CSIRO PUBLISHING
5th Workshop on Galactic Chemodynamics
www.publish.csiro.au/journals/pasa
Publications of the Astronomical Society of Australia, 2004, **21**, 207–211

Physical Parameters of SDSS Stars, the Nature of the SDSS 'Ring around the Galaxy', and the SEGUE Project

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Received 2003 October 1, accepted 2004 January 21

Abstract: Although the Sloan Digital Sky Survey (SDSS) was primarily envisioned as a tool for understanding the nature of the 'high redshift' universe, significant discoveries have already been made at lower redshift, $z \sim 0$, through studies of stars in the Milky Way galaxy. We have begun to explore the nature of the Milky Way by detailed investigation of the publicly accessible SDSS archive, using spectroscopically targeted stars of special interest (e.g. field horizontal-branch stars, carbon-enhanced stars, and F- and G-type turnoff stars), as well as the stars originally selected as photometric and reddening standards. The first step is to use the SDSS data (which includes independently calibrated five-band photometry and spectrophotometry of individual stars) to derive reliable estimates of the stellar physical parameters, such as $T_{\rm eff}$, $\log g$, and [Fe/H], for stars that have been observed to date. Of particular interest, at present, are the stars that are apparently associated with the Monoceros Stream (also known as the SDSS 'Ring around the Galaxy'), for which we report derived metallicities. The techniques we have developed for derivation of the physical parameters for these stars are presently being applied to other stars in the SDSS database, including the Early Data Release (EDR), as well as the first official public database, DR-1. Here we report on the progress made to date, and comment on what might be explored in the near future from a dedicated extension of the SDSS survey (SEGUE) that specifically targets stars in the Milky Way.

Keywords: Galaxy: Chemical abundances — Galaxy: Halo — Galaxy: Thick Disk

1 Introduction

The Sloan Digital Sky Survey (SDSS; Gunn et al. 1998; York et al. 2000) was designed to observe the high-redshift universe and to provide unprecedented knowledge of the large-scale distribution of galaxies and quasars. This is, of course, of great importance. However, it has also become clear to many astronomers that the SDSS telescope/detector combination could make equally important contributions to exploration of the universe at low redshift, through observations of well-selected stars in the Milky Way galaxy. It should be kept in mind that, even though one studies stars that are still shining at present, the most metal-deficient stars of the halo population have been 'alive' for on the order of 13–14 Gyr, and were witnesses to the epochs of light- and heavy-element formation that took place shortly after the Big Bang. In fact, the 'look-back time' to these stars *exceeds* that of the most distant known quasars.

The stellar subset of the SDSS survey is, after all, the first data return from what is expected to be an onslaught of new surveys that will provide detailed spectroscopic and photometric information for stars in the Milky Way, and for other stars in galaxies of the Local Group (e.g. RAVE: Steinmetz 2003; *Gaia*: Perryman 2002). Hence, it is deserving of special efforts to fully exploit the information contained within the spectrophotometric data that has already been obtained, and that which will be obtained in the near future.

We have initiated an effort to develop the tools and methodology required to make full use of the present SDSS stellar database (which at present includes spectroscopy of some 20 000 stars in the public archive, and by time of publication, will number in excess of 50 000 stars). This effort includes methods to refine the determination of stellar radial velocities (to accuracies of $\sim$10 km s^{-1}, substantially better than obtained from the previous pipeline SDSS reductions), as well as the determination of stellar physical parameters ($T_{\rm eff}$, $\log g$, and [Fe/H]). We expect to soon implement methods for the determination of individual elemental abundances for SDSS-targeted stars, including C, Ca, Mg, and Na, and perhaps other species as well.

10.1071/AS04010 1323-3580/04/02207

As a first example of the power of existing SDSS stellar spectroscopy, herein we report on the determination of [Fe/H] for stars in the recently reported (Ibata et al. 2003; Yanny et al. 2003) detection of a possible 'Ring around the Galaxy', the Monoceros Stream, which is a structure that may be associated with the debris from a previous dwarf-galaxy interaction with the disk of the Milky Way, and may also be linked with the origin of the thick disk of the Milky Way. In addition, it remains possible that the stars in the metal-weak thick disk of the Galaxy (see for example Beers et al. 2002, and references therein) may have originated from the (presumed) dwarf-galaxy progenitor of this structure (see Section 4 below for updated information on this hypothesis).

In the final section of this paper, we speculate on what might be learned from a *dedicated* study of stars in the Milky Way (SEGUE), based on an extension of the present SDSS survey to one that obtains additional photometry and targeted spectroscopy for stars of particular interest within the Milky Way.

2 The SDSS Early Data Release and DR-1

The SDSS Early Data Release (EDR) contains roughly 5000 (of 5604 total) stars that are in the range of temperature amenable to our analysis techniques. Most of the stars we cannot immediately make use of are either too hot (e.g., white dwarfs, subdwarf O- and B-type stars), too cool (late M-type dwarfs of the disk populations, as well as M-type subdwarfs), or their spectra were of insufficient signal-to-noise. Stoughton et al. (2002) describe the sample selection in the EDR. Even though the complexity of the sample selection precludes the use of stars in the EDR for unravelling many questions of interest concerning the nature of the stellar populations of the Milky Way, the EDR stars provided an important first sample for development and refinement of our analysis techniques.

The first official data release from SDSS, known as DR-1 (Abazajian et al. 2003), provides on the order of 20 000 stars with available spectrophotometry (and independently calibrated *ugriz* photometry); the EDR sample is contained within DR-1, and has benefitted from the application of recalibrations of the photometry and spectrophotometry. It should be noted that as the SDSS is an ongoing survey, there is continuous effort to refine and improve the photometric and spectrophotometric quality of the data. Of the stars in DR-1, roughly 15 000 are suitable for our present analysis. DR-2 is expected to be publicly released in early 2004, and will contain on the order of 30 000 additional stellar targets.

3 Tools for Determination of Stellar Physical Parameters

Allende Prieto et al. (2003) have described our basic approach to semi-automated analysis of SDSS stellar targets in some detail. Here we simply summarise the procedures employed, and point out where refinements have since been made to the methods. The methods we employ can be relatively easily ported to other applications, such as analysis of the RAVE spectra; we are presently in the process of developing these extensions of our techniques.

Radial velocities of the stars are provided in the SDSS headers, and are determined by pipeline reduction routines. It has been noted by a number of workers that the errors in these velocities are rather large, on the order of 20–30 $\mathrm{km\,s^{-1}}$, which is too high for useful analysis of stellar populations in the Galaxy. The origin of these errors has been traced to the lack of accurately measured zero points of the template spectra used in the SDSS reduction procedures (this difficulty has since been corrected, and these errors have been substantially reduced in the DR-2 release). For now, we first re-measure the radial velocities for each stellar spectrum, using our own (synthetic) stellar spectral templates, as well as methods based on line-fits to the strong spectral features such as Ca II K, the Balmer lines, and so forth (for details of these approaches, see Beers et al. 1999). Based on a limited amount of comparison with stars with independently measured spectra, we estimate that the external errors for the improved radial velocity measurements are on the order of 10–15 $\mathrm{km\,s^{-1}}$, a factor of two improvement over the SDSS pipeline values in DR-1, and much more suitable for kinematic analyses. A paper discussing the determination of the external velocity errors, and the repeatability of the SDSS velocity determinations, based on multiple observations of a large sample of stars, is planned for the near future.

Starting from the SDSS-released photometry and flux-calibrated spectroscopy for Galactic stars, we are interested in a detailed classification based on the fundamental atmospheric parameters. Given the large wavelength coverage in each spectrum (3800–9200 Å), we can also quantify the interstellar reddening towards the observed stars, for comparison with the reddening determined by other methods, for example the maps of Schlegel, Finkbeiner, & Davis (1998). Stellar metallicities, surface gravities, and effective temperatures are derived in the following manner.

