# Potassium in the Galactic thin and thick discs

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2018-EXA138

Degree project of 15 higher education credits
June 2018

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**Abstract**

To understand the evolution of our galaxy, the chemical abundance patterns and trends within the stars of the different regions are explored. The process of synthesizing these elements reveals key details about the way the stars and, therefore, the galaxy formed.

This project focused on the element potassium, K, and specifically its absorption line 7699 Å. The local thermodynamic equilibrium (LTE) departures into non-local thermodynamic equilibrium (NLTE) must be taken into account, as potassium is highly affected. At first, synthetic spectra were applied to calculate the potassium abundances, but the NLTE effects were too strong, so equivalent width measurements were taken instead. To account for the NLTE effects, a table of NLTE corrections with corresponding stellar parameters was interpolated through with the data from 714 F and G dwarf stars in the Solar neighborhood. The tabulated NLTE corrections and stellar parameters were first analyzed to notice any outstanding trends. Then the interpolated corrections were analyzed against the same parameters. A dependence on temperature, surface gravity, and micro-turbulence was found. These corrections were then applied to the potassium abundances.

Using the corrected potassium abundances, ratios were taken between K and Fe, Mg, Ti, and iron-peak elements as well as r- and s- process elements. The [K/Fe] plot revealed an initially increasing and then decreasing trend, as the [Fe/H] increased. This showed behavior dissimilar to $\alpha$ elements. However, the [K/Mg] trends revealed a slightly increasing trend leading to a flat trend, with little scattering, indicating a potential link to the production site of $\alpha$ elements, type II SNe. In addition, [K/Mn] also had an increasing and then decreasing trend, owing most likely to the production of Mn in type Ia SNe. Furthermore, [K/Eu] revealed a flat trend, linking K again to production in type II SNe, where Eu is produced.

Amongst these [K/X] trends, a clear distinction was noticeable between trends of the thin and thick discs. The thick disc stars in the more metal poor regions of the plots were showing increasing trends of the [K/Fe] and [K/Mg] ratios, while the thin disc stars showed either flat or decreasing trends at the higher metallicity regions.

## Populärvetenskaplig beskrivning

Nyfikenhet om stjärnorna och galaxerna runt om oss har fascinerat civilisationer i tusentals år. Rörelsen, ljuset, och mönster av himlakroppar har studerats av astronomer som försker förstå universum och dess utveckling. En fascinerande aspekt av studien av ljuset som emitteras från avlägsna stjärnor är att man observerar det förflutna. Dessutom är det detta ljus och strålning som flyr stjärnorna som bär värdefull information, vilket avslöjar stjärnornas sammansättning och stjärnpopulationers utvecklingshistoria. Den data och kunskap som spektroskopi erbjuder är därför avgörande för att skapa en grundlig och djupgående förståelse av vår galax, Vintergatan, och i slutändan vårt universum.

Spektroskopi används fr att observera det ljusmönster som stjärnor sänder ut, och som avslöjar viktiga egenskaper hos stjärnan. Stjärnspektra uppvisas absorption såväl som emissionstoppar vid vissa våglängder beroende på vilka grundämnen som är närvarande i stjärnans atmosfär. Topparnas, eller dalarnas, egenskaper, såsom djup, bredd och position, beror på faktorer som temperatur, ytgravitation, och mikro- och makroturbulens. Kopplingen mellan sådana fenomen och deras effekter på det utsända spektrumen analyseras för att bestämma stjärnornas egenskaper. Exempelvis tenderar högre temperaturer att påverka spektrallinjernas bredd och vingar, och ytgravitationen påverkar den relativa styrkan hos linjer av olika jonisationsgrad. En noggrann analys av spektrallinjerna avslöjar därför kritiska egenskaper hos stjärnan.

Förutom att man observerar formen av spektrallinjer anger deras position och mönster de grundämnen som är närvarande. Spektrallinjerna fungerar som fingeravtryck, eftersom varje grundämnes linjer har specifika våglängder av ljus som den kan avge. Ymnigheten av dessa grundämnen kan hjälpa till att bestämma stjärnans ålder och dess ursprung. Istället för att bara analysera en stjärna åt gången, kan det vara mycket mer värdefullt att titta på grupper eller hopar av stjärnor eftersom de skapades samtidigt och borde ha liknande sammansättningar. På detta sätt kan en rad stjärnmassor och luminositeter undersökas. Dessutom kan man jämföra den kemiska sammansättningen och styra forskningen mot stjärnhopens, eller stjärnpopulationens, ålder och utveckling.

Att observera dessa grupper av stjärnor är särskilt användbar när man studerar vår egen galax, Vintergatan, eftersom den innehåller två definierade skivor av stjärnor, två olika stjärnpopulationer. Om Vintergatan kunde ses utifrån och från sidan så skulle man kanske kunna se en tunnare skiva av stjärnor som ligger inbäddad i en tjockare. Stjärnorna som finns inom dessa två skivor har även de olika egenskaper. Stjr̈norna i den tjocka skivan har visat vara ldre stjärnor av lägre metallicitet, vilket betyder lägre ymnigheter av grundämnen som är tyngre än väte och helium. Den tunna skivan har å andra sidan stjärnor som är yngre än de i den tjocka skivan innehåller också större mängder av de tyngre grundämnena. Medan dessa trender och egenskaper hos skivorna är någorlunda kända, är det fortfarande oklart hur de har bildats och utvecklats.

Detta projektarbete, som fokuserar på spektrallinjerna som produceras av kalium i 714 stjärnor i Vintergatans tunna och tjocka skivor, är ett grundläggande exempel på den forskning och analys som utförs i dagens Vintergatsforskning. Mängden, eller ymnigheten, av grundämnen mäts och analyseras med målet att bestämma stjärnornas kemiska sam-

mansättning och stjärnpopulationernas evolutionära väg. Studier av individuella grundämnen, med hjälp av nyare och mer exakta data och teknik, kan en klarare och mer välbestämd förståelse av vår galax.

# Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction

Studying the chemical abundances of stars in different regions of galaxies allows for an insight into the evolution and creation of the galaxy itself. The chemical abundances, alongside the timescale, position within the galaxy, and the stellar parameters, reveal patterns that can guide our understanding. These patterns become crucial when considering our own Milky Way Galaxy, and its potential origins.

The process of generating and synthesizing new elements as well as creating stars is an ongoing cycle. The elements comprising the galactic gas are the light elements of H, He, and Li, which are also the elements present in the primordial gas (Mushotzky 2015; Samland 1998). The elements heavier than these are referred to as the metals, and are generated in stars. All the elements up to Fe are able to be produced in the core of the stars when there is enough energy to overcome the threshold energy to fuse nuclei. When the galactic gas comes together to form a star, it is then able to create these new heavier elements out of its existing atoms, or through nucleosynthesis. Then, as the star ages, the enriched material is dispersed into the interstellar medium through various means. The common processes leading to the ejection of this material are mass loss and supernovae (SNe). The cycle begins again, where the gas forming the new stars has been enriched with heavier metals from the older stars. As the cycle continues, the stars generated as well as the interstellar medium become more enriched with heavier elements (Mushotzky 2015). In this way, the chemical evolution of the galaxy can be traced through the differing element abundances.

In addition to tracing the chemical evolution of the galaxy through the element abundances, the data can also reveal the influence of events such as type II and type Ia SNe. The type II core collapse SNe occur in massive stars and are one of the main generators of the $\alpha$ elements, like C, O, Ne, Mg, Si, S, Ar, and Ca. They are induced usually around $10^7$ yr after the stars have formed (Mushotzky 2015). In contrast, the type Ia SNe occur in binary systems with the presence of a carbon-oxygen white dwarf (Matteucci 2016). The explosion is caused primarily by dynamical and thermal instabilities (Prialnik 2010). These type Ia SNe do not produce the $\alpha$ elements, but they do create Fe. They tend to take place later than $10^8$ yr after the stars had formed. Applying this knowledge to the resulting element abundance ratios exposes the links between the production of elements.

In other words, it can show if the elements are synthesized during the same events or through events occurring at different times and in different spaces.

When observing most of these galaxies edge-on, a distinction can be made in terms of stellar population in a thin and thick disc. After Gilmore & Reid (1983) published a paper that began to apply this thin and thick disc distinction to the Milky Way Galaxy, research was inspired to characterize the differences of the stars present in the two discs. Exploring and elaborating on patterns concerning the metallicity, abundance, and other parameters with continuous newly acquired data enables newer and more accurate hypotheses to be developed. Such hypotheses outlining the formation of the thick disc include phenomena such as the accretion of galaxy satellites, implying extragalactic origin for the thick disc stars. Another is the heating of thin discs, occurring at a range of timescales from fast to over the lifetime of the galaxy (Minchev et al. 2012).

Exploring the origins of the Milky Way Galaxy leads to the examination of the stars within the thin and thick disc separately. In this way, finding trends linking the stars within each respective disc can direct and focus research. The thick disc holds the older and metal-poor stars, meaning the thin disc is comprised of relatively younger stars with higher metallicities. The analysis of the chemical abundances is therefore conducted in depth to fully comprehend the principal characteristics of these stellar populations.

One of the main methods of examination of these stars is through spectroscopy, which reveals a wealth of information simply from the emitted light from the stars. The resulting absorption lines create fingerprints identifying the elements present within the star. The importance of the placement of the observational instrument becomes evident when observing data collected from an Earth based instrument, as the effect of the Earth's atmosphere on the spectra can produce additional lines known as telluric lines.

