Label Transfer From APOGEE to LAMOST and BOSS

Research Thesis

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Abstract

In this century, large spectroscopic stellar surveys observe stars in a large range of spectral types at different wavelengths, different resolutions with different data analysis methods. In order to further study Galactic evolution, measurements of stellar parameters for different surveys must be made precise and consistent. With The Cannon 2, a data driven method, we can transfer stellar parameters between two different surveys on the same scale directly. Using The Cannon 2, I investigated the effect of the training set size on the accuracy of the predicted results. As the size of the training set increasing, the accuracy of the inferred parameters increasing. The training label’s quality is the other factor that influences the label transfer results. In this thesis, The Cannon 2 is also used to predicate stellar parameters for 10,000 F, G, K stars, with estimate $T_{\text{eff}}$ less than 6000 K, from BOSS under the APOGEE scale to reduce the labels’ inconsistencies between two surveys.
This is dedicated to my parents.
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Chapter 1: Introduction

In this era, there are many spectroscopic stellar surveys, such as the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; Zhao et al. 2006, 2012; Cui et al. 2012), the Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009), and the Apache Point Observatory Galactic Evolution Experiment (APOGEE; Majewski et al. 2017), that measure the spectra of stars in the Milky Way. Stellar spectra are also obtained as a by-product of other surveys: for example, SDSS’s Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013) observed stars as part of its calibration data and ancillary programs. The Milky Way Mapper (Kollmeier et al. 2018) is now using the BOSS spectrographs to observe $\sim 10^6$ stars until 2026.

The spectra of stars contain absorption features whose depth depends on the temperature, gravity, and composition of the star. Originally, the stars were classified by the similarity of their absorption lines into ”spectral types” such O stars or M stars. These large surveys observe target stars in a large range of spectral types at different wavelengths, different resolutions and with different data analysis methodologies. APOGEE (high spectral resolution survey, $R^1 \approx 22,500$), for instance, has observed stars near-infrared and targeted giants in the mid-plane of the Milky Way, whereas $^1\!R=\lambda/\Delta\lambda$.
LAMOST (low spectral resolution survey, $R \approx 1,800$) observes O to M type stars (Liu et al. 2019).

The stellar parameters and elemental abundances like effective temperature, gravity, metallicity and alpha enhancement, are derived from observed stellar spectra via dedicated pipelines using spectral fitting routines. However, each survey has its own stellar parameter pipeline: the LAMOST Stellar Parameter Pipeline at Peking University (LSP3; Ren et al. 2016), and APOGEE Stellar Parameter and Chemical Abundances Pipeline (ASPCAP; García Pérez et al. 2016). Thus, the stellar parameters and abundances of the same star between many spectroscopic surveys are different. For example, Chen et al. (2015) compared 9952 objects observed and analyzed by both APOGEE and LAMOST. There are systematic biases in $\log g$ and $[\text{Fe/H}]$ between these two surveys.

To further study Galactic evolution, measurements of stellar parameters must be made precise and consistent across the large sample of modern spectroscopic surveys, Casey et al. (2016) have explained how we can use, the open-source code, The Cannon Method 2 to transfer stellar parameters between two different surveys. Ho et al. (2017) predicted precise parameters for 450,000 LAMOST giants with The Cannon Method 2.

The paper is organized as following:

- In Section 2, I present the data are used in this research thesis.

- In Section 3, I describe the the Cannon 2, followed by the training set selection, the training step, and the inferring step.

- In section 4, I describe the method of the Cannon.
• In section 5, I present the results from the inferring step and how the number and distribution of labeled stars affects the reliability of the transfer between APOGEE and LAMOST.

• In section 6, I describe the conclusion of this thesis.
Chapter 2: Data

The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; Zhao et al. 2006, 2012; Cui et al. 2012), is a low-resolution (R \approx 1,800) optical (3,650–9,000 Å) spectroscopic survey. The sixth data release (DR6; Zhang et al. 2016) is public and consists of spectra for over 9.9 million objects, as well as three stellar labels (T_{eff}, log g, [Fe/H]) for \sim 8.2 million stars.

