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RAVE-Gaia and the impact on Galactic archeology

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Abstract. The new data release (DR5) of the RAdial Velocity Experiment (RAVE) includes radial velocities of 520,781 spectra of 457,588 individual stars, of which 215,590 individual stars are released in the Tycho-*Gaia* astrometric solution (TGAS) in *Gaia* DR1. Therefore, RAVE contains the largest TGAS overlap of the recent and ongoing Milky Way spectroscopic surveys. Most of the RAVE stars also contain stellar parameters (effective temperature, surface gravity, overall metallicity), as well as individual abundances for Mg, Al, Si, Ca, Ti, Fe, and Ni. Combining RAVE with TGAS brings the uncertainties in space velocities down by a factor of 2 for stars in the RAVE volume – 10 km s^{-1} uncertainties in space velocities are now able to be derived for the majority (70%) of the RAVE-TGAS sample, providing a powerful platform for chemo-dynamic analyses of the Milky Way. Here we discuss the RAVE-TGAS impact on Galactic archaeology as well as how the *Gaia* parallaxes can be used to break degeneracies within the RAVE spectral regime for an even better return in the derivation of stellar parameters and abundances.

Keywords. astronomical data bases: RAVE, surveys, stars: kinematics, stars: abundances, stars: Hertzsprung-Russell diagram, Galaxy: kinematics and dynamics, Galaxy: stellar content, Galaxy: structure

1. Introduction

Our Milky Way galaxy contains stars that are distinctly closer and brighter to us than stars in neighbouring galaxies, so the level of detail with which the stellar populations in our Galaxy can be seen provide important information regarding the formation and evolution of large spiral galaxies. The motions of stars combined with their chemical abundances in particular place powerful constraints on the formation of spiral galaxies such as the Milky Way (e.g., Minchev, Chiappini & Martig 2013). Today, the astrometric satellite *Gaia* is providing its first measurements (Data Release 1, Gaia Collaboration *et al.* 2016), and the Tycho-*Gaia* Astrometric Solution (TGAS, Lindegren *et al.* 2016) contains positions, parallaxes, and proper motions for about 2 million of the brightest stars in common with the Hipparcos and Tycho-2 catalogues. With typical accuracies of $\sim$1 mas yr^{-1} and 0.3 mas in proper motion and parallax, respectively, this is comparable to the precision of Hipparcos, but on a sample that is more than an order of magnitude larger.

In TGAS, exquisite astrometry is given in the positions and proper motions of stars. Combined with external spectroscopy, the measure of stellar atmospheric parameters, individual chemical abundances and radial velocities allow a full definition of the motion of stars in the Galaxy. Among existing spectroscopic surveys, the Radial Velocity Experiment (RAVE, Steinmetz *et al.* 2006, Zwitter *et al.* 2008, Siebert *et al.* 2011, Kordopatis *et al.* 2013, Kunder *et al.* 2017) has the largest overlap with TGAS (>200,000) so is a

Table 1. Overlap of large spectroscopic surveys with *Gaia*-TGAS.

Survey	Number TGAS stars
RAVE DR5	215,600
LAMOST DR2	124,300
GALAH DR1	8,500
APOGEE DR13	21,700

particularly attractive database for astronomers seeking to simultaneously use chemical and dynamical information to complement the available *Gaia* astrometry.

2. RAVE Overview

RAVE is a magnitude-limited survey of stars randomly selected in the $9 < I < 12$ magnitude range, obtained from spectra with a resolution of R$\sim$7 500 covering the CaT regime. It currently containts the largest spectroscopic sample of stars in the Milky Way which overlaps with the *Gaia*-TGAS proper motions and parallaxes (Table 1).

Radial velocities are available for all RAVE stars, where the typical signal-to-noise (SNR) ratio of a RAVE star is 40 and the typical uncertainty in radial velocity is $< 2\,\mathrm{km\,s^{-1}}$. For a subsample of RAVE stars, stellar parameters are also provided. These temperatures, $T_{\rm eff}$, gravities, $\log g$, and metallicities, [M/H], are obtained using the DR4 stellar parameter pipeline, which is built on the algorithms of MATISSE and DEGAS, with an updated calibration that improves the accuracy of especially the $\log g$ values of stars. The uncertainties vary with stellar population and SNR, but for the most reliable stellar parameters, the uncertainties in $T_{\rm eff}$, $\log g$, and [M/H] are approximately 250 K, 0.4 dex and 0.2 dex, respectively. RAVE stars with the most reliable stellar parameters are those which have `Algo_Conv`=0 (meaning the stellar parameter algorithm converged), SNR > 40, and `c1`=n, `c2`=n and `c3`=n. (which means the star has a spectrum that is "normal"). Error spectra computed for each observed spectrum is used to assess the uncertainties in the radial velocities and stellar parameters.