This project attempts to explore the origins of the thin and thick disc through one element, potassium. This element was chosen as there is limited knowledge about its role in the galactic evolution, both theoretically and observationally (Takeda et al. 2002). Potassium is typically created through the burning of lighter elements. The main event producing potassium from a lighter element is the burning of oxygen in type II supernovae (Shimansky et al. 2003). Furthermore, it is a low ionization energy element (Zhang et al. 2006a) that is known to be collision dominated (Zhao et al. 2016). Even though potassium is collision dominated, the assumption of local thermodynamic equilibrium (LTE) can not be applied as it would produce inaccurate potassium abundance values (Shimansky et al. 2003). The cause of the LTE departures into non-LTE (NLTE) environments is the sensitivity of potassium to over-recombination (Shimansky et al. 2003; Zhao et al. 2016). Therefore, it is the ionization balance of the potassium energy levels that contributes to the deviations from LTE, compelling the method of analysis to cater towards the resulting effects on the spectra from the stars.

After exploring the possible potassium lines available for analysis, the 7699 Å line was chosen. A database of the spectra of 714 F and G dwarf stars was investigated, with a focus on the 7699 Å line. Taking into consideration the need to account for the NLTE effects, the equivalent width method was chosen as a means of analysis. Since the abundances were found under the LTE assumption, a table of stellar atmosphere parameters from Takeda

et al. (2002) with NLTE corrections were applied. These corrections then allowed for the more accurate potassium abundances to be compared to the parameters of the stars in the thin and thick disc.

# Chapter 2

# Method

## 2.1 Stellar sample

The stellar sample analyzed in this project was collected from Bensby et al. (2014). The data includes a total of 714 solar neighborhood F and G dwarf stars and subgiant stars. The elements observed included O, Na, Mg, Al, Si, Ca, Ti, Cr, Fe, Ni, Zn, Y, and Ba. The spectra were recorded with the following instruments: MIKE, FEROS, HARPS, UVES, SOFIN, and FIES. The typical signal-to-noise ratio of the spectra is as high as 200. This sample selection was chosen by the kinematics of the stars, such that they had Gaussian velocity distributions and that they inhabit a certain portion of the of the Solar neighborhood. These properties were chosen to be in between thin and thick disc stars. In addition, they were chosen to trace the metal-poor limit of the thin disc, the metal-rich limit of the thick disc and the metal-poor limit of the thick disc (Bensby et al. 2014).

The stellar parameters, chemical abundance ratios, ages, and kinematics of all 714 stars were gathered from table C.3 in Bensby et al. (2014). Furthermore, this table contained the corresponding calculated uncertainties for parameters such as [Fe/H], logg, microturbulence, as well as for the chemical abundance ratios. The data concerning the odd-Z iron peak elements was collected from Battistini & Bensby (2015), including the line synthesis of the Sc, V, Mn, and Co lines. The data for the r- and s- process elements was retrieved from Battistini & Bensby (2016), which also contained line synthesis data but for the elements of Sr, Zr, La, Ce, Nd, Sm, and Eu.

From the stellar spectra of the 714 stars, the potassium lines are added to the data and used to uncover additional details about the evolution of the thin and thick disc.

## 2.2 Analysis

### 2.2.1 Abundance measurement

To measure the abundance of an element from the stellar spectra, there are two main methods used. The first is the line synthesis method, where synthetic spectra are fitted to

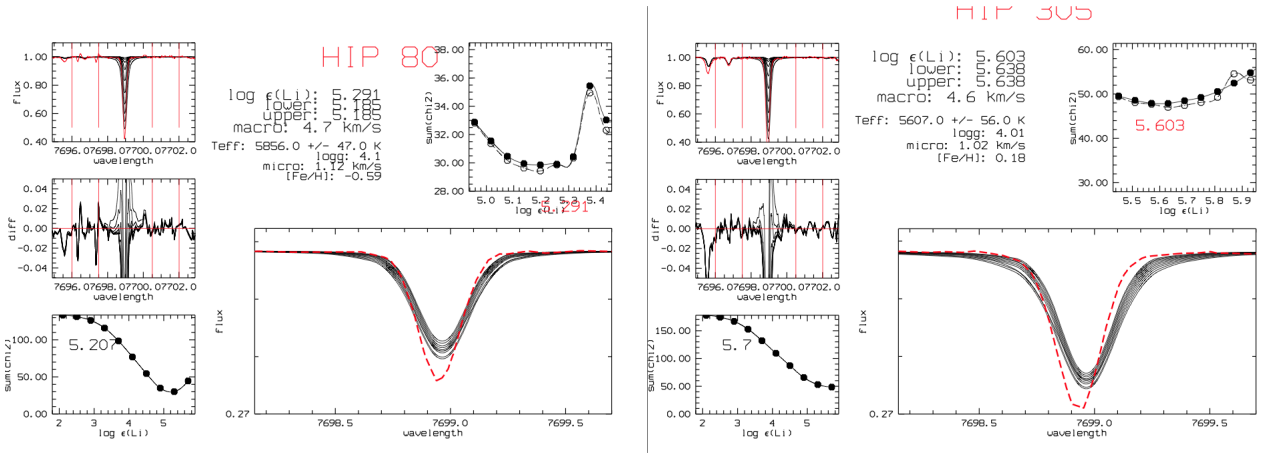
the data to measure the abundance. The second method is the equivalent width method, where the absorption lines are fit with a Gaussian or Voigt distribution to extract the equivalent width of the line. For both of these methods, detailed information is required on the behavior of the atoms of the element of interest. Vienna atomic line database (VALD) information is gathered and applied to the program calculating the abundances. The VALD data reveals the oscillator strength of the atomic energy transitions, or the log gf values, which reflects the probability of an excitation or de-excitation and affects the strength of a line. In addition, the VALD data records the damping parameters of the absorption lines. These damping parameters affect the width of the produced lines and include the Van der Waals and Stark collisional broadening. In addition, to calculate the abundances, model stellar atmospheres are needed, which in this case are the same as those presented in Bensby et al. (2014).

### 2.2.2 Potassium lines

To begin the analysis of the stellar spectra, a strong identifying absorption line for potassium was chosen, at 7699 Å. Other potassium lines exist at 6938 Å and 5802 Å (Zhang et al. 2006a), however these were not strong enough to evaluate clearly. In addition, another potassium line appears at 7664 Å but is typically too blended with $O_2$ telluric lines to measure (Zhao et al. 2016; Takeda et al. 2002). An important consideration in the analysis of the absorption lines is the presence of hyperfine splitting, but for this 7699 Å K I line it can be neglected (Zhang et al. 2006a). Before measurements were taken, atomic information and details were gathered to accommodate the properties of potassium. This included querying valuable information about the atomic parameters of potassium from VALD, (Kurucz 2004, 2007, 2008, 2010, 2012, 2013, 2014; Barklem & Aspelund-Johansson 2005; Barklem et al. 2000; O'Brian et al. 1991; Fuhr et al. 1988; Ralchenko et al. 2010; Raassen & Uylings 1998). The requested information outlined the elements corresponding to characteristic peak wavelengths in the range of wavelengths indicated, as well as damping parameter values and astrophysical gf values.

### 2.2.3 Line synthesis

The first method of analysis chosen was the line synthesis. The synthetic spectra method generates spectra to fit the collected data, however, it does not take into consideration the effects of NLTE and even as the code was manipulated to try to fit the spectrum data, the synthetic spectra did not match the data, as shown in figures 2.1(a) and 2.1(b). As parameters, such as abundance, of the program were altered to attempt to fit the data, the synthetic line profiles only grew wider and wider and were not able to reach the depth of the absorption line. These results revealed the extent of the severe effects of the NLTE on the potassium line, and directed the analysis to a different form of measurement, equivalent widths. The NLTE effects on the potassium line were confirmed when Takeda et al. (2002) was consulted.




(a) (b)

Figure 2.1: Synthetic spectra for HIP80 and HIP305 showing the line profile widening and not deepening. Even though it says Li, these measurements were done with K, the program was previously used for Li.

### 2.2.4 NLTE

After realizing the influence of the NLTE and LTE assumptions on the K line at 7699 Å, the basis of these concepts were explored. Takeda et al. (2002) also show the effects of NLTE on this K line. In the modeling of stellar photospheres, the LTE and NLTE assumptions and approximations made are crucial in understanding and analyzing the spectral data from the stars. A useful concept is the black-body, where the emitted and absorbed radiation develop an equilibrium. This black-body is in thermodynamic equilibrium as long as the temperature remains constant. Relating this concept to the photosphere of a star, observing the lowest depths reveals that little radiation is able to escape the photosphere. This behavior is due to the photons being re-absorbed close to where they were emitted. The main parameter causing this effect is a large optical depth, $\tau_\nu$, which is known as optically thick,

$$\tau_\nu = \int \alpha_\nu ds, \tag{2.1}$$

where $\alpha_\nu$ represents the extinction-coefficient parameter of the star. From the relation (2.1) it is clear that if $\tau_\nu$ is large, that $\alpha_\nu$ is also large, signifying a large extinction, or re-absorption of radiation. In this deep area of the photosphere, the LTE assumptions can therefore be applied to maintain the benefits of this equilibrium, as the medium is given by the local temperature. Such assumptions include allowing the distribution of the particle velocities to be Maxwellian, and using the Saha-Boltzman distribution for the excitation and ionization states (Kubát 2014). Furthermore, to remain in an LTE approximation, the main process dominating the excitations must be collision based. The ionization equation for such a process is given by the following (Gray 2005),

$$\frac{N_1}{N_0}P_e = \frac{(2\pi m_e)^{3/2}(kT)^{5/2}}{h^3}\frac{2u_1(T)}{u_0(T)}e^{-I/kT}, \tag{2.2}$$

where $\frac{N_1}{N_0}$ represents the ratio of ionized to neutral atoms and $\frac{u_1}{u_0}$ represents the ionized to neutral partition functions. As can be seen, this expression is dependent on the temperature.