The Apache Point Observatory Galactic Evolution Experiment (APOGEE; Majewski et al. 2017), is a high-resolution (R \approx 22,500), high-S/N (S/N \approx 100), H-band (15,200–16,900 Å) spectroscopic survey, part of the Sloan Digital Sky Survey-IV. The most recent data release, DR 17 (Abdurro et al. 2022), comprises spectra for > 384,000 red giant stars together with their basic stellar parameters and 15 chemical abundances.

The SDSS’s Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013) is a low-resolution (R \approx 2,000) optical (3,000–10,000 Å) spectroscopic survey, mapped the spatial distribution of luminous red galaxies and quasars to detect the characteristic scale imprinted by baryon acoustic oscillations in the early Universe. The Milky Way Mapper (Kollmeier et al. 2018) is now using the BOSS spectrographs to observe \sim 10^6 stars until 2026.
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Table 2.1: Summary of data.

The MaNGA Stellar Library (MaStar) is a project in SDSS-IV to build a large library of well-calibrated empirical stellar spectra, covering a wide range in stellar parameter space, roughly from 2,500 K to 35,000 K in effective temperature ($T_{\text{eff}}$), from -1 to 5.5 in surface gravity ($\log g$), and from -2.5 to 0.5 in metallicity ([Fe/H]). Most of the observations were done by piggybacking on APOGEE-2N.

The latest available data release of APOGEE (DR17), LAMOST (DR6), BOSS and MaStar are used in this research thesis. The fundamental stellar parameters: $T_{\text{eff}}$, $\log g$, [Fe/H], and [$\alpha$/Fe] for each star are from those catalogues.
Chapter 3: Theory

The Cannon Method 2 (Ho et al. 2017) is a data-driven method which can do the label transfer between different surveys. In this thesis, we use the term “label” to collectively describe the stellar parameters and element abundances like $T_{\text{eff}}$, $\log g$, $[\text{Fe/H}]$, and $[\alpha/\text{Fe}]$. The Cannon Method 2 relies on the following key assumptions: stars with the similar labels have the similar spectra, and the normalized flux is a smooth function of the labels. The change in the label leads to a smoothed change in the spectrum function. This function is the “training model”, fitting the spectral labels at each pixel of the spectrum. Based on the training model, the labels for the target set can be inferred under the same scale with the training set.

The Cannon Method consists of three steps:

1. The first step is choosing and pre-processing the training set. The Cannon Method needs the input spectra should have high SNR and the stellar parameters and abundances should have accurate estimates. The training model also requires incoming spectra to be normalized in the way that is independent of signal to noise and at rest wavelength.

2. The second step is to train the model at each wavelength pixel using the training set.
3. The third step is to use the model infer stellar labels for the target spectra set.

In the section below, details about each step are explained.

3.1 Training Set

The training set includes stars in common between two surveys. I use the cross-match function in the application Topcat (Taylor, 2020) to find the suitable training set. The "right ascension" and "declination" columns, which describe the stars’ positions on the sky, in two surveys are used during cross-match. The next step is to select the spectra with high-signal-to-noise ratio and high-quality labels. For example, the effective temperatures for APOGEE are best in the range 4000 to 6000 K, thus stars observed with APOGEE with effective temperature out of this range will be deleted.

As we mentioned above, the training model is a function fitting the spectral labels at each pixel of the spectrum. However, flux at each pixel is affected by photon noise, poor sky subtraction, instrument response, and the intrinsic color of the star. The blue stars will have more blue flux and the detector can be more sensitive at certain wavelengths. Thus, for the training model, it is necessary to set the input spectra with uniform start and end wavelength and remove instrument response to derive reliable stellar parameters. I use the 3900–9000 Å segment to avoid the low instrument efficiency near the edges of wavelength. Then, the training set has satisfied all the requirements for the training step.

3.2 Training Step

In the training step, the Cannon Method uses the spectra and corresponding trustworthy stellar parameters fit for the spectral model coefficients at each pixel of
the spectrum independently. During the label transfer from APOGEE to LAMOST, the APOGEE labels are considered as the trustworthy parameters because they have higher spectral resolution ($R \approx 22,500$) and higher signal-to-noise ratio (S/N) than those of LAMOST, which means they have higher accuracy. For LAMOST, a low resolution survey, many labels’ accuracies need to be improved, especially for $Log_g$. The $T_{eff}$, $Log_g$, [Fe/H], and [$\alpha$/Fe] columns in APOGEE DR17 are used in this step. While keeping the labels for the training set fixed, the spectral model coefficients are fit at each wavelength pixel. The resulting spectral model describes the flux at each wavelength pixel as a function of the given label, and the label coefficient value describes the effect of the corresponding label at a given wavelength pixel.

