| 34   | float   | ...   | Y     | N_Gauss_fit | Number of components required for multi-Gaussian distance modulus fit |
| 35   | int     | ...   | Y     | Gauss_mean_1 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 36   | float   | ...   | Y     | Gauss_sigma_1 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 37   | float   | ...   | Y     | Gauss_frac_1 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 38   | float   | ...   | Y     | Gauss_mean_2 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 39   | float   | ...   | Y     | Gauss_sigma_2 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 40   | float   | ...   | Y     | Gauss_frac_2 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 41   | float   | ...   | Y     | Gauss_mean_3 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 42   | float   | ...   | Y     | Gauss_sigma_3 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |
| 43   | float   | ...   | Y     | Gauss_frac_3 | Property of multi-Gaussian distance modulus fit, see Section 9, Equation (5) |

Note. The contents of Table 8 can be accessed at doi.org/10.17876/rave/dr5/002.

20060123_0456m20 is removed
2. Renamed fields—fields that were renamed
20060627_0003m13 is renamed 20060629_0003m13
20070207_0734m34 is renamed 20070918_0734m34
3. Incorrect FITS headers—coordinates in header do not appear to be correct, so the proper stars that were observed cannot be identified; these fields were removed
20050814_2314m31
20060629_0003m13
4. Poor quality fields that were released in DR4
20110705_2028m00b
20091201_0206m84
5. DR4 stars with S/N < 10, spectra of too poor quality to process
We are left with 296 DR4 stars with S/N > 10 that were not able to be processed with SPARV.

APPENDIX B
APPENDIX MATERIAL

The descriptions of the individual columns of the main DR5 catalog are specified in Table 7, and the descriptions of the individual columns of the asteroseismically calibrated red giant