In addition, the source function while within LTE can be approximated by a Planck function, $S_\nu = B(T)$. The Planck function applied here is used to solve the transport equation for the star's atmosphere where these LTE approximations are valid.

As the depth into the photosphere decreases, the photons are less likely to be reabsorbed near where they were emitted, and the concept of local thermodynamic equilibrium is no longer valid. Here, in the higher layers, an NLTE application must be implemented. In these regions, the excitations are no longer collision based, but are radiation dominated, which clearly emphasizes the non-local property. Whereas previously the source function could be approximated to a Planck function, in NLTE regions the exact source function must be used, with exact emissivity and extinction coefficients (Kubát 2014). However, the Maxwell distribution for the particle velocities remains valid. Therefore, in NLTE, instead of focusing on thermodynamic equilibrium, the attention shifts to kinetic equilibrium, where the radiative transport equation is solved using the exact source function.

In this case with potassium, even though it is collision based, implying LTE, the ionization balance of its energy levels render the Saha-Boltzman distribution inaccurate. While potassium does not immediately direct analysis to focus on NLTE since it is not radiation dominated, it still demands the departures from LTE to be applied, requiring NLTE corrections. Therefore, the analysis method was revised to take this into consideration.

### 2.2.5 Equivalent widths

The second commonly used method in spectral analysis is Equivalent Width (EW) measurement. To do so, a Voigt fit was placed over the desired absorption line in the spectra and the EW value was extracted into a table to later use to calculate the potassium abundance, initially under LTE assumptions. The Voigt fit was used because it is the convolution of the Lorentzian and Gaussian distributions, where the wings of the Lorentzian and the body of the Gaussian are applied. The SPLOT function in IRAF was used to measure these EWs. Each potassium line EW around 7699 Å was manually measured applying the Voigt fit, which allowed for a detailed scan of the data to ensure it useful. This revealed around 80 of the 714 sets of data were not useful due to line blending. The principal origin of the line blending was the presence of telluric lines. The characteristic that affected these 80 stars, causing the potassium line to blend with the telluric lines was their radial velocity, which shifts the absorption lines.

Since many observations of stellar spectra are made from Earth, the effect of the Earth's atmosphere on the data must be taken into account. A common phenomenon appearing on

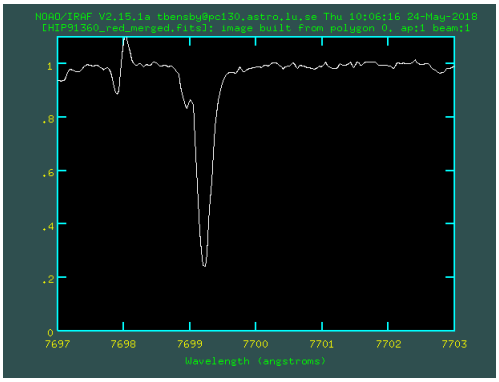



Figure 2.2: The potassium line blended with a telluric pair as seen by the merged line.

the observed spectra are telluric lines. These lines are created as a result of the interaction between the incoming light and the molecules comprising the atmosphere. The temperature at which these molecules remain is of the order 275 K (Adelman et al. 1996), which allows their atoms to absorb incident radiation and cause the telluric lines. These molecules include $O_2$, $N_2$, and Ar. The telluric lines appearing as result of the interaction tend to affect the red and infrared section of the spectra, which is exactly the location of the chosen potassium line (Adelman et al. 1996). Furthermore, an identifiable characteristic is the occurrence of pairs of telluric lines. An example of blending with telluric lines cam be seen in figure 2.2. The effect of the blended telluric lines was a deeper absorption line and as well as a shift of position. At the risk of skewing the data, these heavily and obviously blended lines were omitted from the analysis.

### 2.2.6 NLTE corrections

After calculating the potassium abundances for the valid datasets, the next step was applying the NLTE corrections. Since the corrections depended on effective temperature, surface gravity, metallicity, and micro-turbulence, a table of stellar atmosphere parameters was used to interpolate through with the actual stellar parameters and determine the corresponding exact NLTE correction to be applied. The table of these stellar atmospheres parameters and NLTE correction was found from Takeda et al. (2002). The tables are a set of three files, each file pertaining to values for a micro-turbulence of either 1.0 km/s, 2.0 km/s, or 3.0 km/s. Three sample LTE potassium abundances are used for each set of temperature, metallicity, and surface gravity values. The effective temperature ranges from 4500 K to 6500 K, the surface gravity ranges from 0.0 to 5.0, and the metallicity ranges from 0 to -3. To get a sense of the dependency of the corrections on the stated stellar parameters, a series of plots were made reflecting the relationships between the corrections and the stellar parameters. The first set of plots, figures 2.3(a) to 2.3(e), reflect the trends between the NLTE corrections and the temperature.

Observing these plots reveals the sensitivity of the corrections to temperature in the lower ranges of the surface gravity. With a surface gravity of 1.0 and [Fe/H]=0, the

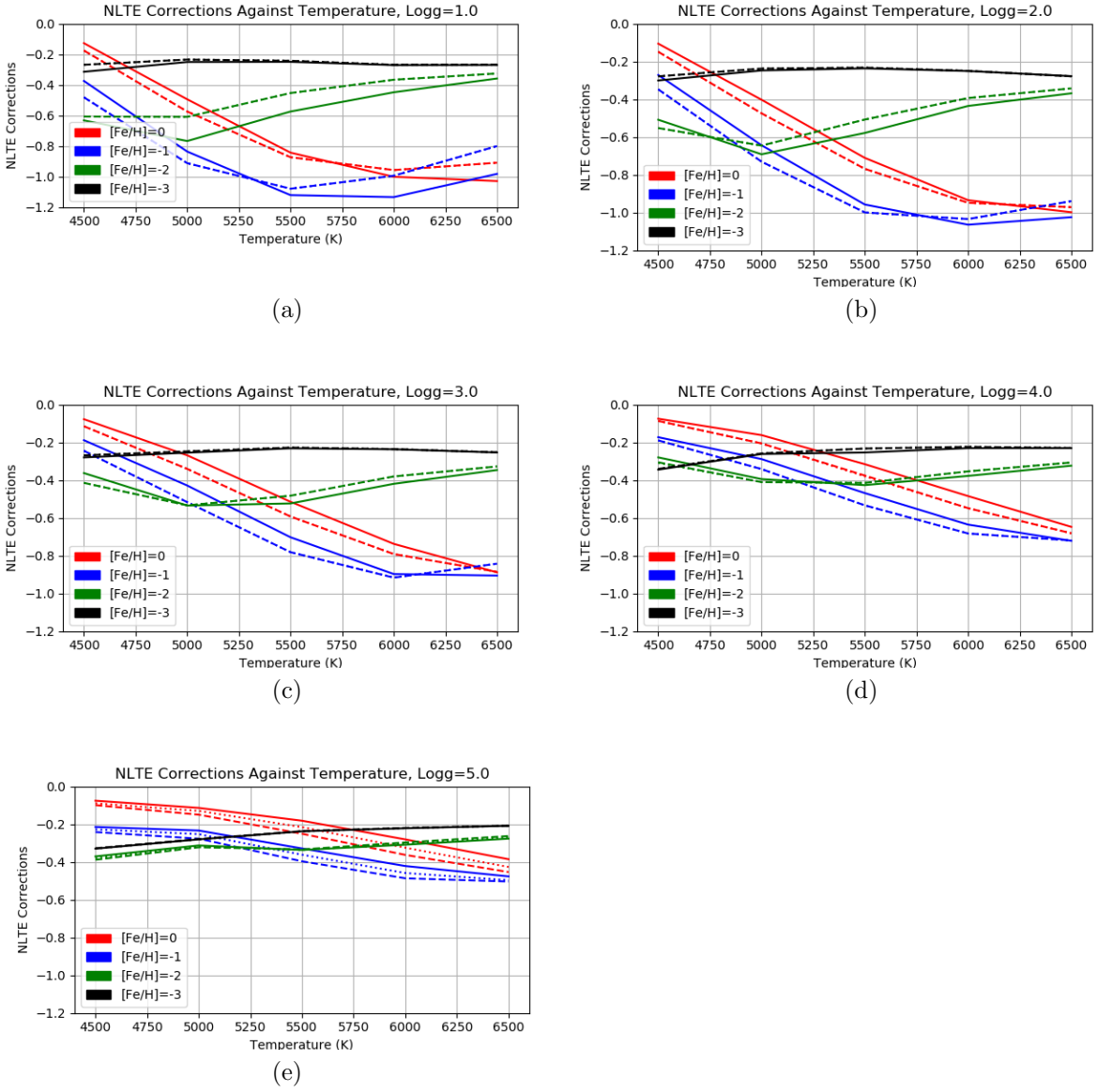



Figure 2.3: Stellar parameter table NLTE corrections plotted against $T_{eff}$(K), the solid lines correspond to a micro-turbulence of 1.0 km/s, the dotted lines to 2.0 km/s and the dashed lines to 3.0 km/s (Takeda et al. 2002).

corrections span values from -0.1 to -1.0. Comparing the same metallicity with a surface gravity of 5.0, the corrections only span values from -0.05 to -0.4. Furthermore, another trend is evident regarding the corrections pertaining to the different metallicities. For each surface gravity value, the [Fe/H] = 0, -1 tend to decrease, while the [Fe/H] = -2, -3 tend to increase or remain constant.

