THE RAVE SPECTROSCOPIC SURVEY: RESULTS FROM THE FIRST 44 000 OBSERVED STARS

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ABSTRACT

RAVE (RA*dial* V*elocity* E*xperiment*) is a medium resolution all-sky spectroscopic survey conducted with the 150 fiber 6dF spectrograph at the UK-Schmidt telescope in Australia. The wavelength range (8430–8740 Å) and resolving power (8500) are similar to those currently baselined for the Gaia spectroscopic observations (8480–8740 Å and 11 500, respectively). The survey began on 11 April 2003 and by 1 September 2004 a total of 44 109 high galactic latitude field stars have been observed in the magnitude range 9 $\leq I_{\rm C} \leq$ 12, about three mag fainter than the Geneva–Copenhagen all-sky survey of solar neighbourhood solar-type dwarf stars. Cross-correlation against suitable synthetic spectral templates provides good radial velocities, the error distribution of which peaks at 1.0 km s^{-1} on $I_{\rm C} \leq$ 10 stars, 1.3 km s^{-1} on 10 $\leq I_{\rm C} \leq$ 11 stars stars and 2.0 km s^{-1} for 11 $\leq I_{\rm C} \leq$ 12 stars. Preliminary results on atmospheric parameters obtained with a simplified automatic pipeline indicates errors of ∼6% on $T_{\rm eff}$, 0.4 dex on [Fe/H] and 0.9 dex on $\log g$ for solar-type spectra of moderate to high S/N. Improvements in the continuum normalization, automatic pipeline and synthetic reference grid for the final data reduction and analysis are expected to further improve the performances in both radial velocities as well atmospheric parameters, especially when used in conjunction with optical and IR photometry available for most of the programme stars.

Key words: RAVE; Gaia; Radial velocities; Atmospheric analysis; Galactic kinematics; Galactic evolution.

1. INTRODUCTION

RAVE (RA*dial* V*elocity* E*xperiment*; Steinmetz 2003) is an all-sky medium resolution spectroscopic survey carried out with the 6dF fiber spectrograph at the UK-Schmidt telescope in Siding Spring, Australia. It was originally meant to complement the astrometric sky survey by the German DIVA satellite by providing the 6th component in the phase-space, i.e., the radial velocity, as well as an analysis of the atmospheric properties of the observed stars ($T_{\rm eff}$, $\log g$, [Fe/H], [α/Fe], $V_{\rm rot}\sin i$, ξ). Following the cancellation of DIVA by the German space agency DLR, RAVE has evolved into a self-consistent survey aiming to investigate kinematics, structure and chemical evolution of the Galaxy.

The observations are carried out in a wavelength range and at a spectral resolution similar to those currently baselined for Gaia. The RAVE interval is 8430–8740 Å and the resolving power 8500. The 6dF positioner handles two bundles composed of 150 fibers each: when one is exposing on the sky, the other one is re-configured for star positions on the next field. This is the same instrumentation used for the 6dF redshift survey of galaxies, which however operates in a different wavelength range and at a lower resolution.

The observations began on 11 April 2003. Seven nights per lunations are allocated to RAVE, when the sky is too bright for the 6dF-GS redshift survey. Until 1 September 2004 RAVE has observed on 112 nights and collected 47 792 spectra of 44 109 stars, with an average of 2515 spectra per lunation and 423 spectra per night. The observations will last to at least 2006, with the goal of 100 000 observed stars that should be achieved by 2005.

This note is a status report on the advancement of the survey and a first estimate of the accuracies attainable in the derived radial velocities and atmospheric parameters. It does not deal with the scientific results about the galactic structure, dynamics and history that have to wait for the final data reduction that will be discussed elsewhere.

2. RAVE SPECTRA

RAVE spectra cover the wavelength range 8430–8740 Å at a resolving power ∼8500. This combination is similar to that currently baselined for Gaia RVS spectra which are planned to cover the range 8480–8740 Å at a resolving power of 11 500. RAVE is therefore of great relevance for Gaia, allowing a direct probing of stellar spectra and their analysis so as to gain considerable experience on *real* stars well in advance of the launch of the satellite. Available surveys of real spectra in this wavelength