We make use of the SDSS ($ugriz$) photometry and the $\sim$3800 pixels in an object's spectrum altogether. We found it helpful to trade resolution for signal-to-noise, hence the spectra are smoothed from the original SDSS resolving power of $R = 1800$ to $R = 1000$, by convolution with a Gaussian profile. The complete set of data inputs are assembled and then modelled with plane-parallel, line-blanketed LTE model atmospheres and radiative transfer calculations, as a function of the stellar parameters, using the atmospheres and low-resolution synthetic spectra of Kurucz (1993).

In a previous attempt at this approach, both photometric magnitudes and spectra were computed for a discrete $12 \times 4 \times 6$ grid spanning the ranges 4500 to 10 000 K, 2.0 to 5.0 dex, and -4.5 to $+0.5$ dex in T_{eff}, $\log g$, and [Fe/H], respectively. The interstellar reddening, $E(B-V)$, is parameterised as in Fitzpatrick (1999), adopting $A(V) = E(B-V) = 3.1$. This parameter gives one more dimension to the grid. We have improved the resolution of our grid by a factor of five, leading to substantial improvement in the derived parameter estimates. Model spectra and photometry for sets of parameters off the grid nodes are derived by multi-linear interpolation.

Some elements show abundance ratios, relative to iron, that are non-solar in metal-poor stars. This is largely ignored (at present) in our modelling. However, we consider enhancements to the abundances of Mg and Ca in metal-poor stars when calculating synthetic spectra because these elements produce strong lines on which our analysis heavily relies. We perform a search for the model parameters that minimise the distance between the model vector $\boldsymbol{T}$ and the observations vector $\boldsymbol{O}$, adjusting a set of weights across the differences between $\boldsymbol{T}$ and $\boldsymbol{O}$ for optimum performance. The search is accomplished by using either the Nelder–Mead simplex method (Nelder & Mead 1965) or a genetic algorithm (Carroll 1999). Classification of a single spectrum takes a few seconds on a 600 MHz linux workstation.

The inclusion of the Ca II K line and the seven first members of the Balmer series in SDSS spectra makes them suitable for the application of well-tested techniques developed for the analysis of medium-resolution spectra for stars in the HK survey (Beers, Preston, & Shectman 1992; Beers et al. 1999). After measuring the pseudo-equivalent widths of the relevant spectral features and estimating the $(B-V)_0$ colours from the SDSS photometry, we obtain a second, relatively independent, measure of the metallicities of the stars. In Allende Prieto et al. (2003) it was noted that there appeared to exist a disagreement in the two sets of metallicity determinations, in the sense that the [Fe/H] estimated from our spectral fits was consistently too low, as compared with that obtained from the Ca II K/$(B-V)_0$ methods. This discrepancy has now been repaired, by an improvement in the weighting scheme to allow metallicity determinations to rely more strongly on, for example, the alpha elements, in cases where the signal-to-noise of the spectrum and/or the low overall metallicity precludes reliable determination of abundance from the collection of weak Fe-peak-element features in the spectra. For warmer stars, near the main-sequence turnoff and beyond (including blue stragglers and field horizontal-branch stars), we also make use of refinements of the Wilhelm, Beers, & Gray (1999) methods for determination of [Fe/H]. For our final abundance determination, we take a straight average of the 'best two of three' (those that agree best with one another) estimates obtained by these methods, for stars with [Fe/H] ≤ -1.5, but prefer the value obtained by the grid search for more metal-rich stars, since it is known that the Beers et al. (1999) calibration is less accurate for more metal-rich stars, owing to the gradual saturation of the Ca II K line index employed.

