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(A&A accepted, arXiv 1512.01546)
RAVE (Radial Velocity Experiment) is a large spectroscopic survey which observed half million stars of the Milky Way.

RAVE spectra are secured by using the 1.2-m UK Schmidt Telescope of the Australian Astronomical Observatory (AAO).

- The 6dF instrument (six-degree-field multi-object spectroscopy system)
- fiber optic technology
- up to 150 objects in one shot
- up to 800 spectra in 1 clear night
What is RAVE?

From the RAVE spectra we obtain:
- radial velocities, $\sigma$(RV)~2 km/sec
- stellar parameters $T_{\text{eff}}$, $\log g$, $[M/H]$
  $\sigma$(Teff)~200K, $\sigma$(logg)~0.5, $\sigma$(M/H)~0.1 dex
- chemical abundances for Mg, Al, Si, Ti, Fe, Ni, $\sigma$(X/H)~0.1-0.2 dex

The RAVE stars have:
- Proper motions (Tycho2, PPMXL, UCAC)
- Distances (by Breddel+, Zwitter+, Binney+)

$\Rightarrow$ we can locate the stars in the 6D phase-space and chemical space
The RAVE chemical pipeline

input
- normalized spectrum
- wavelength range
- resolution (guess)
- Teff
- log g
- [m/H] (guess)

RAVE chemical pipeline

1D LTE analysis

output

chemical abundances
[Fe/H], [Mg/H], [Al/H], [Si/H], [Ti/H], [Ni/H]

The 7 more reliable elements
Mg, Al, Si, Ca, Ti, Fe, Ni

The RAVE chemical catalogue holds chemical abundances for ~400,000 stars of the Milky Way

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The relation between chemical and and kinematics of the MW disc (Boeche et al., 2013, A&A 553, 19)

Gratton et al., 2003, A&A 406, 131
150 subdwarfs, high resolution spectroscopy

- Thin disc: $e<0.25$, $Z_{\text{max}}<0.8$ kpc (1079 stars)
- Thick disc: $V\Phi>40$ km/sec (1024 stars)
- Halo: $V\Phi<40$ km/sec (64 stars)

sample of 2167 RAVE giant stars
The relation between chemical and kinematics of the MW disc (Boeche et al., 2013, A&A 553, 19)

Gratton et al., 2003, A&A 406, 131
150 subdwarfs, high resolution spectroscopy

sample of 2167 RAVE giant stars
S/N > 75

- Thin disc: e < 0.25, Zmax < 0.8 kpc (1079 stars)
- Thick disc: VΦ > 40 km/sec (1024 stars)
- Halo: VΦ < 40 km/sec (64 stars)
Disentangling Galactic stellar populations

Gratton's selection criteria

\[ \sqrt{Z_{\text{max}}^2 + 4e^2} < 0.35 \]

Our modified selection criteria

Different population cannot be disentangled with pure kinematic criteria
Let's try a different approach...

Rp=perigalactic
Let's try a different approach...

$V\Phi = \text{velocity tangential to the orbit}$
Let's try a different approach...
Interpretation

Heated thin disk

Scattered thin + thick disk

Thin disk
For all samples we used guiding radius (Rg) and maximum distance from the Galactic plane (Zmax) of the integrated orbits.

We divide the samples in 3 subsamples as function of Zmax:

- Zmax > 0.8 kpc
- 0.4 < Zmax < 0.8 kpc
- Zmax < 0.4 kpc
for the GALAXIA/Besancon mock sample we learn that:

- the mock sample seems to have:
  1) too many thick disc stars w.r.t the RAVE sample
  2) [Fe/H]_{thick}=-0.78dex is too low (-0.5dex would fit better)

- thick disc stars shift to low left in (Rg,[Fe/H]) plane because the larger asymmetric drift and lower metallicity
  → fictitious flatter/positive gradient which is function of the ratio thin/thick in the sample

- the thin disc (mock sample) has d[Fe/H]/dR=-0.07dex/kpc but d[Fe/H]/dRg=0.00dex/kpc
  → in the Besancon model there is no correlation between kinematic and metallicity
SP_Ace front end web page
http://dc.g-vo.org/SP_ACE

Webpage by Markus Demleitner and Hendrik Heinl at ARI Heidelberg

ArXiv 1512.01546
How do we measure stellar parameters and chemical abundances?

1) Equivalent Width (EW) measurement: measure the EW of the lines and recover the \([X/H]\) from their curve of growth (MOOG abfind driver)

2) Spectrum synthesis: synthesize a spectrum with the proper atmosphere model and change the \([X/H]\) until the best match with the observed spectrum is found
How do we measure stellar parameters and chemical abundances?

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We use an alternative method

SP_Ace

(Stellar Parameters And Chemical abundances Estimator)

is the code that implement such method
**SP_Ace**

*a new code for Teff, Log g and [X/H] estimation*

SPACE is the evolution of the RAVE chemical pipeline

**input**
- normalized spectrum
- wavelength range
- resolution (guess)

**1D LTE analysis**

**SP_Ace**

**output**
- Teff
- log g
- chemical abundances
- [Fe/H], [Mg/H], [Si/H], [Ca/H], [Ti/H], [Cr/H], [Co/H], [Ni/H]
- and more....

Algorithm (simplified)

1. Construct spectra models on-the-fly
2. $X^2$ analysis model vs. observed spectrum looking for the best match
3. The model with the smallest $X^2$ has the most probable the stellar parameters
How to construct a spectrum model

given
• stellar parameters
• EW of the lines
• **Voigt** profiles of the lines
\( V(\lambda, \mu, \sigma, EW) \) (\( \mu \) = central wavelength)

the reconstructed spectrum can be described as

\[
\text{spectrum}(\lambda) = \sum_i V_i(\lambda, \mu_i, \sigma_i, EW_i)
\]

This is valid only under weak line approximation!

*(Solution: correction for the opacity of the neighbor lines, see later...)*

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How to construct a spectrum model

If we know the expected EWs of the lines we can reconstruct a spectrum model that match the observed spectrum.

The EW of every lines is described by a function that we call **General Curve of Growth**.

\[
EW_{ij} = GCOG\left( T_{\text{eff}}, \log g, [X_j/H] \right)
\]
What do we need to construct a realistic spectrum model?

*at present the whole work is based on 1D atmosphere models and LTE assumptions (but extension to 3D-NLTE are possible)*

1) Line list

2) A library that contains the expected EWs for a grid of stellar parameters (EW library)

   2a) Complication: Correction for the opacity of the neighbour lines (corrected EW library)

3) Creation of the General Curve-Of-Growth (GCOG) library (that permit to continuously vary the EW of the lines as function of the stellar parameters in order to construct spectrum models of any stellar parameters and chemical abundances)
1) The line list

1) Select from the VALD database all the lines in the wavelength range 5212-6860A and 8400-8900A that has strength > 1% of the flux on the spectra of the Sun, Arcturus, Procyon (8424 atomic+molecular lines)

2) Calibrate the oscillator strengths (log gf) by matching at best the intensity of the lines with 5 spectra (astrophysical calibration). After calibration the line list counts 4620 lines
1) The line list: log gf calibration

Eps Eri
Teff=5050K logg=4.60 [M/H]=-0.09dex

Arcturus
Teff=4286K logg=1.66 [M/H]=-0.52dex

Eps Vir
Teff=4983K logg=2.77 [M/H]=+0.15dex

Procyon
Teff=6554K logg=3.99 [M/H]=-0.04dex

Sun
Teff=5777K logg=4.44 [M/H]=0.00dex
Why do we calibrate log gfs?

We do not expect to improve the (few) good and reliable log gfs from laboratory measurements, but

*We calibrate log gfs to amend the badly wrong log gfs of some lines that can spoil the whole analysis*

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**Eps Vir**
- $T_{\text{eff}} = 4983\, \text{K}$
- $\log g = 2.77$
- $[\text{M/H}] = +0.15\, \text{dex}$

**Procyon**
- $T_{\text{eff}} = 6554\, \text{K}$
- $\log g = 3.99$
- $[\text{M/H}] = -0.04\, \text{dex}$

**Sun**
- $T_{\text{eff}} = 5777\, \text{K}$
- $\log g = 4.44$
- $[\text{M/H}] = 0.00\, \text{dex}$

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The EWs can be obtained from ewfind driver of MOOG (Sneden, 1973) for different Teff, log g and [X/H]

I built the EW library which holds the EW of every absorption lines considered for the grid of stellar parameters and abundances

3600<Teff(K)<7400   step 200K
0.2<logg<5.4         step 0.4dex
-2.4<[M/H](dex)<0.4 step 0.2dex
-0.4<[X/M](dex)<+0.6 step 0.2dex

a) Microturbulence is defined as a function of Teff and log g

b) All the EWs contained in the library are computed as the lines were isolated!
We employed 620 stars which $\xi$ has been measured in high-res works (Fuhrmann 1998; Allende Prieto+2004; Bensby+2005; Fulbright+2006, Luck+2006, 2007)

The microturbulence has been approximated with a polynomial function over the plane (Teff, log g)

The EW library has been computed by using this polynomial microturbulence.
2b) Correction for the opacity of the neighbor lines

If the opacity of the neighbor lines is neglected in a blend (i.e. the EWs of the lines are computed as isolated) then the total EW is underestimated

\[ EW_{blend} < \sum EW_i^{iso} \]

We need corrected EWs so that

\[ EW_{blend} = \sum EW_i^c \]

**Empirical correction**

\[ EW_{iso}^{i,c} = \frac{EW_i^{i} \cdot (\delta \text{COG}_i^{blend})}{(\delta \text{COG}_i^{iso})} \]

\[ EW^{i,c} = EW_{blend} \cdot \left( \frac{EW_{iso}^{i,c}}{EW_{blend}^{i,c}} \right) \]
3) Construction of the GCOG library

For each absorption line the EW library (corrected for the opacity of the neighbor lines) provides the expected (synthesis) EW which covers the stellar parameters space with a grid of points. We want a continuum solution.

We fit the EWs of every line with a polynomial function in the parameter space, so that this function represent the GCOG

The coefficients of the polynomials are stored in the GCOG library
The code SP_Ace

SP_Ace is a FORTRAN95 code

It assumes an initial starting point in the parameter space
[Teff, logg, [M/H],[El/M]] = [5000, 3.0,-0.4,0.0]

1) put these values into the polynomial GCOG to obtain the expected EWs for these stellar parameters

2) construct the spectrum model by using the EWs provided

3) Compute the $\chi^2$ between the observed and the model spectra

4) Change the point in the parameter space and repeat 2) and 3) until minimization
The code SP_Ace:
internal re-normalization

- synthesis
-Normalized with IRAF
-re-normalized with SP_Ace

R=5,000 S/N=100

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how the continuum and spectrum model look like
Tests on real spectra

- S4N (Allende Prieto+, 2004)
- Benchmark stars (Jofre'+, 2014)
- ELODIE spectra (Prugniel+, 2007)
Tests on real spectra

S4N (Allende Prieto+, 2004)
Benchmark stars (Jofre'+, 2014)
ELODIE spectra (Prugniel+, 2007)

Wave=[5212-6270,6310-6860]Å
R=5,000
S/N=100
Tests on LAMOST spectra
(with M. Smith and J. Hou from Shanghai Astr. Obs.)

LAMOST spectra
R=1800, S/N>100
Wave=[5212-5700, 5900-6270, 6310-6860] Å

APOGEE
N=4036
Calibr.
Non calib.

SPAce
N=4036

[Fe/H]

Isochrone 10Gyr, [M/H]=-2.0dex
Isochrone 10Gyr, [M/H]=-1.0dex
Isochrone 5Gyr, [M/H]= 0.0dex

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The code SP_Ace: features

- SP_Ace is highly automatized. No human supervision is needed during processing. Suitable for spectroscopic surveys.

- Possibility to constrain the Teff and/or log g values by the user

- SP_Ace estimates stochastic errors (but not systematic errors)

- Relatively fast (few seconds to process one spectrum at R=2,000, up to ~40 seconds (with no error estimation) for R=20,000

- Possibility to extend the wavelength coverage (at present 5212-6860A and 8400-8920A)

- Extension to NLTE and/or 3D atmosphere models possible

- The code will be publicly available soon
SP_ACE spectral analysis tool

SP_ACE computes stellar parameters (gravity, temperature) and element abundances from optical stellar spectra (sample spectrum). It employs 1D stellar atmosphere models in Local Thermodynamic Equilibrium (LTE).

- Spectrum: ASCII file with two columns: wavelength (in Ångstrom) and continuum normalized flux. The spectrum must be radial velocity corrected (wavelengths in rest frame). The spectral resolution power should be between 2000 and 20000. SP_ACE handles spectra in the stellar parameters intervals: $T_{eff}=[5000,7400] K$, $log(g)=[1.5,3]$, $[Fe/H] = [-2,0]$.


- Wave intervals: Give up to five wavelength intervals you want to analyze, starting from the lowest. Intervals not covered by the library will be ignored. The default setting is the range of wavelengths currently processed by the software.

- Fixed $T_{eff}$ (K): Force solver to assume this temperature. Leave empty to let SP_ACE estimate this parameter.

- Fixed gravity: Force solver to assume this gravity. Leave empty to let SP_ACE estimate this parameter.

- Compute Errors?: Make SP_ACE estimate errors (this increases runtime significantly).

- Output format: HTML

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If the opacity of the neighbor lines is neglected in a blend (i.e. the EWs of the lines are computed as isolated) then the total EW is underestimated

\[ EW_{\text{blend}} < \sum EW_{i}^{\text{iso}} \]

We need corrected Ews so that

\[ EW_{\text{blend}} = \sum EW_{i}^{c} \]

Can we find such corrected Ews?

Good news: these corrected EW can be exactly computed
Bad news: we cannot use them!

Solution: approximation!

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Expected uncertains

Estimated errors in synthetic spectra

Estimated errors in real spectra
Tests on real spectra

$\text{Wave} = [5212-6270, 6310-6860] \, \text{Å}$

$R = 12,000$

- S4N (Allende Prieto+, 2004)
- Benchmark stars (Jofre'+, 2014)
- ELODIE spectra (Prugniel+, 2007)
The code SP_Ace: the line profile

Voigt function

\[ I(\lambda) = \int G(\lambda') L(\lambda - \lambda') d\lambda' \]

Gaussian

\[ G(\lambda) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{\lambda^2}{2\sigma^2}\right) \]

Lorentzian

\[ L(\lambda) = \frac{a_L}{1 + 4(\lambda/\gamma_L)^2} \]

Implementation by McLean (1994)

\[ I(\lambda) = \frac{\gamma_L}{\gamma_G} a_L \sqrt{\pi \ln(2)} V(X,Y) \]

\[ a_L = \frac{EW}{(\gamma_L * 0.5 * \pi)} \]
The code SP_Ace: the line profile

Implementation by McLean (1994)

\[ I(\lambda) = \frac{\gamma_L}{\gamma_G} a_L \sqrt{\pi \ln(2)} V(X,Y) \]

\[ \gamma_G = \text{instrumental FWHM} \]

\[ \gamma_L = dl \cdot EW \cdot dp \left( 1 - \exp \left( -\left[ \frac{EW \cdot dp}{\sigma} \right]^2 \right) \right) \]

\[ \sigma = 0.14, \; dl = 0.8 \quad \text{if } \log g > 4.5 \]
\[ \sigma = 0.16, \; dl = 0.7 + (\log g - 3.5) \times 0.1 \quad \text{if } 3.5 < \log g < 4.5 \]
\[ \sigma = 0.20, \; dl = 0.6 + (\log g - 2.5) \times 0.1 \quad \text{if } 2.5 < \log g < 3.5 \]
\[ \sigma = 0.20, \; dl = 0.6 \quad \text{if } 1.5 < \log g < 2.5 \]
\[ \sigma = 0.20, \; dl = 0.6 + (1.5 - \log g) \times 0.1 \quad \text{if } \log g < 1.5 \]
Synthetic spectra
Wave=[5212-6860]Å

- Mock Thin disk
- Mock Thick disk
- Halo/accreted

R=12,000
S/N=100
1) The line list: log gf calibration. comparison

Atomic lines
offset = 0.011
\( \sigma = 0.287 \)
N = 4628

NIST log gf (error < 10%)
offset = -0.125
\( \sigma = 0.107 \)
N = 223

Calibrated log gf vs. VALD log gf
Calibrated log gf vs. NIST log gf