Figure 3.2 shows the leading (linear) coefficient for each label as a function of wavelength, as well as the scatter as a function of wavelength. The magnitude of the leading coefficient can be thought of as the sensitivity of a particular pixel to that particular label. Thus, Figure 3.2 visualizes which regions of the spectrum are...
Figure 3.2: Leading (linear) coefficients and scatter from the training model which contains 8505 spectra

important for which labels. The effective temperature is low at the pixel with high peak. Otherwise, the pixel with deeper depth, for the effective temperature, means the higher $T_{\text{eff}}$ is has. By looking through the magnitude of the [Fe/H], we can know all the pixels are sensitive to the metallicity. It is because metallicity represents the abundance of elements in an object that are heavier than hydrogen and helium. At 5890 Å, we can find $T_{\text{eff}}$, $\log g$, and [Fe/H] all have strong sensitivity which corresponds to the Na I strong spectral line. And [$\alpha$/Fe] has no sensitivity at this position, which consistent with sodium feature.
3.3 Inferring Step / Testing Step

In the inferring step, the Cannon method solves for the new labels for the inferring set based on their normalized spectra and the spectral model coefficients we get at the training step. For the inferring step, the large uncertainties of flux calibration and unknown extinction values for some survey targets may affect the inferring result a large amount. It is therefore important to do the normalization for the spectra in the inferring set, as we do for the training set, to get new reliable labels. In order to test the reliability of training model, a testing step is usually added before the inferring step. The testing step is to apply the training model to infer new labels for the training set or a subset of stars with known labels that were not used for training. At the end of this process, each spectrum in the training set has a new set of labels determined by The Cannon. By comparing the stellar labels in the training set versus corresponding values estimated by the Cannon, scatter and bias for each label are calculated. If the scatter and bias values are in our expected range, like the bias for $T_{\text{eff}}$ is smaller than 20 K and other parameters are less than 0.02. Then, I use the same way to get the new labels for the inferring set.
Chapter 4: Method

This is the chapter that describes how to use the methods in the thesis.

4.1 Label Transfer From APOGEE to LAMOST

I first find 181,473 stars by using the crossmatch function in the application Topcat (Taylor, 2020). The RA and DEC columns in APOGEE DR17 and LAMOST DR6 are used during crossmatch. And we set the max error equals to 0.05 second of arc for the crossmatch. The next step is to select spectra with the following criteria:

1. the signal-to-noise ratio of the APOGEE spectra: $SNR_{APOGEE} > 100$

2. the signal-to-noise ratio in G band of the LAMOST spectra: $SNR_g > 80$

3. the ASPCAP stellar label flag: $ASPCAPFLAG = 0$

4. the ASPCAP effective temperature $4000 < T_{eff,APOGEE} < 6000$

5. the ASPCAP surface gravity $0 < Log_{g,APOGEE} < 5$

6. the ASPCAP overall metallicity $-4 < [M/H] < 2$

7. the ASPCAP carbon abundance $-0.4 < [C/Fe] < 1$

8. the ASPCAP nitrogen abundance $-0.5 < [N/Fe] < 1$
9. the ASPCAP star warn, star_bad metallicity warn, and alpha warn:
   
   np.bitwise_and(ASPCAPFLAG, 2**3, 2**4, 2**7 2**23) != 0

10. the star class of the LAMOST spectra: class = ”STAR”

11. the star subclass of LAMOST spectra: subclass = ”F”, ”G”, and ”K”

With the criteria above, there are 8,505 stars left to be chosen in our training set. Figure 4.1 shows the distribution of the remaining 8505 stars are used to train the spectral model.