*on behalf of the RAVE collaboration, http://www.aip.de/RAVE/

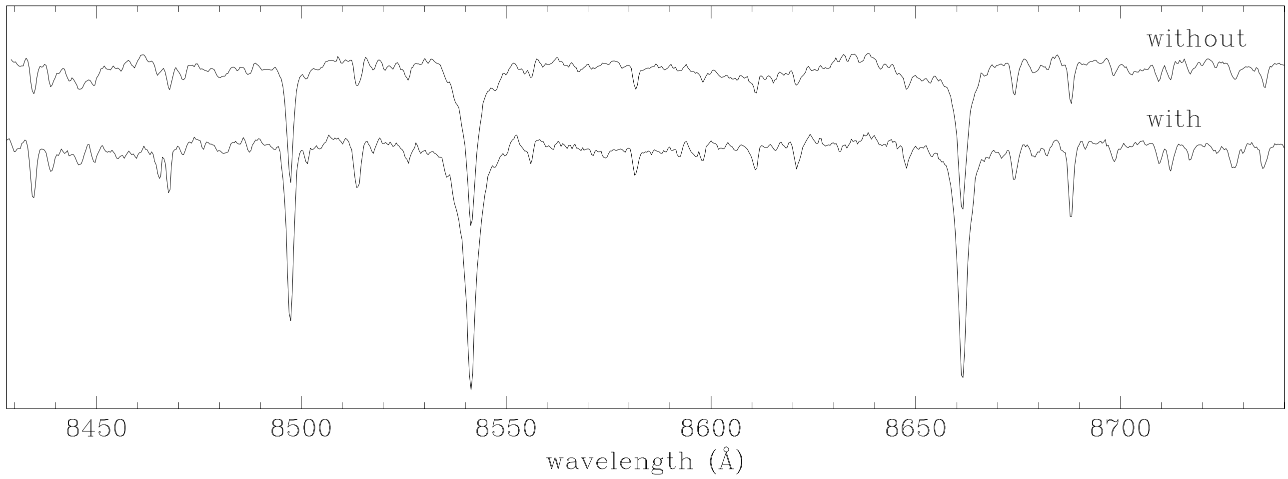

Figure 1. Comparison of the spectrum of the same G5 III star observed with and without the full blocking II order filter.

range and at equivalent or larger resolution are limited to the HR diagram mapping by Munari & Tomasella (1999) and Marrese et al. (2003), survey of peculiar stars by Munari (2003) and of Carbon stars by Pavlenko et al. (2003), all together not exceeding 300 objects, thus not comparable with the RAVE harvest which is already $150\times$ larger, and continuously growing.

During early RAVE operations, some contamination by II order blue light, not properly filtered out, affected the recorded spectra. The contamination was then eliminated from subsequent spectra by insertion in the optical train of a full blocking filter. The contamination is a minor one for spectra of F-G-K spectral types, which are the dominant population among field stars. Second and first order light are rigidly co-shifted in the pixel space by radial velocities, so the effect of contamination in the early spectra is similar to a comfortably small decrease in radial velocity accuracy that could be expected by a somewhat lower S/N of the spectrum.

Second and first order spectra furthermore are obviously characterized by the same atmospheric parameters $T_{\rm eff}$, $\log g$, [Fe/H], [α/Fe], $V_{\rm rot}\sin i$, ξ, so the contamination has the net effect of some reduction in the accuracies of derived parameters as caused by an equivalent reduction in S/N.

The contamination affecting RAVE spectra collected during the early phases of the survey is expected to be properly handled by the end of the survey when iterative re-reduction of all contaminated spectra will provide a detailed knowledge of the relative I- and II-order transmission for each fiber. The amount of II order contamination in early RAVE operations on a typical field star can be estimated by comparing in Figure 1 the spectrum of the same G5 III star observed by RAVE before and after the full blocking filter was inserted in the optical train. All spectra shown in the figures of this contribution, as well as results on accuracy of radial velocities and stellar atmospheric parameters, pertain entirely to observations carried out with the full blocking filter in place.

3. SCIENCE GOALS

The science goals of RAVE are similar to those widely discussed in this Conference on galactic structure, kinematics, chemistry and evolution. They have been already outlined by Steinmetz (2003) and will be not repeated here, being sufficient to summarize them as, among others:

- the degree of chemical homogeneity of the thick disc and its extension as clue to its origin
- the [α/Fe] vs. [Fe/H] as a tracer of early galactic chemical evolution
- chemical/kinematic signatures of galactic satellite accretion
- halo substructures as a test of predicted number of infalling satellites in CDM simulations
- dynamical influence of local spiral arms/inner bar
- ellipticity, warping, lop-sidedness of the disc
- non-local measurement of disc surface density

A discussion of the diagnostic potential of Gaia spectroscopy that is appreciably shared by RAVE data is given by Munari (2000).

4. TARGET SELECTION

The selection of targets for RAVE is performed on Tycho-2 and SuperCOSMOS catalogues, with a bright magnitude limit of $I_{\rm C}$ = 9.0 and a cut-off at $I_{\rm C}$ = 12.0 The brightest RAVE targets are selected from the Tycho-2 catalogue, with a few of them being fainter than 11.5 mag in $I_{\rm C}$. Saturation of available fibers is achieved with generally fainter targets selected from the SuperCOSMOS

