The SDSS-I Value Added Catalog of Stellar Parameters and the SEGUE Pipeline

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We report on the development, calibration, and refinement of the SDSS-I Value Added Catalog (VAC) of stellar abundances, temperatures, and surface gravities. This catalog is based on observations of several hundred thousand stars obtained during the course of the original Sloan Digital Sky Survey, now known as SDSS-I. A spectroscopic pipeline has been developed that obtains estimates of [Fe/H], T_{eff}, and log g based on medium-resolution (R = 2000) spectra and *ugriz* photometry obtained with the ARC 2.5m telescope. This same pipeline is being used for estimation of stellar parameters for the ongoing SEGUE: Sloan Extension for Galactic Understanding and Exploration project. We discuss the methods explored for development of the VAC, as well as tests of the calibration based on high-resolution spectroscopy obtained with the Hobby-Eberly Telescope, the Keck telescopes, and the Subaru telescope.

A. Stellar Observations in SDSS-I and SEGUE

Although the SDSS was conceived and executed primarily to explore the extragalactic Universe, over the course of the period 1999-2005, when it was underway, medium-resolution (R = 2000) spectroscopy of an unprecedented large sample of Galactic stars, numbering roughly 200,000, were obtained. This data is presently publicly available, as SDSS Data Release 5, from http://www.sdss.org. In order to maximize the scientific payback from these stellar observations, we have undertaken to develop, calibrate, and refine methods for the estimation of the atmospheric parameters [Fe/H], T_{eff}, and log g for as many of these stars as possible, and make these estimates available to the astronomical community.

This effort has also been carried out so that the same approaches can be used for parameter estimation of the stars for which similar data is presently being obtained from the SEGUE survey, which will obtain spectroscopy for some 250,000 stars chosen to explore the nature of stellar populations throughout the Milky Way.

The SDSS-I Value Added Catalog (VAC), which we are in the process of preparing for a Fall 2006 release, represents the first summary of stellar parameters in a continuing series of VACs, extending through the lifetime of SEGUE, and perhaps beyond, if future efforts directed at studies of Milky Way stellar populations with the ARC 2.5m telescope are funded. In addition to our derived stellar parameters, the SDSS-I VAC (and later releases) will contain precision *ugriz* photometry, radial velocities (accurate to 7-20 km/s, depending on the apparent magnitude of the star), proper motions, and other information (such as estimates of abundances for C, Ca, Mg, Na, Sr, and Ba) that we will be able to derive from the data, once appropriate calibrations have been carried out.

B. Design Philosophy of the Spectroscopic Pipeline

Since the stars observed during the course of SDSS-I, and which are being observed in SEGUE, cover a wide range of stellar atmospheric parameters, we have decided to develop a pipeline that makes use of multiple techniques, some of which will be better than others, depending on the particular region of parameter space we are exploring. The use of multiple techniques has the additional advantage that one can estimate internal errors in the determination of parameter estimates from the scatter obtained by different approaches. some require *ugriz*, others do not (useful for regions of high E(B-V) or where measured colors are suspect. The present pipeline involves:

- [Fe/H] estimates based on 7 techniques – CaII K, CaII triplet, ANN, Autocorrelation, Spectral matching (3 regions)
- T_{eff} estimates based on 5 techniques – Balmer lines, ANN, Spectral Matching (3 regions), Half power point integration over flux-calibrated spectrum
- Log g estimates based on 6 techniques – Ca I 4227, MgH, ANN, Spectral Matching (3 regions)

In the construction of the VACs, we keep track of the results of the individual estimation procedures, and make an informed choice on which ones to weight more (or less) depending on the region of parameter space being explored. We also check for potential problems that might arise due to (occasional) incorrect colors that are obtained, and provide estimated colors, derived from the spectra themselves, which can be used as substitutes.

C. Example VAC Output

SDSS STAR	RA (DEG)	DEC (DEG)	G_MAG	G-R	~B-V	VEL	FEH	SIGF	NF	LOGG	SIGG	NG	TEFFA	SIGT	NT
52518-0737-001	336.810840	12.047003	18.428	1.08	1.26	-24.4	-1.14	...	1	...	...	0	4279	...	1
52518-0737-030	337.549880	12.628333	17.338	0.41	0.56	-2.5	-1.00	0.22	6	3.82	0.28	5	5845	64	5
52518-0737-032	337.552970	13.147942	18.399	0.77	0.93	-36.0	-1.08	0.37	5	4.42	0.52	3	4766	...	1
52518-0737-039	337.488620	12.759767	19.220	0.52	0.65	-46.0	-2.05	1.48	3	3.95	0.80	3	5375	...	1
52518-0737-047	336.371220	12.346197	17.415	0.49	0.65	-73.7	-0.67	0.11	5	3.84	0.14	6	5607	21	4
52518-0737-065	336.663620	12.607524	20.903	0.76	0.88	56.8	-0.78	...	1	4.15	0.00	4	4732	...	1
52518-0737-075	337.092970	12.769260	16.007	0.29	0.44	-217.7	-1.44	0.22	7	3.31	1.19	2	6220	158	3
52518-0737-080	337.035320	12.970552	18.716	0.03	0.19	-351.8	-1.33	0.99	2	4.36	...	1	7631	164	3
52518-0737-086	336.298600	12.112614	17.997	0.40	0.58	-109.4	-1.02	0.31	6	3.59	0.39	5	5844	32	5
52518-0737-094	336.297150	12.284820	18.463	0.72	0.91	-1.9	-1.12	0.39	5	4.10	0.55	4	4986	...	1
52518-0737-112	336.478040	12.656192	19.099	0.89	1.07	-67.7	-2.01	0.73	3	1.40	0.40	4	4575	...	1
52518-0737-128	336.043610	12.122969	17.736	0.43	0.57	-7.8	-1.04	0.42	6	3.68	0.59	4	5664	...	1
52518-0737-129	336.095300	12.053612	20.473	0.52	0.67	-291.4	-1.55	...	1	4.36	0.04	6	5391	...	1
52518-0737-178	336.018120	13.123265	16.768	0.26	0.40	-262.4	-2.06	0.16	6	3.74	0.26	4	6390	92	3
52518-0737-235	335.638350	13.102211	15.973	0.43	0.58	-116.9	-0.75	0.06	7	3.82	0.08	5	5774	46	3
52518-0737-237	335.615940	13.010118	16.588	1.01	1.18	-46.3	-1.02	...	1	3.89	0.41	3	4377	...	1
52518-0737-241	335.526850	11.932741	16.831	0.31	0.47	-27.7	-1.24	0.46	6	3.71	0.64	3	6154	...	1
52518-0737-249	335.492610	12.278062	18.428	1.09	1.26	11.8	-1.11	...	1	...	...	0	4278	...	1
52518-0737-267	335.176260	12.736045	17.511	0.41	0.56	57.3	-0.93	0.21	6	3.79	0.26	6	5822	35	4
52518-0737-283	335.349100	12.182276	20.142	0.82	0.98	-37.5	-1.88	0.65	3	2.74	0.35	4	4580	...	1
52518-0737-286	335.276540	12.043587	20.624	0.73	0.86	-80.3	-0.06	...	1	5.53	...	1	4961	...	1
52518-0737-288	335.093170	12.234200	16.629	0.23	0.37	-124.4	-1.83	0.14	4	3.80	0.19	3	6593	51	3
52518-0737-313	334.837850	13.114356	17.457	0.39	0.54	10.0	-1.16	0.35	6	3.81	0.45	5	5884	110	5
52518-0737-322	335.336110	14.301547	16.887	0.51	0.67	-40.6	-0.47	0.09	7	4.47	0.13	4	5544	...	1
52518-0737-324	335.003250	13.971341	17.385	1.03	1.22	15.2	-0.54	...	1	...	...	0	4342	...	1
52518-0737-361	335.517290	14.330617	18.814	0.96	1.12	-70.4	-2.30	...	1	3.55	0.44	3	4454	...	1
52518-0737-362	335.531240	14.218181	16.835	0.42	0.58	-11.1	-0.55	0.23	5	4.20	0.32	6	5988	...	1
52518-0737-372	335.419960	14.191317	17.485	0.72	0.89	-44.3	-0.80	0.15	6	4.44	0.20	6	4986	...	1

The above is a VERY abbreviated version of the VAC listing. The full catalog will contain on the order of 100 pieces of information concerning each star, including line index measures of important spectral features, colors (including transforms to several systems), results of individual parameter estimates, distance estimates, astrometry, flags indicating where possible problems might exist, etc. All of this information will be in searchable format from the SDSS web page. One stop shopping !

D. Calibration and Refinement of the Pipeline

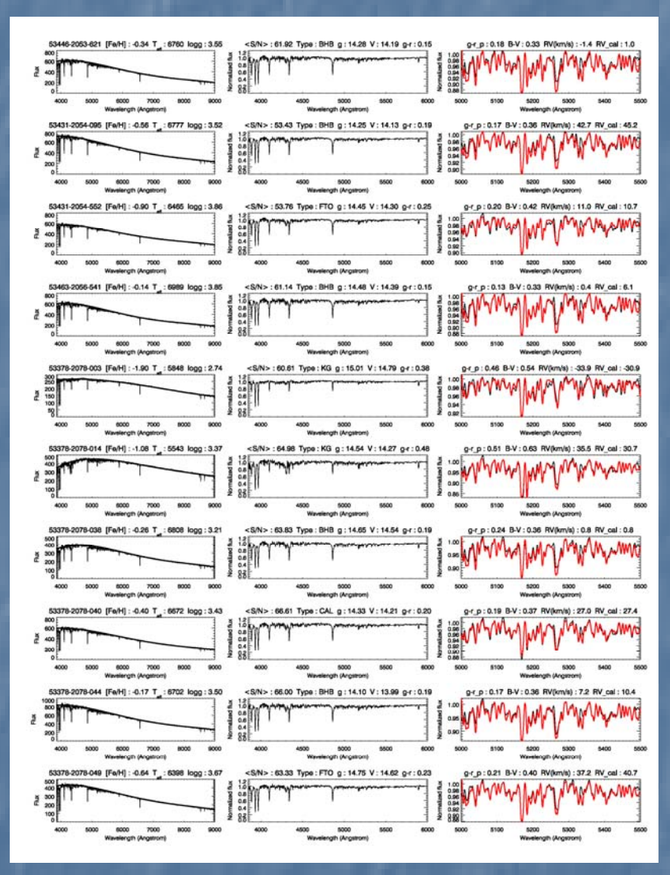
We have initiated a program to obtain high-resolution spectroscopy for on the order of 100-150 SEGUE stars with available pipeline estimates of atmospheric parameters, so that an external comparison of the accuracy of our determinations can be derived. This work is still underway, but we already have indications that our pipeline predictions are accurate and robust. This calibration work is expected to be continued throughout the course of the SEGUE survey, with the ultimate goal of having several hundred external determinations of atmospheric parameters that can be compared with the SEGUE pipeline predictions. These same data are being used to quantify our radial velocity offsets and scatter. Below we summarize the telescopes, resolving power, wavelength coverage, and numbers of stars observed as part of this effort thus far:

Telescope	Instrument	Resolving Power	λ Coverage (Å)	Stars
Keck-I	HIRES	40000	3800-10000	14
Keck-II	ESI	6000	3800-10000	20
HET	HRS	15000	4400-8000	65
Subaru	HDS	45000	3000-5800	5