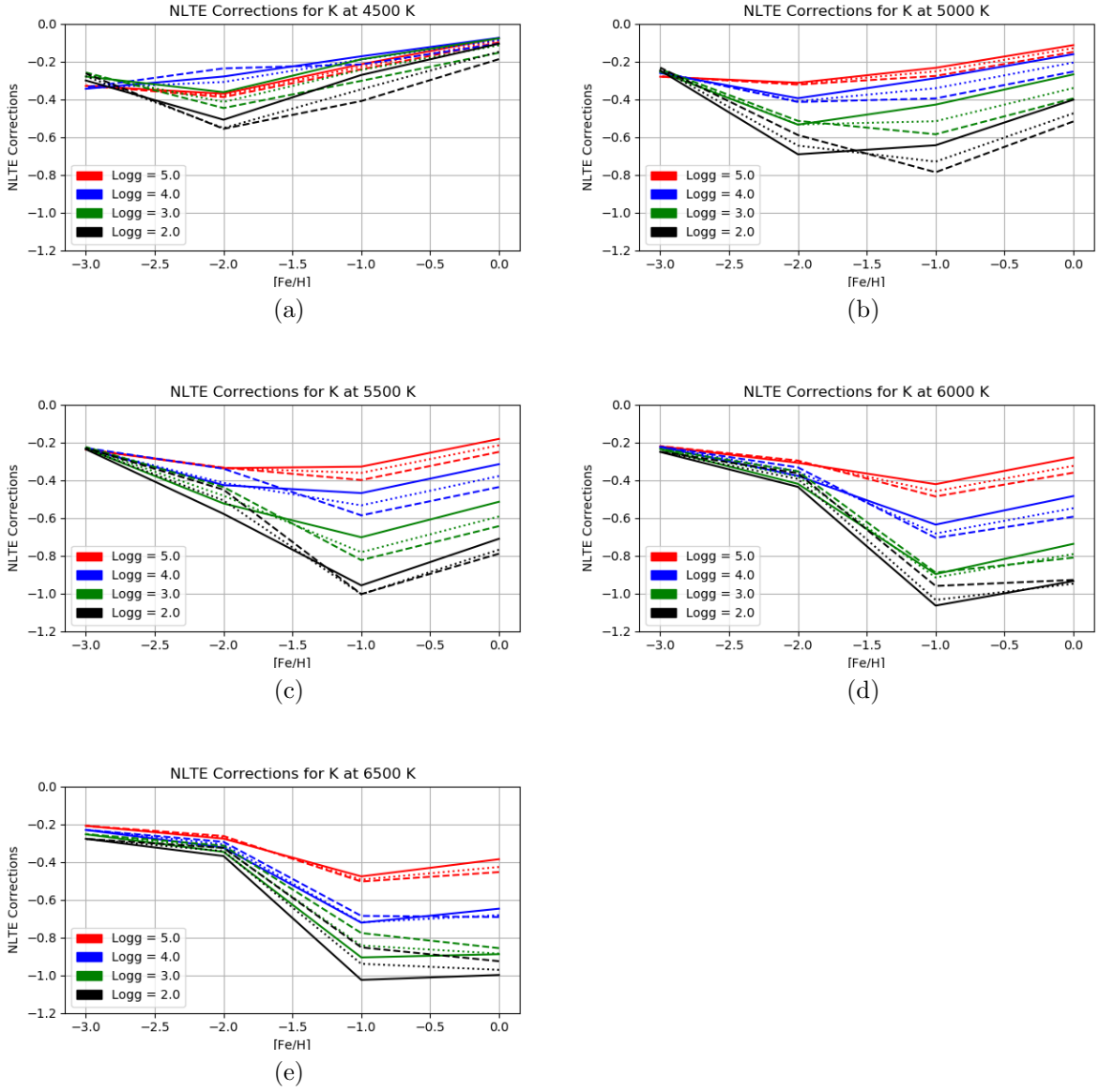



Figure 2.4: Stellar parameter table NLTE corrections plotted against [Fe/H], where the solid line represents a micro-turbulence of 1.0 km/s, the dotted line a micro-turbulence of 2.0 km/s, and the dashed line a micro-turbulence of 3.0 km/s (Takeda et al. 2002).

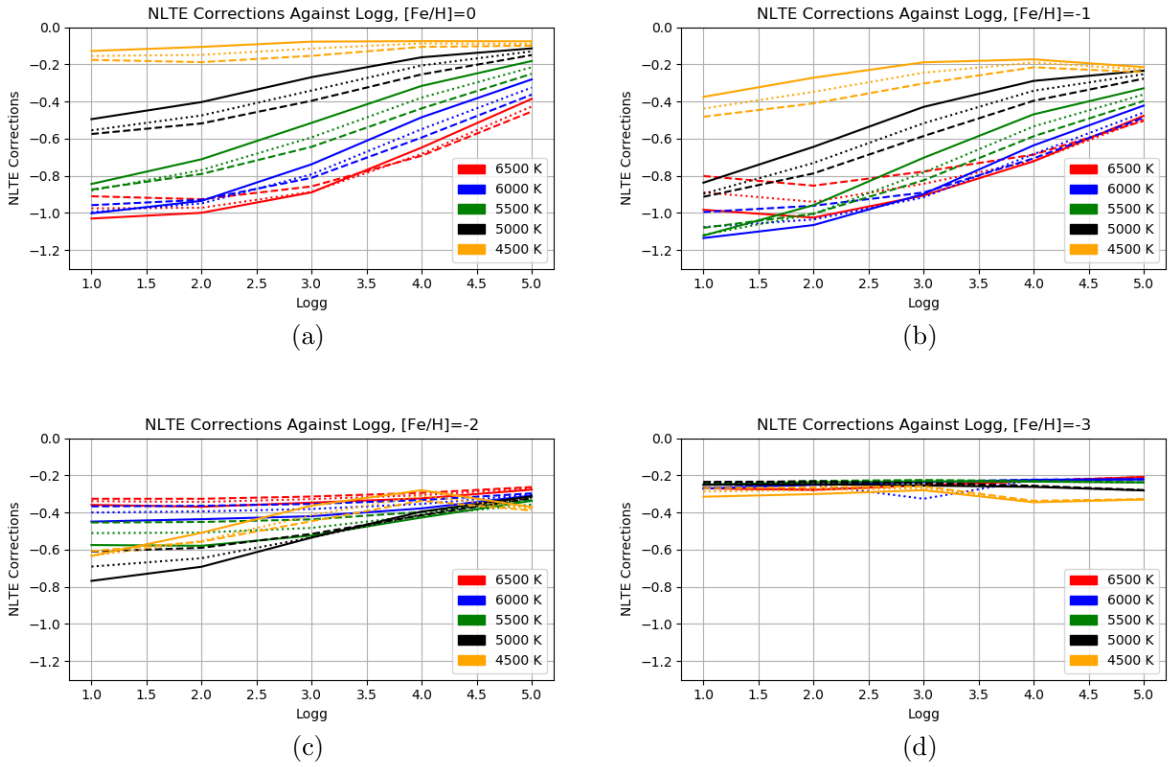



Figure 2.5: Stellar parameter table NLTE corrections plotted against log(g) for a given metallicity, where the solid line represents a micro-turbulence of 1.0 km/s, the dotted line a micro-turbulence of 2.0 km/s, and the dashed line a micro-turbulence of 3.0 km/s Takeda et al. (2002).

Figures 2.4(a) through 2.4(e) present the relationships between the corrections and the metallicity for a given temperature. Each graph distinguishes between the varying surface gravity values. As can be seen, as the temperature increases, the corrections span a larger range of values. In addition, as the metallicity increases, the corrections first seem to decrease slightly before increasing.

Figures 2.5(a) through to 2.5(e) reflect the relationship between the NLTE corrections and the surface gravity of the stars for the given metallicity values. As can be seen, at [Fe/H] = 0 and -1, the NLTE corrections for temperatures larger than 4500 K vary a lot with increasing surface gravity. At [Fe/H] = -2 and -3, the corrections span a smaller range with increasing surface gravity.

These tables were then used to calculated the exact NLTE correction corresponding to each star. First, the form of the measured potassium abundances were converted from relative to the sun to absolute abundances by adding the non-corrected value of the Sun's abundance. Then the measured LTE abundances were interpolated through the tables to reach one correction value for each set of temperature, metallicity, and surface gravity val-

ues. The surface gravity values from table C.3 Bensby et al. (2014) were then interpolated through the Takeda et al. (2002) tables to reach one set of corrections for each temperature and metallicity. This procedure was repeated until only one correction value remained to interpolate between the three micro-turbulence files. This correction value was stored and applied to the original measured LTE potassium abundances. After these final corrected absolute abundance values were determined, the corrected Sun's abundance was subtracted to convert back to the relative form.

After calculating and applying the corrections to the potassium abundances, the analysis seeking trends and exploring the relationships between these abundances and several parameters was conducted. Initially, the [K/Fe] and [Fe/H] trends were observed before and after the corrections were applied. Then a distinction was made between the thin and thick disc stars to notice any differentiating patterns. Furthermore, potassium's relation to other elements was investigated, by plotting [K/X] by [Fe/H]. The elements included $\alpha$, odd-Z iron peak, and r- and s- process elements.

### 2.2.7 Uncertainties

The errors applied to the [K/Fe], [K/Mg], and [Fe/H] values were calculated using the four observables associated with the main stellar parameters of temperature, micro-turbulence, surface gravity, and metallicity. Each observable has a corresponding error, which is taken as the uncertainty of the linear regression of the associated observable plot (Bensby et al. 2014; Epstein et al. 2010).

From the method of analysis conducted in this project, there are several steps that could have contributed to potential errors. These include the measurements of the EWs as the placement of the Voigt fit and continuum were done by hand, the placements could have shifted with each absorption line. This influences the subsequent abundance calculations. Furthermore, since the severity of the blended lines was measured by eye, some retained data may have telluric blending that was not obvious. This may have affected the abundance values. In addition, during the interpolation calculations of the NLTE corrections, the relationship within the respective parameters was assumed to be linear, which could have skewed the final correction values if the relationship were actually of some other form.

# Chapter 3

# Results

## 3.1 Potassium NLTE corrections

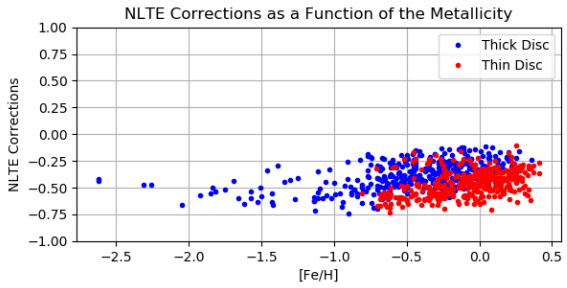
After investigating the trends present in the tables of the NLTE corrections and stellar parameters, they were used to determine the corresponding NLTE potassium corrections for the previously measured LTE abundances. To do so, the models were interpolated through using a Python script. The parameters guiding the interpolation were the effective temperature, the surface gravity, the metallicity, and the micro-turbulence values of the stars, found in table C.3 of Bensby et al. (2014). The resulting NLTE correction values for each star can be found recorded in table A.1, alongside the corrected abundances. The mean value of the corrections was -0.44.

Observing figures 3.1(a) to 3.1(e) reveals the trends between the calculated corrections and the parameters of the corresponding stars. Figure 3.1(a) represents the dependence of the corrections on the metallicity, which shows a constant trend, meaning little dependence. Figure 3.1(b) shows the relation between the corrections and the temperature, reflecting a clear decrease (or larger NLTE effect) as the effective temperature increases.

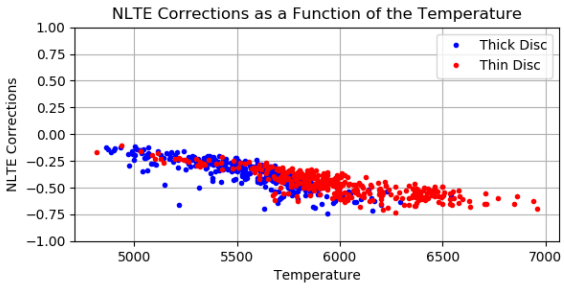
Figure 3.1(e) presents the relation between the corrections and the surface gravity. The corrections seem to decrease slightly between logg = 3.50 and 4.25 and then increase slightly between logg= 4.25 and 4.50. These three trends agree with Zhang et al. (2006b) who states the same patterns. Figure 3.1(c) presents the dependence of the NLTE corrections on the LTE absolute potassium abundances. No clear trend is noticeable here, the thick disc stars tend to correspond to the lower K abundance values. Figure 3.1(d) reveals the relationship between the corrections and the micro-turbulence and shows an immediate decrease in the correction values with an increase of the micro-turbulence.

The Sun's uncorrected potassium abundance was 5.41, which was added to the LTE abundance values in the beginning of the analysis. To find the Sun's correction value, the same interpolation procedure was used, producing a correction of -0.33.

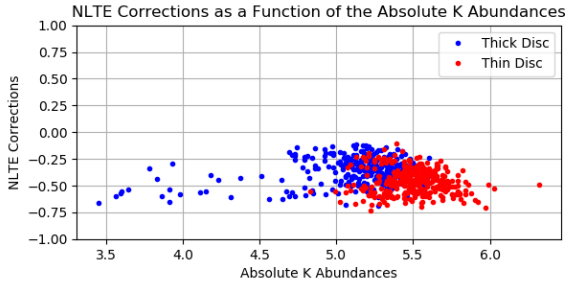
To get an overview of the data, two plots were made comparing the [K/Fe] with [Fe/H] before and after the NLTE corrections were made, shown by figures 3.2(a) and 3.2(b), respectively. Keeping in mind that the Sun's correction was -0.33 and the mean correction



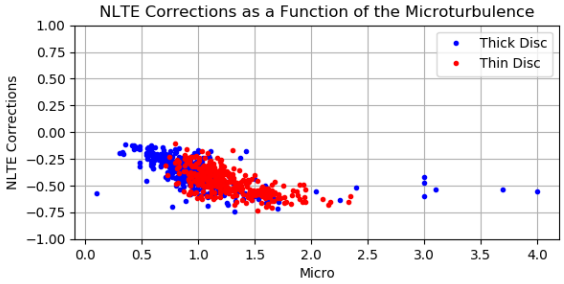

(a)



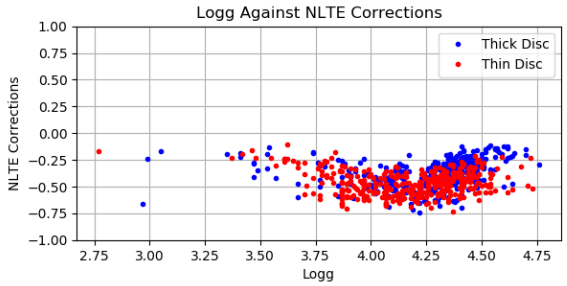

(b)




(c)

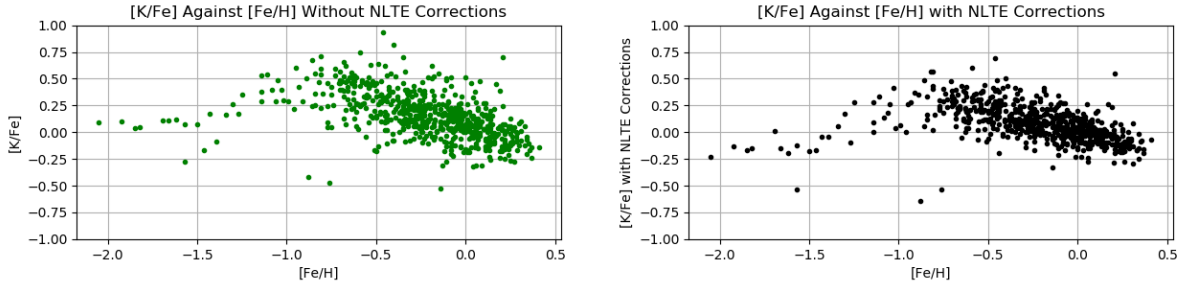



(d)




(e)

Figure 3.1: Calculated NLTE corrections plotted against the stellar parameters




(a) (b)

Figure 3.2: Potassium abundances without and with NLTE corrections plotted against [Fe/H]

value was -0.44, it makes sense that the data points shift down slightly when the corrections are applied. Overall the trend remains similar, with an initial increase in the [K/Fe] with [Fe/H], and then a decrease starting around [Fe/H] = -0.75, which seems to match most closely to the model shown in Timmes et al. (1995) as they represent an initial increase as well. Moreover, after applying the NLTE corrections, there was less scatter in the data points, indicating better results after applying the corrections.

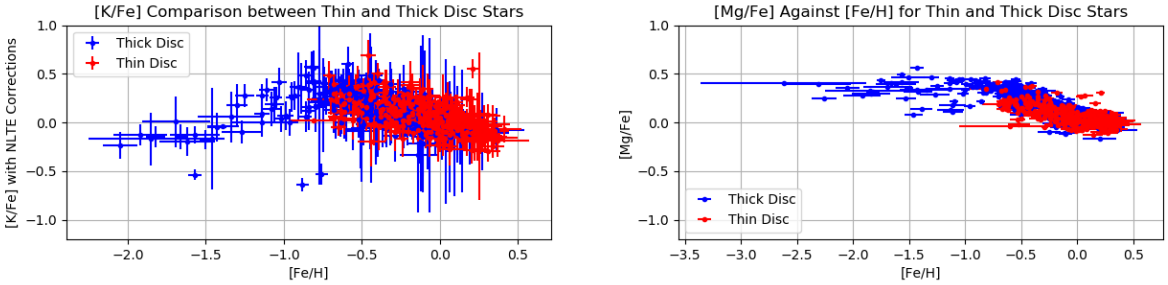
## 3.2 K trends in the thin and thick discs

Once the potassium abundances were corrected for the NLTE effects, they were used to compare to other elements present in the stars, as well as to investigate the differences between the thin and thick disc.

The next step was to look closer into the differences between the thin and thick disc. To distinguish between the thin and thick disc stars, the limiting age for the thin disc stars was set to be 8 Gyr, which left the thick disc stars to be those older than 8 Gyr. It is possible to identify the thin and thick disc stars through their stellar orbit radius variations as well as their kinematic properties, however their ages are a clearer distinguisher (Bensby et al. 2014).

The resulting plot is shown in figure 3.3(a). As shown, it is dominantly the thick disc stars in the metal-poor region, reflecting an increasing trend. It is interesting to compare K to an $\alpha$ element such as Mg. The [Mg/Fe] against [Fe/H] trend is shown figure 3.3(b). Here, the metal poor, thick disc stars maintain a relatively constant ratio between Mg and Fe, which is consistent with the production of Mg and Fe from type II supernovae. The decreasing trend in the in the more metal-rich region is also consistent with the ratio of production of Mg and Fe from type Ia supernovae, since Mg is not produced in type Ia SNe. Therefore, the differing trends of the metal-poor regions for these two elements prompts a further investigation.

Zhang et al. (2006b) agrees with the decreasing [K/Fe] trend from [Fe/H]= -1.0 to 0.2.



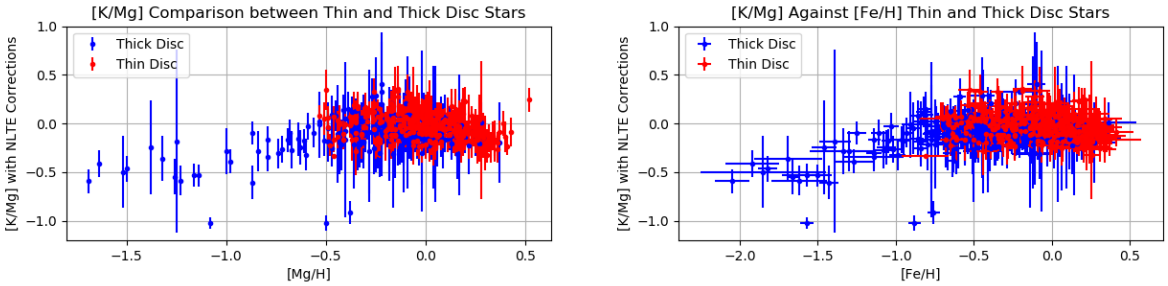

(a) (b)

Figure 3.3: (a) NLTE corrected potassium abundance plotted against [Fe/H] with a distinction of the thin and the thick discs, (b) [Mg/Fe] plotted against [Fe/H]

Meanwhile, Cayrel et al. (2004) found that the [K/Fe] decreases slowly with a decreasing [Fe/H] for metal-poor stars with [Fe/H] $<$ -2.5. This trend would then agree with the presented data here where the [K/Fe] tends to decrease for metal-poor stars as the metallicity decreases. In addition, Timmes et al. (1995) predicted decreasing [K/Fe] with decreasing [Fe/H], while Samland (1998) predicted [K/Fe] to remain constant from [Fe/H] = -1.0 to -3.0. Therefore, the contradicting predictions and findings indicate the need for the analysis of more data.

Furthermore, the different abundance ratios of [K/Fe] for the thin and thick disc stars indicates support to the idea that the discs were created in different spaces and times.

To investigate more into the production of potassium in the thin and thick discs, K was compared to Mg through plots of [K/Mg] vs. [Mg/H] and [Fe/H], shown in figures 3.4(a) and 3.4(b) respectively.

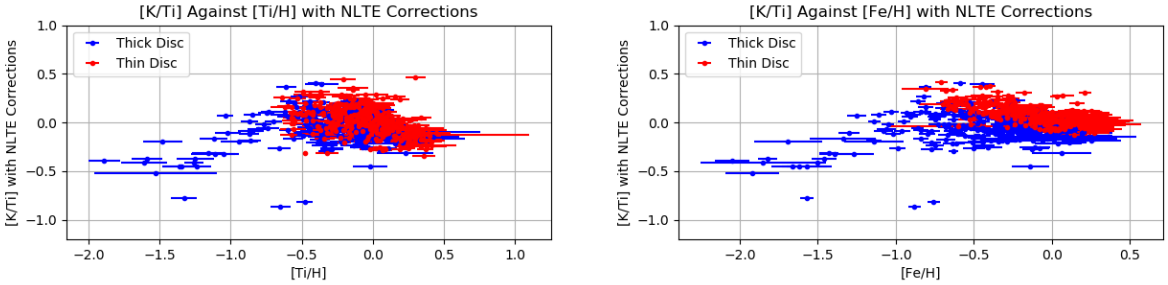



(a) (b)

Figure 3.4: (a) [K/Mg] plotted against [Mg/H], (b) [K/Mg] plotted against [Fe/H]

Since the [K/Mg] ratio values do not span a wide range of values, for either [Mg/H] or [Fe/H], the production of potassium can be said to be connected to the production of $\alpha$ elements Zhang et al. (2006b).

Then K was compared to another $\alpha$ element, Ti. The plots are shown in figures 3.5(a), where [K/Ti] is plotted against [Ti/H], and 3.5(b), where [K/Ti] is plotted against [Fe/H]. The trends are similar to those of [K/Mg], where there seems to be a slight increase in [K/Ti] before a flat trend. Again, this points to a connection to the production of $\alpha$ elements.




(a) (b)

Figure 3.5: (a) [K/Ti] plotted against [Ti/H], (b) [K/Ti] plotted against [Fe/H]

### Potassium comparison to odd-Z iron peak elements Sc, V, Mn, and Co

The potassium abundances were also compared to odd-Z iron peak elements to explore the links in their production. The data analyzed was collected from Battistini & Bensby (2015) and corresponded to 662 stars, so the identifying HIP numbers were matched to the measured potassium data stars. The resulting plots are shown in figures 3.6(a) to 3.6(d).

The synthesis of Sc is said to originate from neon and carbon burning (Woosley & Weaver 1995), while V, Mn, and Co are said to be created in type II SNe through silicon burning (Woosley & Weaver 1995) as well as through type Ia SNe (Battistini & Bensby 2015).

Elements Sc, V, and Co reveal a flat relation with K, while the [K/Mn] trend seems to increase and then decrease as [Fe/H] increases. This is a similar trend to the [K/Fe] plot, which agrees with the idea that Mn and Fe are created in the same places (Battistini & Bensby 2015). Therefore, it seems as though for lower metallicities, the productions of K dominates over Mn, perhaps through the type II SNe, and as the type Ia SNe occur, the production of Mn begins to dominate, lowering the ratios. Meanwhile, the [K/X] ratios for Sc, V, and Co remain flat, indicating the same amount of each produced during the type II SNe.

Inspecting the plots further reveals the distinctions between the thin and thick disc. For [K/Sc] and [K/Mn] the thick disc stars have a different trend from the thin disc stars at the lower metallicities. [K/V] and [K/Co] show the thin and thick disc stars to have more similar trends.

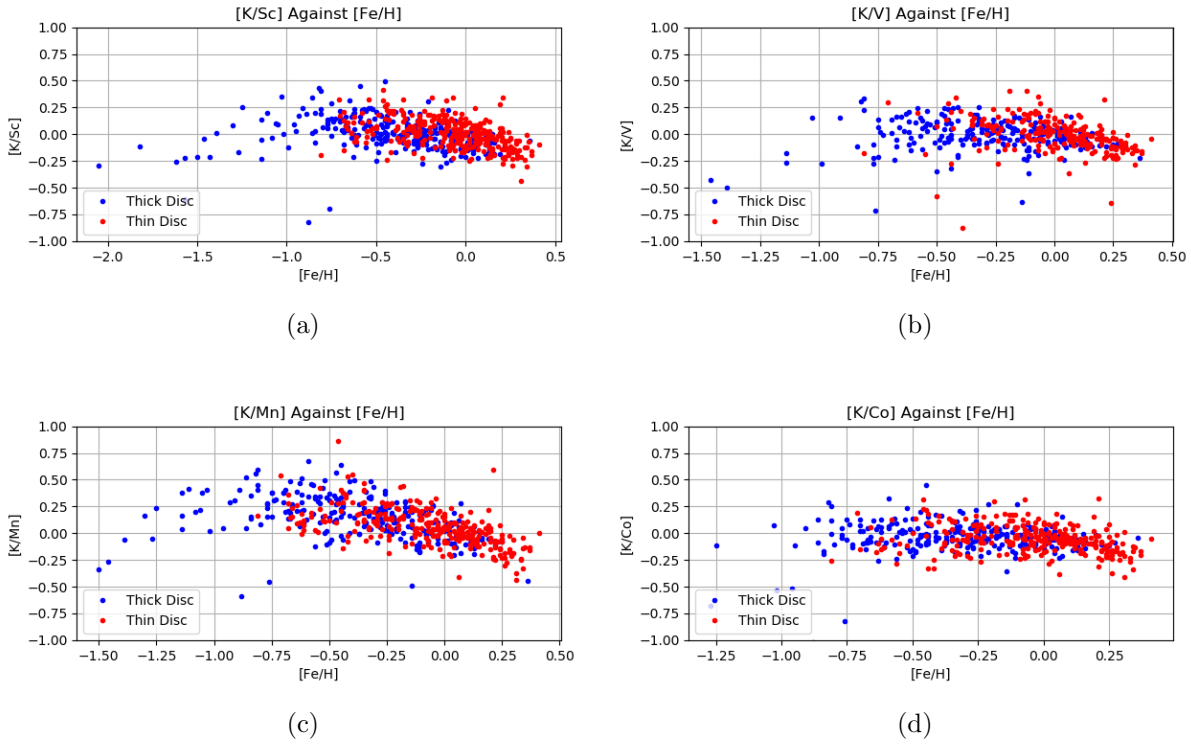


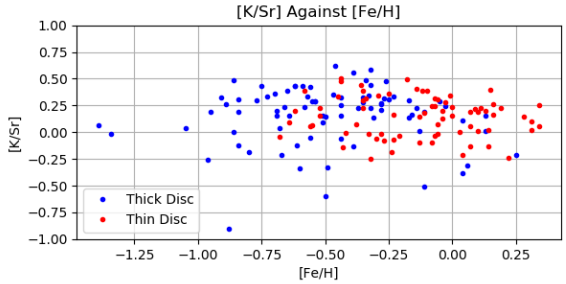

Figure 3.6: (a) [K/Sc] plotted against [Fe/H], (b) [K/V] plotted against [Fe/H], (c) [K/Mn] with NLTE corrections plotted against [Fe/H], (d) [K/Co] with NLTE corrections plotted against [Fe/H]