For the label transfer from APOGEE to LAMOST, I mainly investigate how the number and distribution of labeled stars affects the reliability of the transfer. Thus, I randomly choose 1000, 2000, and 4000 spectra from the training set and called them as training set N = 1000, N = 2000, and N = 4000. Then, these training sets are trained as model M = 1000, M = 2000, and M = 4000. These models are evaluated on the test set containing 1000 stars which are also from the training set and not used in training. Figure 4.2 shows the SNR comparison between the training set N = 1000, N = 2000, and N = 4000 and the testing set. As the size of the training set increases, the training set consists of higher SNR spectra than the test set.

Through comparing the $T_{eff}$, $log_g$, [Fe/H], and [$\alpha$/Fe] that are predicted by these models with their original APOGEE values, bias and scatter are calculated. Bias and scatter are two main ways to do the evaluation. “Bias” represents mean value of residuals and “scatter” represents standard deviation of residuals. I expect the larger number of stars in the training set will have the high accuracy to infer new labels for target stars.
Figure 4.1: The Kiel diagram for all stars in the training set before data cleaning (left panel) and the training set after data cleaning (right panel).

Figure 4.2: The SNR comparison between the training set $N = 1000$, $N = 2000$, and $N = 4000$ and the testing set.
4.2 Label Transfer From APOGEE and MaStar to BOSS

The stars in the MWM survey taken with the BOSS spectrograph just have approximate parameter values, so it is necessary to use the Cannon Method to get clear parameter values for the MWM survey. The spectral resolution for the MWM survey is around 2200. Thus, APOGEE parameters are also suitable to use as the reference labels because the higher spectral resolution (R ≈ 22,500) and higher signal-to-noise ratio (S/N) they have. However, the MWM survey mostly targets O and B stars (Zari et al. 2021) with high effective temperature while the APOGEE survey only has high quality effective temperatures in the range 4000 to 6000K. Thus, the stars with APOGEE parameters can only infer the labels for the stars with approximate effective temperature less than 6000K in the BOSS survey. To infer the labels for the stars with approximate effective temperature larger than 6000 K, we use the stars that have high effective temperature from the MaStar survey, which is a stellar spectral library with a wide coverage of stellar parameters, as the training model.

By doing the crossmatch between APOGEE and BOSS, we find 2,465 stars. After deleting the spectra with null values and low-quality parameters, only 1301 stars can be used as the training set. The MaStar spectra were taken with the BOSS spectrograph. Thus, we do not need to find the stars in common between two surveys. All the star with effective temperature higher than 6000 K in MaStar can be considered as the training set.

Then, these two training set are be trained to infer labels for the BOSS stars at different effective temperature ranges.
Chapter 5: Results

This is the chapter that describes the results in this thesis.

5.1 Label Transfer From APOGEE to LAMOST

I first use the Cannon method to train the three training sets of different sizes that I get from the previous chapter and infer the labels for the same testing set which contains 1000 spectra from the cross-match between APOGEE to LAMOST.

Figure 5.1 shows the bias and scatter for every model’s parameters using the Cannon method. The smaller bias and scatter mean the model has higher accuracy. As the size of the training set increases, the accuracy for the inferring result increases at the same time for most of the parameters which is consistent with our expectation. However, the $T_{\text{eff}}$ and $\log g$ results for model $M = 2000$ which contains 2000 spectra has larger bias than the training model $M = 1000$ which contains 1000 spectra. When I do the data cleaning for the original training set, the ASPCAPFLAG value is used just to delete the spectra with metallicity warn and alpha warn information. The spectra with $T_{\text{eff}}$-warn and $\log g$-warn flags set are still included in the training set and the number of them is unknown right now. Also, every spectra is chosen randomly from the "clean" training set, and every model does not have the same spectra with
other models’. This may cause the model $M = 2000$ to contain more spectra with inaccurate $T_{\text{eff}}$ and $\log g$ information.

Then, I train a model using the whole cleaned data set, which contains 8505 spectra and apply this model to infer new labels for the clean training set to test its accuracy. Ho et al. (2017) use the same way to test their training model’s reliability when they do the label transfer from APOGEE Dr 12 to LAMOST Dr 3. I compare our training model’s testing results with Ho’s testing result. Although our training model only has 8505 spectra which is much less than theirs which contains around 11,000 spectra, our model’s testing results have smaller bias and scatter. This is because I select spectra for the training set based on more criteria and the labels in the training set have high quality.