To provide a check on the determination of effective temperatures, the $(B-V)_0$ colours estimated from the SDSS *ugriz* photometry and the stellar metallicities are fed into the photometric calibrations of Alonso et al. (1996, 1999), which are based on the Infrared Flux Method (Blackwell, Shallis, & Selby 1979). Only a small zero-point offset is noted (on the order of 50 K), with an rms scatter between the two determinations on the order of 150 K, which we take to be quite satisfactory. The methods of Wilhelm et al. (1999) also provide estimates of effective temperature for the warmer stars in the sample.

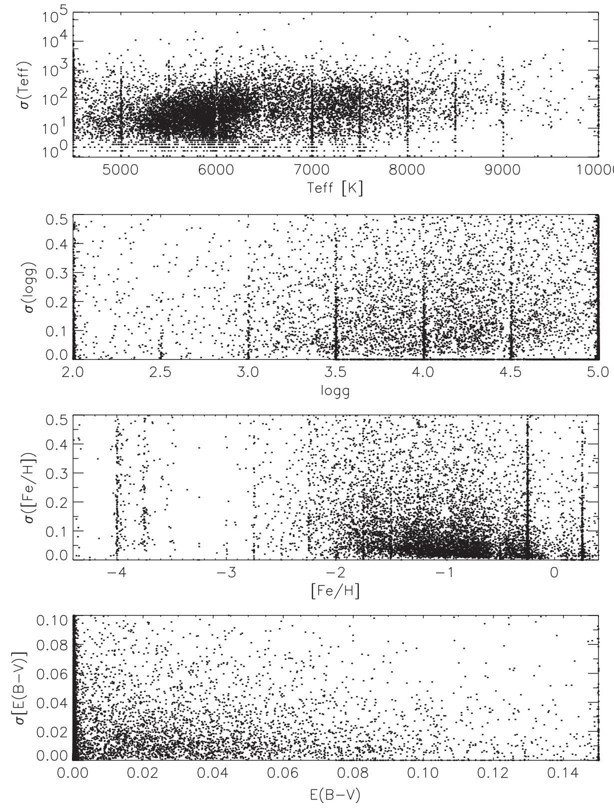

Figure 1 Distribution of internal errors from the grid-matching method for stars in DR-1. Note that the overdensities of objects at the nodes of the grid are spurious — we are working to reduce this effect. The apparently large numbers of stars at [Fe/H] < -3.5 is also an artifact of the grid, which is easily removed by the averaging (best two of three estimates) described in the text.

Checks on the derived surface gravities are clearly desirable, but require that we obtain a set of suitable standards with well-determined $\log g$ (presumably by means of high-resolution spectroscopy). We are in the process of gathering such data for some of the brighter SDSS stars.

In Figure 1 we show the present state of our estimated errors, based on the automated procedures, for the stellar parameters, in this case, for the stars we have analysed to date from DR-1. As can be seen, the estimated internal errors for these parameters in the majority of the stars are satisfyingly low, on the order of $\sigma(T_{\rm eff})$, $\sigma(\log g)$, $\sigma(\rm [Fe/H]) = 100$–200 K, ≤ 0.3 dex, and ≤ 0.3 dex, respectively. The errors in the derived reddening are typically better that 0.03, which is in line with expectation.

Figure 2 shows the result of the application of our methods for the determination of [Fe/H] and distance for the EDR stars. One can easily see the presence of, for example, the canonical thick disk (stars within $\sim$0.5–2 kpc of the disk plane and with metallicities in the range $-1.0 \leq$ [Fe/H] ≤ 0.0), the metal-weak thick disk (stars within $\sim$0.5–2 kpc of the disk plane and with metallicities in the range $-2.0 \leq$ [Fe/H] ≤ -1.0), and members of

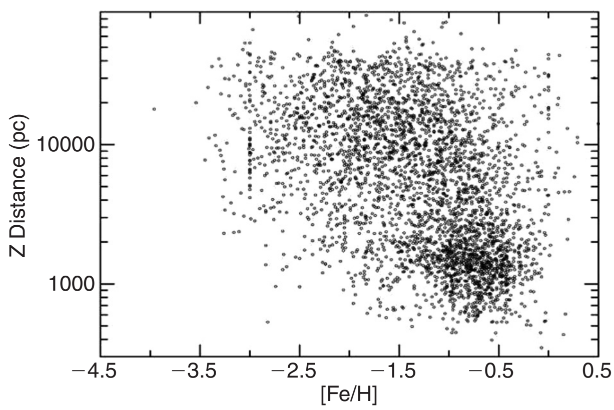

Figure 2 Distribution of estimated distances and metallicities for stars from EDR.

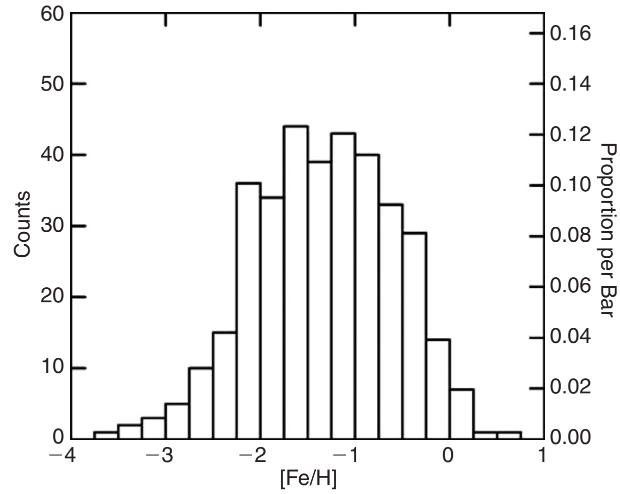

Figure 3 Distribution of estimated metallicity for 357 stars in the direction of the Monoceros Stream.

the inner (stars within 10–15 kpc) and outer (stars outside 10–15 kpc) halo populations.

4 Metallicities for Monoceros Stream Stars

Yanny et al. (2003) and Ibata et al. (2003) present evidence for the existence of a ring of stars in the plane of the Milky Way (in the direction of Monoceros), extending at least from Galactic latitude $l = 180°$ to $l = 227°$ with turnoff magnitude $g \sim 19.5$, and speculate that it could well encircle the Galaxy at a distance $R = 18 \pm 2$ kpc from the Galactic center. See Helmi et al. (2003a) for alternative interpretations of this structure.

Yanny et al. estimate metallicities for the stars in this structure, and conclude that it has a peak at [Fe/H] $= -1.6$, with a fairly broad dispersion. As a check on this determination, we have applied the techniques described above to the stars in the Monoceros Stream. The result, for the stars that had spectra with sufficient signal-to-noise ratios in the direction of this structure, are shown in Figure 3. We verify the peak metallicity, but it is also clear that the shape of the metallicity distribution is inconsistent with origin in a single stellar population; there is a surely a mixture of stellar populations present, including stars which are perhaps not members of the stream itself. Clearly, one requires many more spectroscopic and photometric measurements of potential stream members, and (ideally) measurements of proper motions and improved radial velocities, in order to separate true members of the stream from foreground/background stars. A paper summarising the velocities, abundances, and other observables for these, and other stars in the direction of the Monoceros Stream, is in preparation. Additional measurements might be obtained, either via a dedicated survey, or as part of the planned extension of SDSS described below.

A number of recent papers have verified the tidal nature of the Monoceros Stream structure, and present studies of its chemical nature. These include Rocha-Pinto et al. (2003), who used the 2MASS catalog to identify a density enhancement that is likely connected with this structure; Crane et al. (2003), who collected spectra of possible M-giant members of this structure, selected from the 2MASS catalog; and Frinchaboy et al. (2003), who suggest the presence of open clusters that may be associated with it. Martin et al. (2003) identified (again from M-giant stars selected from 2MASS) the presence of the likely progenitor of this structure, a dwarf galaxy in the direction of Canis Major. Taken as a whole, it appears that there is compelling evidence that the Monoceros ring structure is likely to be tidal debris that has been shorn from the main body of the newly discovered Canis Major dwarf galaxy. It is difficult to compare the derived metallicity peak of Crane et al. (2003), [Fe/H] ~ -0.4, with that derived in the present work, [Fe/H] $= -1.6$, since the Crane et al. study used M-giants, which necessarily are associated with metal-rich populations. The most likely interpretation is that the Canis Major dwarf, and the stars stripped from it, comprises a mixture of stellar generations spanning a wide range of metallicities, as might be expected to be associated with a dwarf galaxy that has undergone multiple bursts of star formation in its history.

5 SEGUE — The Sloan Extension for Galactic Understanding and Evolution

Members of the extended SDSS community (including original consortium members as well as outside collaborators) are presently considering options for carrying out an extension of SDSS beyond its scheduled termination in July 2005. In particular, one option that has been given serious discussion would be to carry out additional low-Galactic-latitude imaging for some 2000 square degrees of sky below Galactic latitude $l = 30°$ and, in particular, dedicated spectroscopic follow-up of stellar targets of interest over a well-sampled region of the sky accessible from Apache Point Observatory. The proposed SEGUE project survey would provide the information required to unravel the structure, formation history, kinematical and dynamical evolution, chemical evolution, and dark matter distribution of the Milky Way. These results underpin our knowledge of the formation and evolution of the Milky Way galaxy, and will provide the cornerstone of our understanding of galaxy formation processes in general.

This survey is envisioned to require on the order of two to three years to complete, and would provide (in addition to the imaging) SDSS spectra for on the order of 250 000 stellar targets in the magnitude range $14 \leq g \leq 20$. The planned $\sim$1200 spectra in each of 200 individual sky directions enables discovery of all major Galactic substructures, including tidal tails from merger events in the Galactic halo as well as in the disks. Additional observations will be obtained in locations of star formation, Galactic satellites, and other regions of high interest. The low Galactic latitude imaging enables studies of the metal-rich Galactic thin disk, the vertical structure of the thin and the thick disks, the Galactic warp and flaring, low-Galactic-latitude tidal streams, the three dimensional structure of the ISM, and present star forming regions. As part of the preparation for such a survey, we are using small test samples of stars already obtained from SDSS observations to optimise a colour-selection algorithm (e.g., Helmi et al. 2003b) that would enable a reasonably efficient identification of stars with [Fe/H] < -1.0, from which on the order of 100 000 low-metallicity targets might be chosen. Depending on the actual shape of the metallicity distribution function of the halo, such a sample might be expected to contain on the order of 10 000 stars with [Fe/H] < -2.0, 1000 stars with [Fe/H] < -3.0, and 100 stars with [Fe/H] < -4.0, distributed throughout the thick disk, inner halo, and outer halo of the Galaxy.

SEGUE includes two related key projects, which both contribute to our knowledge of the Galactic mass assembly and disk formation models. These projects are (1) detection of substructure in the Galactic halo, and (2) defining the structures of the Galactic disks. This proposed project will provide a large homogeneous input data set for a 21st-century model of the Galaxy, one which involves not only accurate multi-colour photometry such as has gone into earlier models (Bahcall & Soneira 1984; Rong, Buser, & Karaali 2001), but large amounts of kinematic velocity and proper motion data which can be used to complete the dynamical and evolutionary picture, similar to but on a larger scale than the technique employed by the Besancon program (Robin et al. 2003).

Acknowledgments

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, Los Alamos National Laboratory, the Max Planck Institute for Astronomy (MPIA), the Max Planck Institute for Astrophysics (MPA), New Mexico State University, the University of Pittsburgh, Princeton University, the United States Naval Observatory, and the University of Washington. We gratefully acknowledge NASA (grants ADP 0200320106 and LTSA 0200170093) and NSF support (grants AST 0098508, AST 0098549, AST 0086321, and AST 0307571), as well as partial funding from the Research Corporation.

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