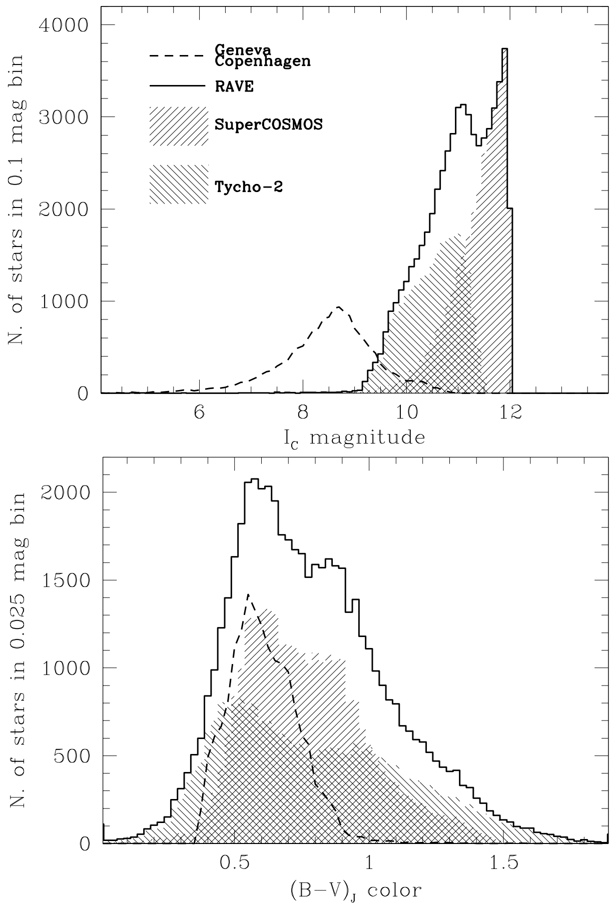

Figure 2. Distribution in $I_{\rm C}$ mag and $(B-V)_{\rm J}$ colour of the 44 109 stars observed by RAVE over the period 11 April 2003 to 1 September 2004.

I-band survey. No colour criterion is imposed on the targets, so that any $B-R_{\rm C}$ for SuperCOSMOS and any $B_{\rm T}-V_{\rm T}$ for Tycho-2 are equally good. The magnitude and colour distributions of the targets are presented in Figure 2, where comparison with the corresponding distribution of targets in the Geneva-Copenhagen survey by Nordström et al. (2004) of the F-G dwarfs in the solar neighbourhood (hereafter referred to simply as the Geneva-Copenhagen survey) is given. In transforming from the original colours into the common $I_{\rm C}$, $(B-V)_{\rm J}$ Johnson-Cousin values, transformation equations from Caldwell et al. (1993), Bessell (2000) and Moro & Munari (2000) have been adopted.

Given the identical exposure time for all fibers, the widest practical range in magnitude between the brightest and the faintest target in the same field of view is $\Delta I_{\rm C}\sim$ 2.5 mag. There must be no field star within 7 arcsec of any target star, this being the field of view of a fiber. Furthermore, fibers cannot be placed on targets closer than 5 arcmin because of the physical dimension of the devices keeping the fibers onto assigned positions. The average allocation numbers for the 150 fibers on a typical RAVE field are: 107 on stars, 10 on background sky and 33 parked. There are a number of reasons for the parked fibers, in particular there could be not enough suitable targets to saturate available fibers according to the above selection criteria, or some fibers could be broken and have to wait the end of the lunation to be replaced.

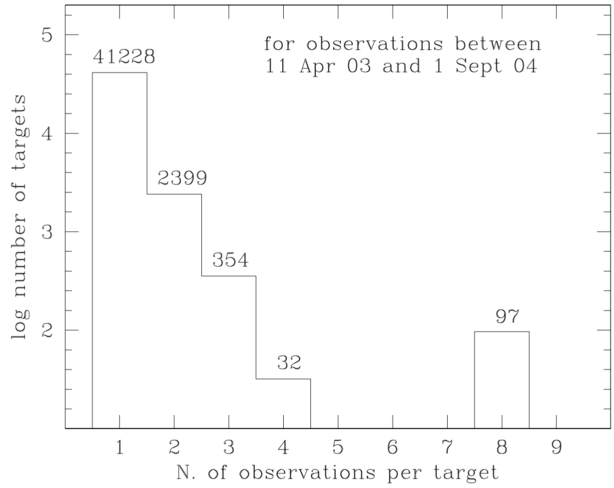

Figure 3. Distribution of RAVE targets in terms of repeated observations of the same object.

Many field stars at the RAVE limiting magnitude of $I_{\rm C}=12.0$ are K giants. At the high galactic latitudes explored by the survey the reddening plays a minor effect, and the distance of such $I_{\rm C}=12.0$ K giants would then be several kpc, which represents the scale distance of the volume sampled by RAVE. For comparison, the Geneva-Copenhagen survey mapped the solar dwarfs within 50 pc of the Sun.

RAVE targets are observed only once. A minimal fraction is re-observed to estimate the fraction of binaries and to evaluate the system stability and performances as a function of the S/N. The distribution in terms of the number of re-observations of the the 44 109 RAVE targets observed until 1 September 2004 is presented in Figure 3.

5. SKY COVERAGE

RAVE observations are focused away from the galactic plane, at galactic latitudes $|b|\geq 25°$. The position in an Aitoff projection in galactic coordinates of the 44 109 stars observed until 1 September 2004 is presented in Figure 4, where the grouping of targets into the 6° wide field of view of the UK-Schmidt is evident. A few sample fields are observed on the galactic equator, mainly for calibration purposes and repeated observations to monitor the system performances with time. One of them, RAVE-1607m492, has been visited 8 times and it is used below in this paper to estimate the performance in the derivation of the stellar atmospheric parameters and radial velocities by comparison of the results obtained independently for each re-observation.

RAVE operation is currently funded till 2006, with the milestone of 100 000 spectra that should be passed within 2005. After September 2005 the observations are planned

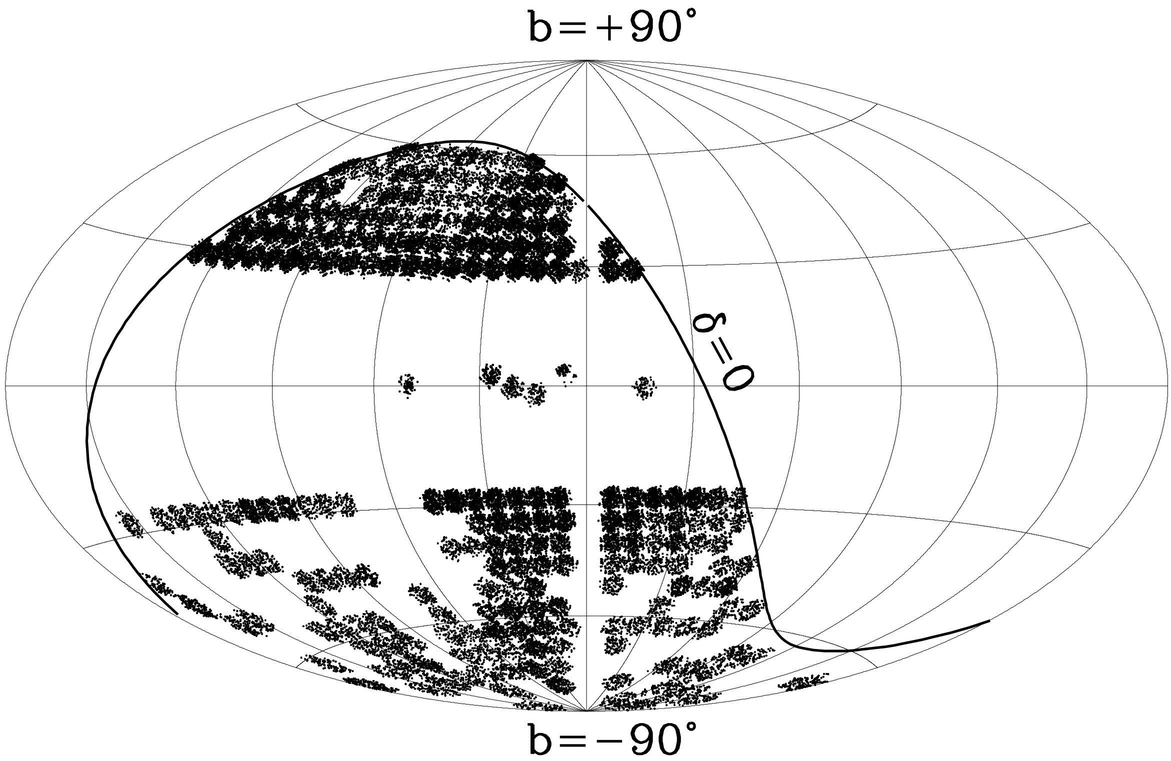

Figure 4. Distribution in galactic coordinates of the 44 109 stars observed by RAVE over the period 11 April 2003 to 1 September 2004. The map centre corresponds to l=0°, b=0°.

to be extended to declinations $\delta > 0°$ and to fields at lower galactic latitudes and on the galactic equator. Possibilities to extend the survey beyond 2006 are currently explored.

6. RAVE SPECTRAL SEQUENCE

A spectral sequence for field main sequence and giant stars is presented in Figure 5. At early spectral types the classification is made straightforward by the decrease in intensity of Paschen hydrogen lines and increase of the CaII triplet lines as the temperature gets cooler. For late spectral types, the increase in intensity with decreasing temperature of TiI lines with respect to FeI ones makes for a similar easy classification.

The broad wings of the core-saturated CaII lines simplify the luminosity classification of F-G-K-M stars in the RAVE wavelength range in comparison with the classical 3900–4900 Å MKK interval. Overall, the classification of F-G-K-M stars is equally easy in the two intervals, with the advantage for the RAVE one of extending over a wavelength interval four times shorter. Only for O and B type stars the RAVE range is under-performing in comparison with the classical MKK one, but the number of such stars that could be picked up by a magnitude limited all-sky survey – especially at high galactic latitudes – is quite negligible.

7. RADIAL VELOCITIES

Radial velocities are derived from RAVE spectra by cross-correlation against a proper library of synthetic stellar spectra. The one in the current pipeline uses spectra extracted from the atlas of Zwitter, Castelli and Munari (2004) that presents 61 196 synthetic spectra computed over the same wavelength range and at the same resolution of RAVE, well covering the HR diagram in terms of temperature, gravity, metallicity, α-enhancement and rotation velocity. Templates to assist in the analysis of the early RAVE spectra contaminated by II-order light are extracted, for the wavelength range and resolution pertaining to RAVE II order spectra, from the synthetic atlas of Munari et al. (2005, submitted to A&A), that covers the whole 2500–10 500 Å range.

Figure 7 compares the radial velocities obtained over two consecutive nights of the same stars in the RAVE-1607m492 field, observed with an identical fiber assignment and as measured by the automatic pipeline. They represent the radial velocity accuracy to be expected for brightest RAVE targets with the current version of the automatic data processing pipeline. Figures 6 displays instead the error distribution of radial velocities as measured by the automatic pipeline over the whole RAVE magnitude range. As it can be seen, the distribution is dominated by the effect of decreasing S/N at fainter magnitudes (all stars are exposed for the same amount of time irrespective of their brightness). The peak in the error distribution of radial velocity is at 1.0 km s^{-1} for $I_{\rm C}\leq$ 10 stars, 1.3 km s^{-1} for 10 $\leq I_{\rm C}\leq$ 11 stars stars and

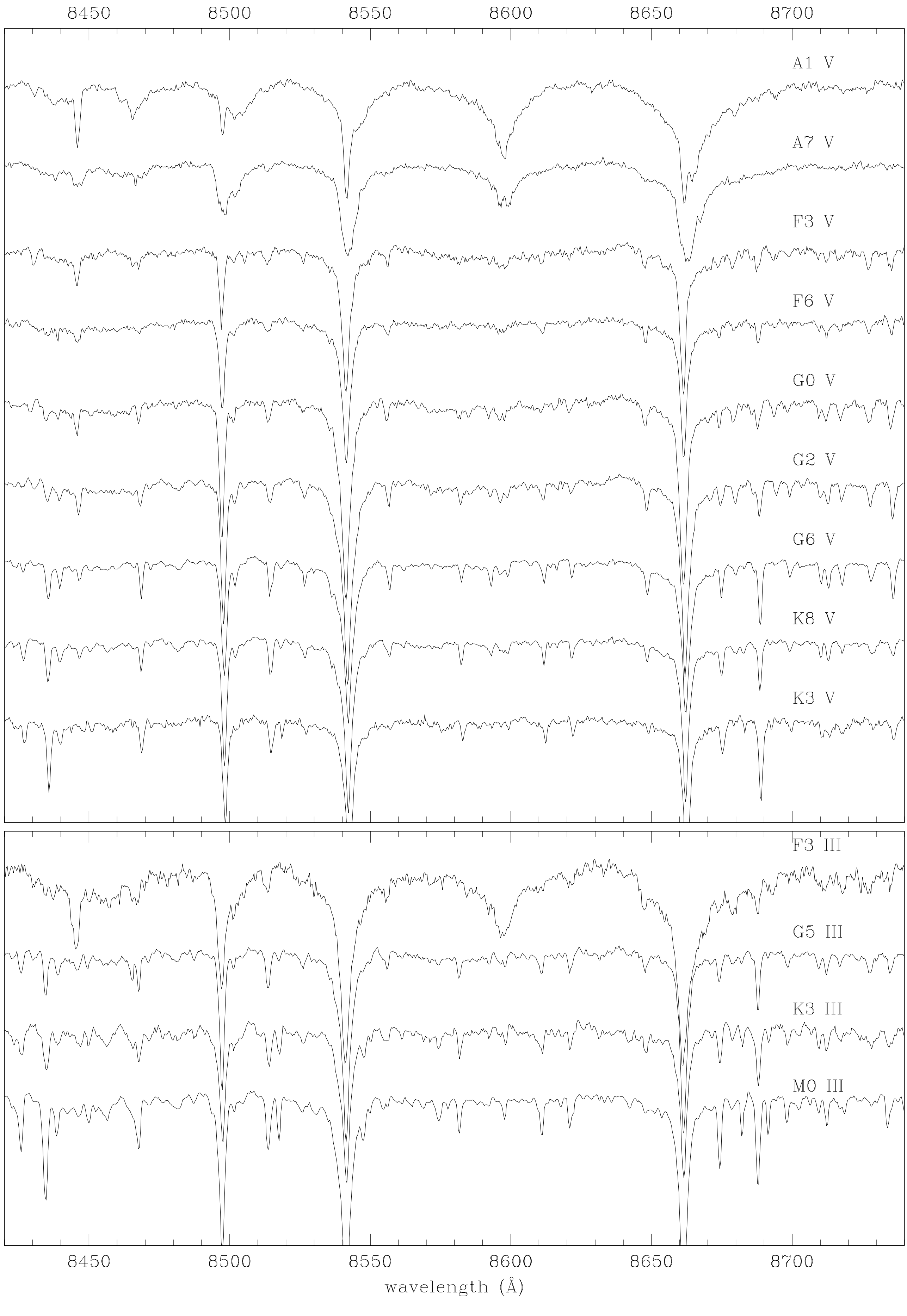

Figure 5. Main sequence and giant sample sequences assembled from RAVE spectra.

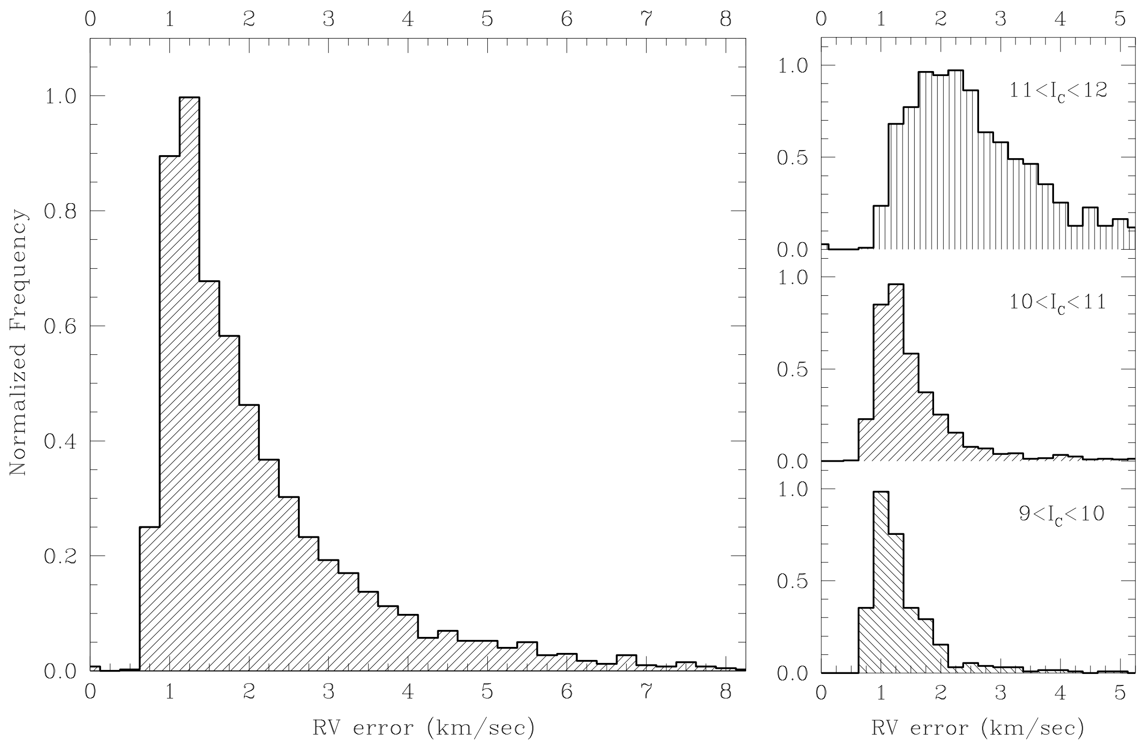

Figure 6. Distribution of errors of RAVE radial velocities

2.0 km s^{-1} for 11 $\leq I_{\rm C} \leq$ 12 stars.

The above results, as displayed in Figures 6 and 7, are based on a preliminary version of the data reduction pipeline which uses a blind cross-correlation approach and a rough normalization of the stellar continuum. Improvements in these areas will be introduced into the final version of the pipeline, which should lead to appreciable refinements of the already quite good radial velocities extracted from RAVE spectra. A version of the pipeline currently under testing (a) refines the continuum normalization based on *fiducial points* given in a pre-defined list and selected according to the iterative solution of the atmospheric modelling, (b) treats different sections of the spectrum according to a weighting scheme based on recorded performances as a function of the atmospheric properties of the star, and (c) uses the derived atmospheric properties to select the best matching template from the full synthetic library.

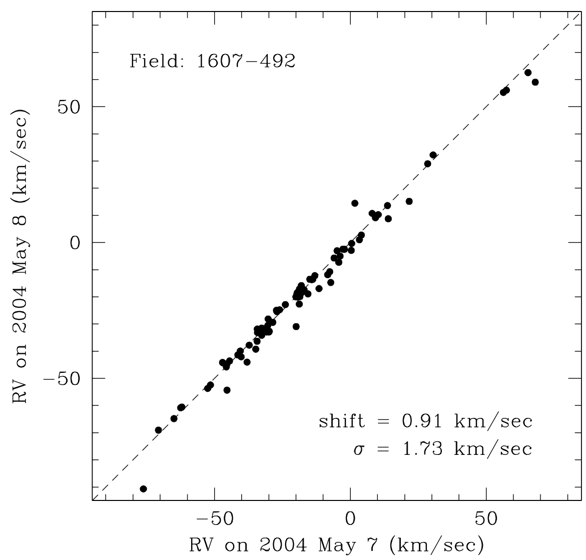

Figure 7. Comparison of the radial velocities obtained with the automatic reduction pipeline for the stars of the same RAVE-1607m492 field observed in two consecutive nights.

8. ATMOSPHERIC PARAMETERS

Atmospheric analysis of RAVE spectra is performed in the current pipeline by a blind χ^2 matching to the above described synthetic spectral libraries. The current χ^2 scheme looks just for the best matching template, and does not interpolate to derive the grid parameters corresponding to the minimum of the χ^2 function.

Within this simplified approach, the eight re-observations of the same RAVE-1607m492 field described above have been independently analyzed. Ideally, each star in all re-observations should have provided the best match against the same synthetic template. However different S/N, spectrograph focusing, accuracy of the background subtraction and continuum normalization between different re-observations days, months or years apart cause a

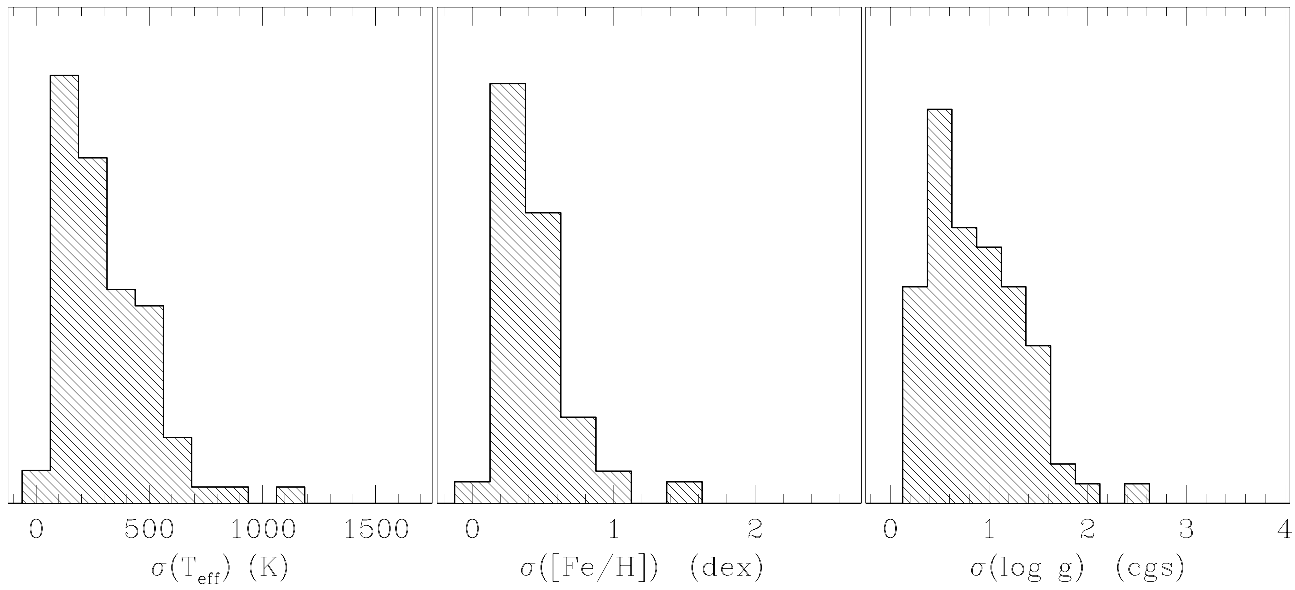

Figure 8. Distribution of errors on $T_{\rm eff}$, $\log g$, [Fe/H] from χ^2 fit to the Zwitter et al. (2004) and Munari et al. (2005) synthetic libraries for 84 stars belonging to field RAVE-1607m492 as re-observed in eight nights. The dispersion of the measurements is taken as an estimate of the external error.

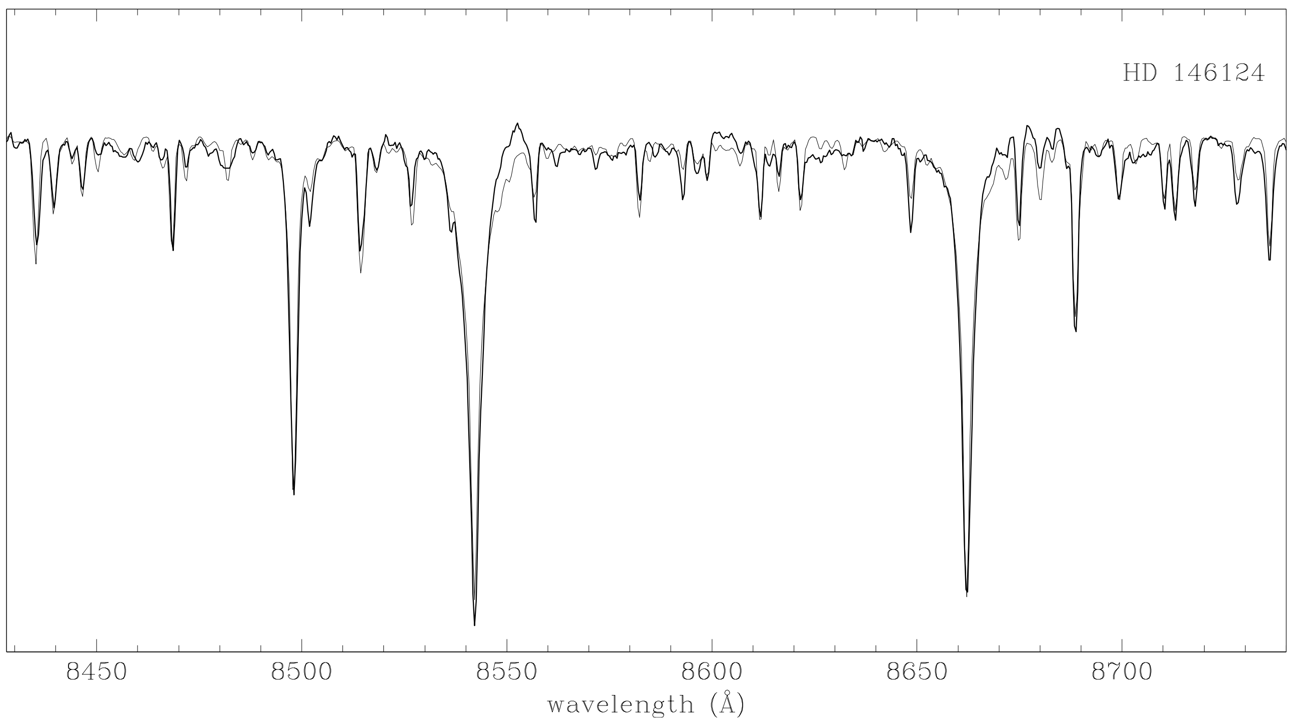

Figure 9. Comparison of the RAVE spectrum of HD 146124 from field 1607m492 (thicker line) and a Kurucz spectrum (thinner line) extracted from the Munari et al. (2005) synthetic library for the parameters $T_{\rm eff}$=5395 K, $\log g$=4.5, [Fe/H]=+0.11 derived for this star by the Geneva-Copenhagen survey (Nordström et al. 2004).

spread in the best matching templates. The dispersion between the results of the analysis of the 8 re-observations provide a direct measure of the internal accuracy of the derived atmospheric parameters. The results for $T_{\rm eff}$, $\log g$ and [Fe/H] are presented in Figure 8, that shows typical errors of ∼6% in $T_{\rm eff}$, 0.4 dex in [Fe/H] and 0.9 dex in $\log g$ for spectra of moderate to high S/N. The errors on $T_{\rm eff}$ and $\log g$ are already good enough for a spectral classification accurate to about a couple of spectral subtypes and one luminosity class for the dominating population of field F-G-K stars.

Stars HD 146124 and HD 143885 have been observed and classified by the Geneva-Copenhagen survey and they are included within the RAVE-1607m492 field. Figure 9 compares the RAVE spectrum of HD 146124, a G6 V star, with a Kurucz spectrum extracted from the Munari et al. (2005) synthetic library for the parameters $T_{\rm eff} = 5395$ K, $\log g = 4.5$, [Fe/H] $= +0.11$ derived for this star by the Geneva-Copenhagen survey. The match between the star and the Kurucz spectra is quite satisfactory. Pretty similar results are derived for HD 143885 too. The differences between the results of the blind χ^2 analysis of RAVE spectra and of the Geneva-Copenhagen surveys are quite good for temperature ($\Delta T_{\rm eff} = 1.8$% and 0.7% for the two stars, respectively) and metallicity (Δ[Fe/H] = 0.24, 0.26 dex), while not so much for gravity ($\Delta \log g = 1.9$, 2.1 dex).

Improvements foreseen for the final data reduction pipeline on atmospheric analysis include those described above on the continuum rectification as well as a smarter χ^2 approach on a complete synthetic spectral grid characterized by a finer step. The smarter χ^2 is based on a series of weighting schemes for the various sections of the RAVE spectra depending on the different atmospheric parameters, so that different sections will affect most the determination of one parameter and will have a minor (or null) impact on the other parameters (like the wings of CaII lines for the surface gravity, or the FeI+TiI group of lines at 8510–8520 and 8670–8695 Å for the temperature). For most of the targets $I_{\rm C}$, J, H, K photometry is available from DENIS and 2MASS surveys, and about half of them have been measured by Tycho-2 in $B_{\rm T}$, $V_{\rm T}$. Inclusion of the photometric information in the data reduction pipeline is foreseen, mainly to the benefit of the determination of the temperature.

9. DATA RELEASE

The first release of RAVE data is expected to occur during the spring of 2005, and others should follow regularly. It is planned to release initially the radial velocities, then the atmospheric parameters and, finally, to make available the calibrated spectra too.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance of Rosanna Sordo and Urtzi Jauregi in the preparation of this report that has been presented to this Conference on behalf of the whole RAVE Collaboration that includes participants from Germany, Australia, UK, Italy, USA, France, Switzerland, Slovenia, Canada and The Netherlands.

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