5.2 Label Transfer From APOGEE and MaStar to BOSS

Two models are used to train the BOSS spectra at different effective temperature ranges. For the BOSS spectra with estimated effective temperature smaller than 6000 K, the spectra from the cross-match between APOGEE and BOSS are used as the training set. However, there are only 1301 stars in the training set after data cleaning which has the poor reliability during the testing step. Then, 10,000 spectra with $T_{\text{eff}}$ less than 6000 K from the MaStar survey are added into the training set. Before this training set is used to infer the labels for the target stars, I test its reliability. Figure 5.5 shows the bias and scatters between the inferred values from the Cannon Method and their original values. The bias for the $T_{\text{eff}}$, $\log g$, [Fe/H], and [$\alpha$/Fe] are -14.03, -0.02, 0.002, and -0.005, which means this model has high accuracy. Then, this
Figure 5.1: The comparison of the inferring values (y-axis) from the Cannon Method and the original values (x-axis) from APOGEE. The comparison for the training set with 1000 spectra (left panel). The comparison for the training set with 2000 spectra (middle panel). The comparison for the training set with 4000 spectra (right panel).
Figure 5.2: The testing results comparison between our training model (left panel) and Ho’s training model (right panel). The inferring values (y-axis) from the Cannon Method and the original values (x-axis) from APOGEE.
Figure 5.3: The testing results for the training model for the label transfer from APOGEE and MaStar to BOSS.

The model predicates the labels under the APOGEE scale for the 10,000 BOSS spectra with estimated effective temperature less than 6000 K.

The inferred labels for these BOSS spectra are not as good as we expected. The inferred effective temperature should be between 4000 to 6000 K because in the training set all the effective temperatures are between this range. However, from Figure 5.6, 6.4% inferred effective temperatures are found out of range.

The 24,000 stars that have high effective temperatures from the MaStar survey are used as the other training set to train the stars with $T_{\text{eff}}$ larger than 6000 K in BOSS survey. For this training set, there are some white dwarfs and low-quality
Figure 5.4: The Kiel diagram for the BOSS stars with estimate $T_{\text{eff}}$ less than 6000 K under the APOGEE scale.

parameters that may cause the training model to have poor reliability. Therefore, I cannot move yet to the inferring step.
Chapter 6: Conclusion

In this thesis, a data-drive method called The Cannon Method estimates stellar parameters from LAMOST spectra through training a model with the normalized LAMOST spectra and APOGEE labels. When I change the size of the training set, the testing step shows the larger size of the training set, the higher accuracy of the inferred labels for the other survey. For the training set with 8505 spectra, the scatter for $T_{\text{eff}}$ is 87.21 K, for $\log g$ is 0.10, for $[\text{Fe/H}]$ is 0.05, and for $[\alpha/\text{Fe}]$ is 0.03, which indicates the Cannon Method has outstanding performance to transfer stellar parameters between two different surveys on the same scale. By comparing our model with the model that is used in label transfer from APOGEE Dr 12 to LAMOST Dr 3 (Ho et al. 2017), I demonstrate that the quality of the training set’s parameters is the other factor that affects the reliability of the model. By using the large sample with highly accurate stellar parameters, more detailed researchs about the Galactic evolution can start in the future.

Stellar parameters of 10,000 F,G,K stars with estimated $T_{\text{eff}}$ less than 6000 K and spectra taken with the BOSS spectrograph, are also predicted in this thesis. Although the training set that I chose has high reliability, with the scatter for $T_{\text{eff}}$ is 105.14 K, for $\log g$ is 0.32, for $[\text{Fe/H}]$ is 0.15, and for $[\alpha/\text{Fe}]$ is 0.07. These results are not
consistent with I what expected because some of the values are out of the range of
the training set.

Future plans include finding a more trustable training set and understanding the
reasons that may cause the poor accuracy for the label transfer between APOGEE
and MaStar to BOSS.
Reference

Appendix A: LAMOST spectra with bad pixel

There are around 250 LAMOST spectra with bad pixel found when I do the normalization of the LAMOST spectra. I send them to the LAMOST team in China in order to investigate them deeply in the future. Some of these spectra are shown below: