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# The SEGUE Stellar Parameter Pipeline and its use with SDSS/SEGUE and non-SDSS/SEGUE spectra

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We describe the motivation, philosophy, and techniques used by the SEGUE Stellar Parameter Pipeline (SSPP), a software tool originally designed to estimate the stellar physical parameters ($T_{eff}$, log $g$, [Fe/H]) for medium-resolution stellar spectra taken by the Sloan Digital Sky Survey (SDSS), and its subsequent extensions, which included the Sloan Extension for Galactic Understanding and Exploration (SEGUE). The SSPP has been recently improved to include the ability to estimate carbon-to-iron ratios, [C/Fe], and α-element-to-iron ratios, [α/Fe], at least for stars with sufficient signal-to-noise and in the temperature range 4,500 < $T_{eff}$ < 7,000 K. We also describe the application of the SSPP to other medium-resolution spectroscopic data with similar resolution as SDSS spectra.

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## 1. Introduction

The reasons for carrying out large-scale survey efforts to identify and study metal-poor stars in the Galaxy are by now well-recognized. Stars of sufficiently low mass (< 0.8 $M_{sun}$) to have survived for a significant fraction of the age of the Universe provide the opportunity to inspect the products of early nucleosynthesis events, as well as the evolution of the chemistry of the Universe over the 13.7 Gyrs since the Big Bang. Among the many questions that are asked, and which are beginning to be answered: (1) What are the abundance patterns of elements produced by the very first generations of stars?, (2) What is the nature of the Metallicity Distribution Function (MDF) of stars in the Galaxy, and how does it change with distance from the Galactic center?, and (3) How can we efficiently identify the rare examples of neutron-capture-element enhanced stars that provide crucial information about the astrophysical site(s) of the *s*-process and *r*-process? More detailed discussions of the motivations for obtaining large samples of low-metallicity stars are available [1,2].

Over the course of the past several decades, ever larger and more comprehensive efforts have been made to carry out dedicated surveys for stars of the lowest metallicity, beginning with the HK Survey of Beers and colleagues [3,4], the Hamburg/ESO Survey (HES) of Christlieb and colleagues [5], and culminating with the modern mega-surveys such as SDSS [6,7]. In order to handle the large volume of spectra that are now obtainable on relatively short timescales from efforts such as SDSS (and even larger ones, such as LAMOST), it has become necessary to develop, calibrate, and implement software pipelines that are capable of estimating the stellar physical parameters, such as effective temperare, $T_{eff}$, surface gravity, log $g$, and metallicity, [Fe/H], in a robust and efficient manner. Such pipelines must also be stable in the face of a variety of defects in the observed spectra, varying levels of signal-to-noise (S/N) ratios, wavelength coverage, and the parameter ranges that are encompassed by the surveyed stellar types. It is for these reasons that we, along with other members of the SEGUE team, developed the tool referred to as the SEGUE Stellar Parameter Pipeline (SSPP).

In this brief summary, we provide some background on what the SSPP actually accomplishes, how it does it, and how it has been improved and given a greater set of capabilities in the past few years. We close with a discussion of the parallel development of a pipeline tool, the non-SEGUE Stellar Parameter Pipeline (n-SSPP), which is being used to explore the spectra of numerous medium-resolution spectra from a variety of sources and surveys.

## 2. Operation of the SSPP

Stellar targets in SDSS/SEGUE were chosen for a variety of reasons, but ultimately the selection is usually based on a considered combination of apparent magnitude and position in a two-color diagram, such as the example shown in Figure 1. Note that the wide ranges of color correspond to considerable variation in stellar temperatures and surface gravities. Metallicity also can influence a star's position on such a diagram, but not an much as the first two variables.

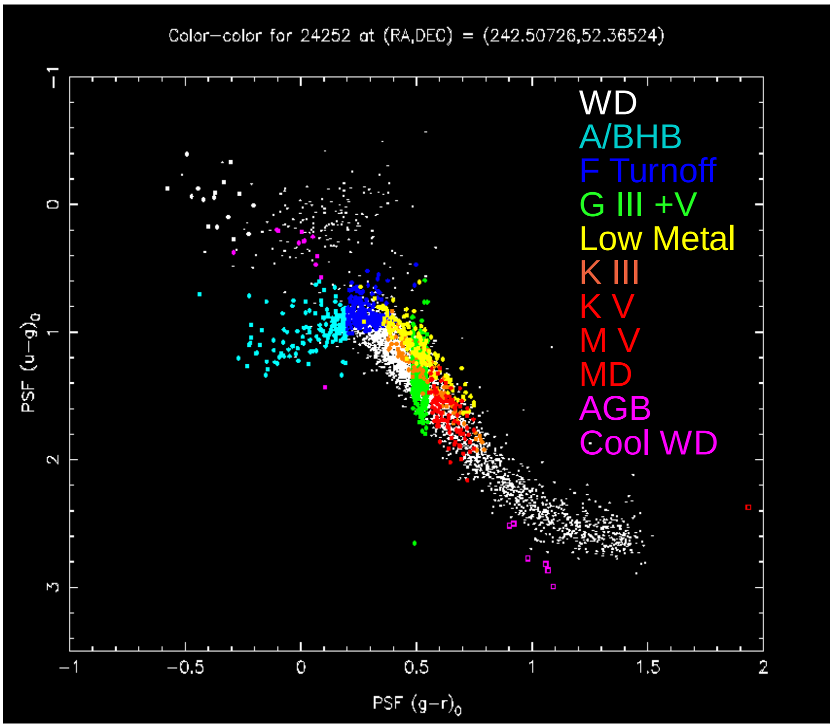


**Figure 1:** Color-based selection of stellar targets in SEGUE. Different regions of this diagram correspond to different categories (and physical characteristics) of stars.

It is immediately clear that a tool such as the SSPP must be designed to provide stellar parameter estimates over as wide a range in parameter space as is feasible.

The wavelength- and flux-calibrated medium-resolution (R ~ 2,000) SDSS/SEGUE stellar spectra are processed through the SSPP and the three primary stellar parameters ($T_{eff}$, log $g$, and [Fe/H]) are reported for most stars in the temperature range 4,000–10,000 K, and with spectral S/N ratios greater than 10. The SSPP estimates the atmospheric parameters through the application of a number of approaches, such as minimum distance methods, neural network analysis, auto-correlation analysis, and a variety of line-index calculations based on previous calibrations with respect to known standard stars. Detailed discussions of the methods involved are available [8, 9,10,11]. This multiple-technique philosophy allows the SSPP to obtain robust estimates of the parameters of interest for stars over a wide range in $T_{eff}$, log $g$, [Fe/H], and S/N. The SSPP is able to determine $\mathrm{T_{eff}}$, log $g$, and [Fe/H] to precisions of 141 K, 0.23 dex, and 0.23 dex, respectively, after combining small systematic offsets quadratically for stars with 4,500 K < $\mathrm{T_{eff}}$ < 7,500 K. Testing and calibration of the SSPP, although already exhaustive, continues to this day, as new methods are introduced and evaluated before being considered for inclusion in future versions. A set of output plots from the SSPP for a handful of stars with SEGUE spectra are shown in Figure 2.

### 2.1 Estimation of [C/Fe] ratios

The existence of a substantial fraction of low-metallicity stars in the Galaxy with enhanced abundances of carbon was initially recognized over 25 years ago [1]. Further studies have shown that both the frequency of the so-called Carbon-Enhanced Metal-Poor (CEMP) stars increases with declining stellar metallicity, and with distance above from the Galactic plane. These results have been argued to indicate the presence of an additional nucleosynthesis site for carbon production in the early Universe, beyond that assocated with mass transfer from AGB binaries, and likely associated with the very first generation stars [12]. Clearly, we would like to be able to measure [C/Fe] for as many stars as possible, hence we have extended the SSPP to accomplish this goal.

The estimates are based on spectral matching (over the spectral region 4290−4318 Å, the location of the most prominent band of CH in typical stars, the G-band) against a custom grid of synthetic spectra. The synthetic spectra are generated from a newly developed set of carbon-enhanced model atmospheres provided by Bertrand Plez (private communication). A chi-square search algorithm is employed to carry out the multi-dimensional matching procedure, from which an estimated [C/Fe] and its error are derived. In a minority of cases the search algorithm does not converge, and a lower or upper limit on [C/Fe] is reported. Although further calibration and testing is warrented, our preliminary comparison with several dozen CEMP stars with available high-resolution determinations of [C/Fe] indicates that our estimates are accurate to about 0.2 dex. Experiments based on noise injection into the synthetic spectra suggests that, for spectra with sufficient S/N (> 15/1), this method is able to estimate [C/Fe], or provide limits on [C/Fe], precise to better than 0.3 dex. The inset plots in the second column of panels in Figure 2 display how well a synthetic spectrum using the measured [C/Fe] (red spectrum in the figure) matches with the observed spectrum (black spectrum in the figure) over the region of the CH G-band. There are several hundred thousand stars in SDSS/SEGUE for which such estimates are now available.

In addition, we plan to examine the use of Sr and Ba lines, which are the strongest features associated with *s*-process elements in optical stellar spectra, and are (at least for cooler stars) visible in the SDSS/SEGUE spectra. The classification of CEMP stars into the sub-classes CEMP-s (indicating *s*-process-element enhancement) or CEMP-no (indicating no enhancement of *s*-process elements) provides crucial information on the likely carbon-production mechanisms [1]. Although it may not be possible to directly estimate accurate abundances of Sr and Br from the medium-resolution SDSS/SEGUE spectra, it may still be feasible to at least identify those stars for which they are detected.

### 2.2 Estimation of [α/Fe] ratios

Although the moderate resolution of the SDSS/SEGUE spectra is not sufficiently high to derive abundances for the individual α-elements, as an alternative, we have sought to estimate the overall α-element ratios, expressed as [α/Fe] (e.g., ([Ca/Fe]+[Si/Fe]+[Ti/Fe]+[Mg/Fe])/4) by inspecting a specific wavelength range over which there exist a number of α-element-sensitive features. As with the case for carbon estimates, the methodology is based on spectral matching against a custom grid of synthetic spectra. Details on the approach and validation of the

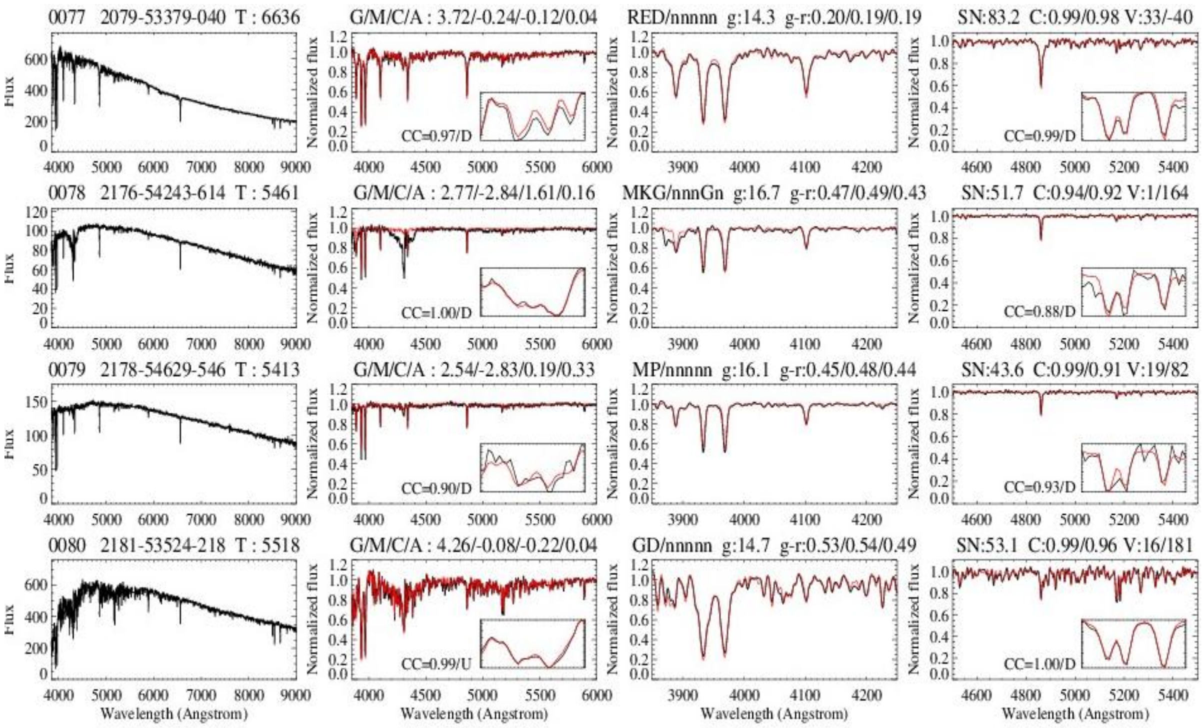


**Figure 2:** Examples of the SSPP output plots. Each row corresponds to a single star, showing different spectral regions. The red over-plotted lines represent the synthetic spectra generated with the adopted $T_{eff}$, log *g*, and [Fe/H] listed at the top of each of the first and second columns of panels. The inset plot in the second column of panels displays the match with a synthetic spectrum with the estimated [C/Fe] over the CH G-band, while the inset plot in the fourth column of panels shows the region of MgH. These are the spectral regions where we estimate the [C/Fe] and [α/Fe] ratios.

estimated [α/Fe] are available [13]. This technique allows us to estimate [α/Fe] with a precision of better than 0.1 dex for most SDSS/SEGUE stellar spectra with S/N > 20, over the parameter space $T_{eff}$ = [4,500, 7,000] K, log *g* = [1.5, 5.0], [Fe/H] = [–3.0, +0.3], and [α/Fe] = [–0.1, +0.6].

The inset plots in the fourth column of panels in Figure 2 show how well a synthetic spectrum using the measured [α/Fe] (red spectrum in the figure) matches with the observed spectrum (black spectrum in the figure) over the MgH band region. This [α/Fe] value will be a powerful indicator to find rare objects with low or high α-element abundance ratios, as well as to trace the general trends associated with different stellar populations in the Milky Way.

## 3. Application of the SSPP to non-SEGUE Data

The SSPP provides a rather general set of tools and approaches that, by design, can be applied to other medium-resolution spectra, even though they might cover quite different spectral regions than SDSS/SEGUE spectra. We have taken advantage of this by developing the so-called n-SSPP, for use with non-SEGUE spectra. The n-SSPP has already been successfully applied to some 15,000 spectra from the HK and HES surveys, and used to refine stellar parameter estimates for a number of published samples based on these data. We are in the process of applying the n-SSPP to many tens of thousands of stars from the SkyMapper follow-up program AEGIS [14], and over three hundred thousand stars with spectra from the LAMOST pilot survey [15]. The LAMOST sample of stellar spectra is expected to be expanded to between 5 and 10 million spectra over the course of the next few years, and the n-SSPP stands ready!

## 4. Conclusions

The SSPP and the n-SSPP have already proven to be extremely powerful tools for the analysis of medium-resolution stellar spectra from SDSS/SEGUE and other sources. We expect to continue to develop this pipeline, and, once it is fully stable, make it available to the general community. In the meantime, we welcome requests for collaborative efforts to use it for the analysis of medium-resolution spectroscopic data having a variety of resolutions and wavelength coverage.

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