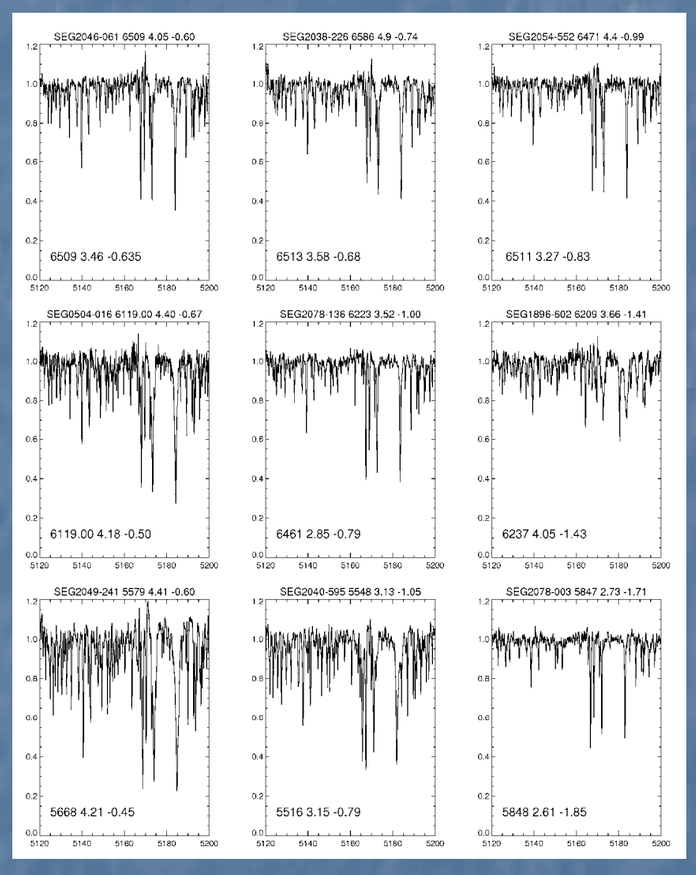
E. Example SDSS Spectra and Example High-Resolution Calibration Spectra from the Hobby-Eberly Telescope

In the left panel below we show some example SDSS spectra. The left most spectra show the full wavelength range from 3800 – 9000 Å with an optimal continuum fit; the middle spectra are the blue portion of the spectra with the continuum removed; the right most spectra compare a metallic line region from 5000 – 5500 Å with a sample synthetic spectrum (in red) generated with parameters assigned by the pipeline procedure. The agreement is often excellent.

In the right panel below we show a region around the MgI b lines for a subset of the high-resolution calibration spectra we have obtained with HET. We have indicated in each panel (at the top) the values of the atmospheric parameters obtained from analysis of the high-resolution spectra. In the lower portion of each panel, we list the atmospheric parameters obtained from the current spectroscopic pipeline. Warmer stars are at the top, cooler stars are at the bottom. Note that more recent calibration observations have included hotter, as well as cooler stars, but we have not completed their analysis.



Example SDSS spectra (from left to right: flux-calibrated / flattened blue / sample match to synthetic spectra.



Example HET high-resolution spectra in the region of the MgI b lines. High-resolution / medium-resolution pipeline parameters are shown above/below each spectrum.

F. Accuracy and Precision of the Current Pipeline

Based on the calibration material available at present, external errors in the SDSS/SEGUE spectroscopic pipeline parameters, obtained from comparison with the high-resolution analysis, are:

$$\langle [Fe/H]\_p - [Fe/H]\_h \rangle = +0.04 \pm 0.18 \text{ dex}$$
$$\langle Teff\_p - Teff\_h \rangle = +17.0 \pm 114 \text{ K}$$
$$\langle logg\_p - logg\_h \rangle = +0.03 \pm 0.33 \text{ dex}$$

Where the _p subscript indicates the pipeline values, and the _h subscript indicates the high-resolution values. A larger range of stellar effective temperatures and metallicites are currently being explored, and will be folded into the final calibration of the VACs. Including stars from the more extended parameter space may degrade the accuracies and precision listed above, however, they are clearly in impressive agreement at the moment, which we take as an encouraging sign for the future effort.