The elemental abundances of Al, Si, Ti, Fe, Mg and Ni are derived for $\sim$2/3 of the RAVE stars, which have uncertainties of $\sim$ 0.2 dex, although their accuracy varies with SNR and, for some elements, also of the stellar population. Distances, ages, masses and the interstellar extinctions are computed using an upgraded method of what is presented in Binney *et al.*(2014).

RAVE DR5 further provides temperatures from the Infrared Flux Method, which are available for > 95% of all RAVE stars. For a sub-sample of stars that can be calibrated asteroseismically ($\sim$ 45% of the RAVE sample), an asteroseismically calibrated $\log g$, as detailed in Valentini *et al.*(2017) is provided. Stellar parameters of the RAVE stars are also found using the data-driven approach of *The Cannon* (Casey *et al.* 2017), for which $T_{\rm eff}$, 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) is presented.

All of the above described information is publicly available, and can be downloaded via the RAVE Web site `http://www.rave-survey.org` or the Vizier database.

3. Reverse Pipeline

It is well-known that stellar spectra with a resolution R <10 000 suffer from spectral degeneracies at the Calcium triplet wavelength range. Specifically, at the RAVE wavelength and resolution, – see for example Figure 1 in Matijeviĉ *et al.* (2017). Parameter

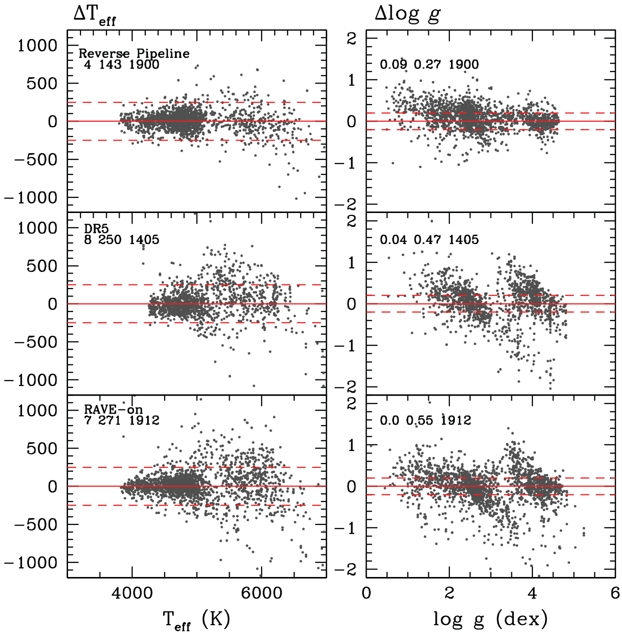

Figure 1. The reverse distance pipeline (top), DR5 main (middle), RAVE-on (bottom) temperatures and gravities compared to RAVE stars that overlap with high-resolution studies. The top left corner indicates the bias, dispersion and number of stars for each comparison. For the DR5 comparison, only stars with AlgoConv = 0 are shown.

degeneracy is usually less severe when the available information about the parameters increases: e.g., with a wider spectral range, higher spectral resolution, etc. The TGAS parallaxes can provide powerful extra information to break degeneracies, thereby constraining stellar parameters.

The RAVE distance pipeline (as described in Binney *et al.* 2014 and Kunder *et al.* 2017) takes as its input $T_{\rm eff}$, $\log g$, [M/H], J, H and K magnitudes and with this information combined with stellar isochrones, descriptions of the posterior probabilities of different properties of the stars (e.g., mass, age, line-of-sight extinction, distance) are generated. It has been modified to now also take the TGAS parallaxes, as well as AllWISE $W1$ and $W2$ magnitudes as an input (McMillan *et al.* 2017, in prep). Using the same prior as in Binney *et al.* (2014), a new $\log g$, $T_{\rm eff}$ and [M/H] is found, and for the first time, descriptions of the posterior probabilities for $T_{\rm eff}$, $\log g$ and [M/H] are obtained. We therefore refer to this as the 'reverse pipeline', because rather than just taking the stellar parameters as input, they are an end product. In fact, these are an inevitable byproducts of the distance pipeline, produced because each "model star" is compared to the data which has an associated $T_{\rm eff}$, $\log g$ and [M/H] as the likelihood is calculated.

Figure 1 shows how the reverse distance pipeline (top), DR5 main (middle), RAVE-on (Casey *et al.* 2017) (bottom) temperatures and gravities compare to RAVE stars that fortuitously overlap with high-resolution studies (e.g., Gaia-ESO, globular and open clusters, GALAH and field star surveys – see DR5 paper for details). The reverse pipeline yields temperatures and gravities that agree better to external, high-resolution studies of RAVE stars than both DR5 and RAVE-on. Note that the reverse pipeline temperatures and gravities are only available for TGAS stars.

The largest discrepancies between the DR5 and reverse pipeline main temperatures and gravities occur at the giant/dwarf interface. This is expected, as this is where the

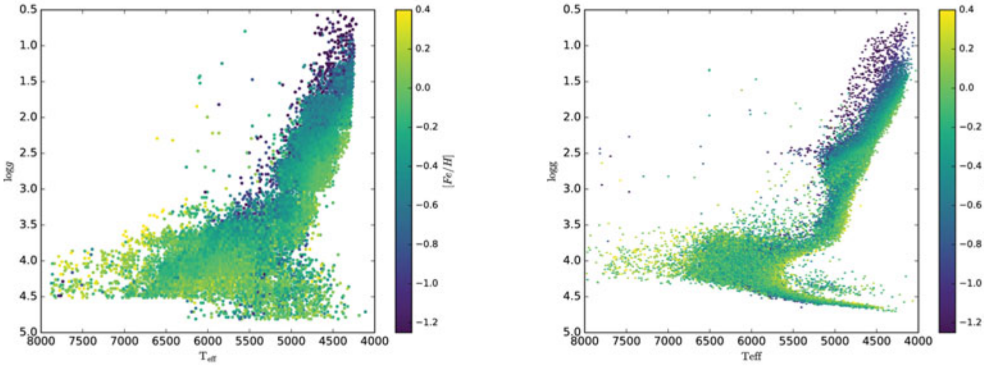

Figure 2. $T_{\rm eff}$-log g diagram for calibrated DR5 parameters (left) and reverse pipeline parameters (right).

degeneracies mentioned above are the most severe. Our preliminary tests show no signs of bias in the reverse pipeline stellar parameters as a function of parallax or TGAS parallax uncertainty. We are carrying out extensive tests to check if any and what kinds of subtle biases may exist when applying the reverse pipeline.

Figure 2 (right) shows the on the Hertzsprung Russel diagram using the DR5 and reverse distance pipeline temperatures and gravities. Of particular interest is the narrow main sequence, and a sequence of stars above the main-sequence separated by a clear gap. The majority of these stars are double-lined spectroscopic binaries (SB2s) which (in the absence of eclipses) are not variable and where the orbital period is short enough to permit any astrometric signature. Hence, they do not fall into photometrically or astrometrically peculiar classes, and are included in *Gaia* DR1.

4. Conclusions

RAVE is continuing to yield exciting results using the data products *Gaia* DR1. The reverse pipeline, described above, is allowing more accurate stellar parameters to be obtained, which can then be fed into a new elemental abundance pipeline designed specifically for the RAVE spectra (Guiglion *et al.* 2016, Guiglion *et al.* 2017, in prep). Jofre *et al.* (2017, submitted) has expanded the number of RAVE stars with TGAS parallax uncertainties less than 20% by applying the twin method to RAVE. McMillan *et al.*(2017, in prep) is using the TGAS parallaxes to find more precise distance estimates for all the RAVE stars, which also has the effect of an improvement in age uncertainties. Therefore, an exploration of the correlation between ages, metallicities, and velocities of stars in the solar neighborhood can be carried out (Wojno *et al.* 2017, in prep). Last but not least, 200 light curves of RAVE stars in the K2-Campaign 6 have been analysed, which will be used as calibration data for log g (Valentini *et al.* 2017, in prep).

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