### Potassium comparison to r- and s- process elements Sr, Zr, La, Ce, Nd, Sm, Eu

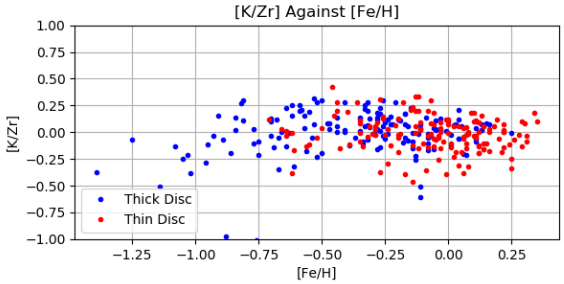
Furthermore, potassium was plotted against the r- and s- process elements of Sr, Zr, La, Ce, Nd, Sm, and Eu. The data on these elements was collected from Battistini & Bensby (2016), which held 593 stars, so again the HIP numbers were matched before analysis. The resulting plots are shown in figures 3.7(a) to 3.7(g).

The r- and s- process is a form of producing the heavy elements. They occur when free neutrons become available for neutron capture, typically from the burning of carbon, oxygen, and silicon (Prialnik 2010). The distinction between the r- and s- processes is whether the capture occurs more rapidly or slowly than the $\beta$ decays.

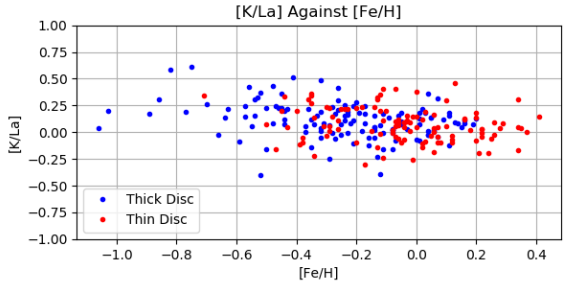
Of the elements used here, Eu is an r-process element, La, Sr, Zr, Ce, Sm are s- process elements, and Nd is equally both.



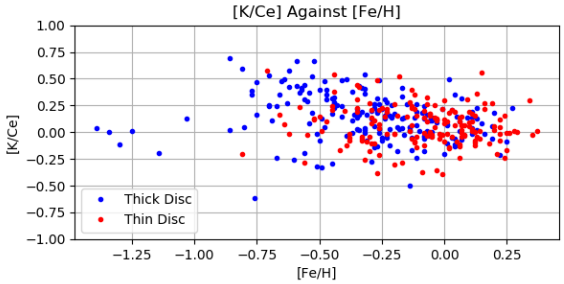

(a)



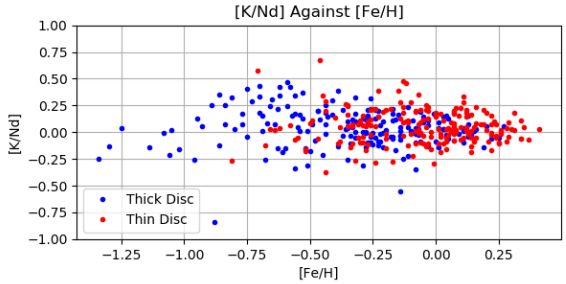

(b)



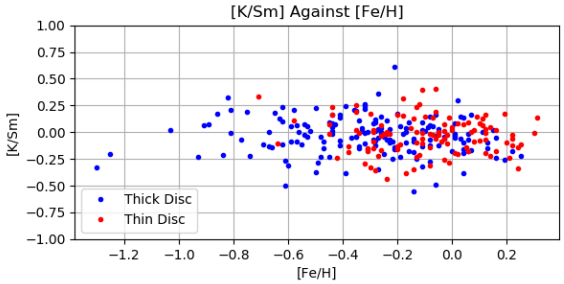

(c)



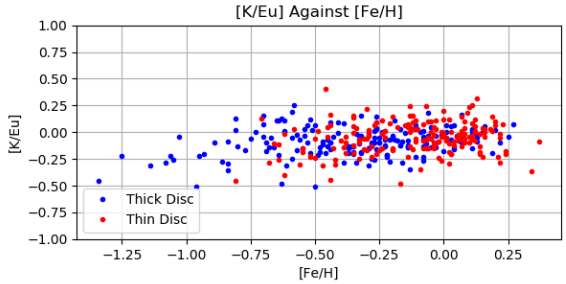

(d)




(e)




(f)




(g)

Figure 3.7: [K/Sr], [K/Zr], [K/La], [K/Ce], [K/Nd], [K/Sm], and [K/Eu] plotted against [Fe/H]

Observing these plots, there seems to be uniquely flat trends for each ratio between potassium and the r- and s- process element. This would suggest that they're produced in the same locations. The r- process elements are typically produced as a result of type II SNe activity (Battistini & Bensby 2016), while the s- process elements are created through the burning of He in the core of massive stars and through C burning (Pignatari et al. 2010). R- process element synthesis requires a large amount of neutron flux, which is provided by the core collapse SNe, and follows the path outside the $\beta$ valley of stability. S- process element synthesis does not require as large neutron flux and follows the $\beta$ valley of stability. Therefore, the He and C burning produces enough neutrons for the s-process to occur (Battistini & Bensby 2016).

## 3.3 Discussion

In order to determine accurate potassium abundances, it was appropriate to take into consideration the NLTE effects on the absorption line 7699 Å of potassium, as they had a great influence over the formation of the line. The corresponding corrections were found to have a dependence on temperature, micro-turbulence, and surface gravity, with little dependence on metallicity and absolute K abundance.

Observing the trends with K and the $\alpha$ element Mg, figures 3.4(a) and 3.4(b) ([K/Mg] against [Mg/H] and [Fe/H], respectively), reveal that the ratios do not span a large range of values. This indicates the link between the production of K and Mg in type II SNe. However, there seems to be different trends for the thin and thick disc where the thick disc has an increasing trend for increasing [Mg/H] and [Fe/H]. This increasing trend would suggest that some process produces enough K to dominate the ratio, until the production of Mg begins to even out the ratio.

Looking at the trends of [K/Fe] compared to [Mg/Fe] in figures 3.3(a) and 3.3(b), since Mg is an $\alpha$ element, the relation with Fe makes sense according to the production of Mg and Fe in type II SNe and of Fe in type Ia SNe. The production of Mg and Fe remains constant as a ratio during type II SNe events, until type Ia SNe activate and the Fe production dominates, making a decreasing trend. If K were produced in the exact same location as the $\alpha$ elements, it would show the same trend. However it does not, as initially the [K/Fe] increases, and then decreases, indicating a process that dominates with the production of K over Fe, and then the type Ia SNe activate and the Fe production dominates. This matches the trend of [K/Mg] at low [Mg/H] and [Fe/H] and of [K/Ti] at low [Ti/H] and [Fe/H].

These trends with Fe, Mg, and Ti are then repeated with the comparison between K and Mn as an iron peak element. The thick disc stars have an increasing trend before decreasing, which is probably due to the Mn production in type Ia SNe. It is interesting that [K/Mn] and [K/Fe] show the same trends as it is known that Mn and Fe are produced in the same production sites. This confirms the results as then these elements should have the same relation with K.

The r- and s- process elements have flat trends with K, indicating similar production

levels during the different synthesizing events. However, it is strange that there is a flat trend with Eu, as it is mainly produced in type II SNe, and according to the trends with Fe, Mg, and Mn, K is not only produced in type II SNe but also in another process altering the ratios and making K dominate.

Consolidating these trends, it seems as though K can be said to be linked to the production of $\alpha$ elements, as the scatter is low in the [K/Mg] plot, if even with a slight increasing trend at the lower [Mg/H] and [Fe/H] values. In addition, it has a flat trend with Eu, a known type II SNe produce. This agrees with Zhang et al. (2006b) and Zhao et al. (2016). On the other hand, the [K/Fe] ratios point to the idea that the production of K is larger than Fe in the type II SNe, which is unlike the $\alpha$ elements, as they maintain a flat trend.

In the comparison between K and Fe, there are distinct trends between the thin and thick disc stars. This distinction also appears when looking at [K/Mg] and [K/Mn]. The defined thick disc stars in the ratios just mentioned, all have an increasing trend at the lower metallicity values, while the defined thin disc stars either have a decreasing trend or flat trend at the higher metallicity values. As stated previously, this indicates that the thin and thick disc were most likely created in different spaces and times, when observing them through potassium.

## 3.4 Summary and conclusion

The NLTE corrections are dependent on certain parameters of the star, and this must be taken into consideration to effectively analyze and calculate the potassium abundances.

K does not show typical $\alpha$ element behavior, as there are some non flat trends with [K/Fe] at lower [Fe/H] values, and non flat trends with $\alpha$ elements such as Mg and Ti, which are generated in type II SNe. However, it does have a flat trend with the r- process element Eu, which is also generated in type II SNe. These trends point towards the possibility of a further investigation of K in connection to more r- process elements to see if that uncovers a more clear connection to the production sites. As of now, it seems like K is produced in relatively the same place as $\alpha$ elements, in type II SNe. However, in the ratios of [K/X], where X is Fe, Mg, Ti, and Mn, the K dominates in the more negative, respective, [X/H] and [Fe/H] regions.

In the plots of [K/Mg] and [K/Fe] and [K/Ti], figures 3.3(a), 3.4(a), 3.4(b), 3.5(a), 3.5(b), distinct trends between the thin and thick disc stars are visible. The thin disc stars tend to have little spread in the [K/X] ratios, and have either a flat or decreasing trend with increasing [X/H] and [Fe/H]. Meanwhile, the thick disc stars have a larger spread in the [K/X] ratios, and have an increasing trend from the lower [X/H] and [Fe/H] regions. This points to the idea that the thin and thick disc stars have different evolutionary patterns when it comes to K.

In terms of the analysis of the thin and thick disc stars in relation to K, this project analyzed the largest sample of data with K abundances. This is useful because there is a view into the trends at lower metallicities, [Fe/H] $\leq$ - 1.5, as well as around and above the

solar metallicity.

To improve the method and results, as well as deepen the understanding of the role of K in uncovering the chemical evolution of the galaxy, there are several steps that could be altered. The first is in the way of measuring the EWs, since it was done by hand, human error most likely skewed the placements of the fits each time the absorption peaks were fitted. A more precise method of measuring the EWs would be useful for more precise abundance calculations. Then, in the interpolation of the stellar parameters with the tables of NLTE corrections, simple linear relationships were assumed both for interpolation and extrapolation. To ensure that the resulting NLTE corrections calculated for the stars were more accurate, either a larger sample of NLTE corrections with larger variations of the temperature, K abundance, log g, micro-turbulence, and [Fe/H] could be used, or a deeper study of the relationship between the NLTE corrections and the stellar parameters could be conducted. In addition, the analysis in this project revealed some connection to the production site of K and $\alpha$ elements, as well to as to other elements also produced in type II SNe like Eu and Co. To further the understanding of the production of K in relation to iron peak elements and r- and s- process elements, more element ratios of these types could be calculated and explored. Moreover, the connection between K and r-process elements seems like an interesting lead to follow, as in the [K/Eu] plot there is little scatter and a flat trend for both the thin and thick disc, meaning that there in a connection to their production sites.

While the results confirm the distinction of K abundance trends in the thin and thick discs, they do not clearly indicate a reason or explanation of the different evolutions of the two discs. Knowing the production sites of K in the two discs as well as that there are distinct trends, adds to the present research and knowledge of how the two discs evolved. With additional data and comparisons of K to other elements and relations to their production sites, a clearer view into the differing evolutionary history of the Milky Way galaxy can be achieved.

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# Appendix A

# NLTE K abundances and corrections

Table A.1: Table of the final K abundances and their NLTE corrections

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 80 | -0.268020413 | -0.447135465 |
| 305 | 0.142937336 | -0.416177717 |
| 407 | 0.058571058 | -0.310543995 |
| 699 | -0.037112493 | -0.536227545 |
| 768 | -0.00510327 | -0.444218322 |
| 910 | -0.13126514 | -0.540380192 |
| 950 | 0.117020504 | -0.532094549 |
| 1128 | -0.534205853 | -0.453320905 |
| 1349 | -0.275724565 | -0.404839618 |
| 1599 | 0.195033486 | -0.454081566 |
| 1746 | -0.375372346 | -0.344487399 |
| 1877 | -0.057500526 | -0.196615578 |
| 1931 | 0.093427091 | -0.515687961 |
| 1955 | 0.029798173 | -0.44931688 |
| 1976 | 0.14029369 | -0.428821362 |
| 2021 | 0.080840269 | -0.398274784 |
| 2057 | 0.002986308 | -0.236128745 |
| 2194 | -0.474723724 | -0.243838776 |
| 2235 | -0.16742193 | -0.606536982 |
| 2319 | -0.344483376 | -0.603598428 |
| 2711 | 0.094379123 | -0.58473593 |
| 2743 | -0.306778438 | -0.15589349 |
| 2787 | 0.140411013 | -0.578704039 |
| 2909 | 0.00573605 | -0.353379003 |
| 3026 | nan | -0.713282358 |
| 3086 | -0.071686322 | -0.410801374 |
| 3142 | -0.31830112 | -0.607416173 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 3170 | -0.267092271 | -0.596207324 |
| 3182 | -0.18606666 | -0.355181712 |
| 3185 | -0.300082265 | -0.289197318 |
| 3391 | 0.131227928 | -0.277887124 |
| 3479 | -0.247201641 | -0.366316694 |
| 3497 | -0.257972195 | -0.347087247 |
| 3704 | -0.351448012 | -0.510563065 |
| 3734 | 0.144642012 | -0.48447304 |
| 3909 | 0.068564519 | -0.510550534 |
| 4830 | 0.143439948 | -0.465675104 |
| 4892 | -0.217118722 | -0.476233775 |
| 5054 | -0.42359476 | -0.572709812 |
| 5264 | 0.132519415 | -0.376595638 |
| 5301 | -0.25937646 | -0.458491512 |
| 5315 | nan | -0.189536642 |
| 5700 | 0.006348895 | -0.362766158 |
| 5817 | -0.152878573 | -0.211993626 |
| 5862 | nan | -0.551814732 |
| 6177 | -0.019390976 | -0.148506028 |
| 6607 | -0.29371977 | -0.322834822 |
| 6653 | 0.180621425 | -0.358493627 |
| 6856 | 0.182828056 | -0.176286997 |
| 6949 | -0.213779249 | -0.192894301 |
| 7080 | 0.260924734 | -0.318190319 |
| 7091 | -0.0387001 | -0.207815153 |
| 7162 | -2.284384942 | -0.663499995 |
| 7276 | 0.214725272 | -0.404389781 |
| 7961 | -0.193745489 | -0.392860541 |
| 7978 | 0.073093463 | -0.446021589 |
| 8398 | 0.184904736 | -0.384210317 |
| 8498 | -0.069121431 | -0.428236484 |
| 8572 | nan | -0.437637631 |
| 8674 | -0.45577985 | -0.374894902 |
| 8758 | 0.002392984 | -0.406722068 |
| 8798 | -0.130885295 | -0.400000348 |
| 8859 | -0.20920625 | -0.578321302 |
| 9085 | nan | -0.47917439 |
| 9137 | -0.278407326 | -0.657522378 |
| 9316 | 0.277507196 | -0.311607856 |
| 9381 | -0.151401042 | -0.360516094 |
| 9471 | 0.160065772 | -0.36904928 |
| 9629 | -0.205738585 | -0.254853637 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 9818 | 0.127768126 | -0.301346927 |
| 9911 | 0.075370898 | -0.413744155 |
| 10116 | 0.122402055 | -0.386712998 |
| 10225 | 0.197845587 | -0.631269466 |
| 10306 | 0.219843683 | -0.549271369 |
| 10483 | -0.096807656 | -0.495922709 |
| 10492 | 0.320693652 | -0.318421401 |
| 10694 | 0.108575629 | -0.360539423 |
| 10798 | -0.599781542 | -0.258896594 |
| 10842 | -0.26125878 | -0.330373833 |
| 10977 | -0.474175975 | -0.143291027 |
| 11072 | 0.048804548 | -0.460310504 |
| 11205 | -0.074157822 | -0.233272875 |
| 11309 | -0.141023052 | -0.540138105 |
| 11586 | -0.055430135 | -0.564545187 |
| 12048 | 0.122093685 | -0.337021368 |
| 12186 | 0.163180655 | -0.335934397 |
| 12306 | nan | -0.530464139 |
| 12381 | -0.101765471 | -0.540880523 |
| 12411 | -0.1743325 | -0.313447553 |
| 12444 | 0.073211215 | -0.525903837 |
| 12483 | -0.308485125 | -0.407600177 |
| 12611 | 0.285604645 | -0.243510408 |
| 12653 | 0.137728519 | -0.521386533 |
| 12889 | -0.124340773 | -0.503455825 |
| 13315 | -0.336152125 | -0.575267178 |
| 13341 | -0.134522609 | -0.503637661 |
| 13350 | -0.189922527 | -0.279037579 |
| 13366 | -0.427998749 | -0.557113802 |
| 13388 | -0.287627932 | -0.196742985 |
| 13513 | -0.087519158 | -0.17663421 |
| 13848 | 0.097578046 | -0.211537006 |
| 13902 | -0.171206455 | -0.490321507 |
| 13938 | 0.107630937 | -0.511484116 |
| 14016 | 0.005495034 | -0.273620019 |
| 14023 | 0.054007114 | -0.165107938 |
| 14086 | -0.265306236 | -0.274421288 |
| 14241 | -0.205672989 | -0.284788042 |
| 14339 | -0.172035232 | -0.491150284 |
| 14561 | 0.17579877 | -0.483316283 |
| 14879 | -0.079650116 | -0.578765169 |
| 14954 | 0.015914542 | -0.553200511 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 15131 | nan | -0.471754575 |
| 15158 | -0.051910544 | -0.561025596 |
| 15371 | -0.28122033 | -0.470335382 |
| 15381 | 0.083076348 | -0.406038704 |
| 15510 | nan | -0.273436635 |
| 15940 | -0.217991086 | -0.407106138 |
| 16169 | -0.366801268 | -0.40591632 |
| 16365 | -0.133048233 | -0.392163286 |
| 16391 | 0.100969471 | -0.328145582 |
| 16404 | nan | -0.472335331 |
| 16492 | -0.30351562 | -0.192630672 |
| 16788 | -0.291424418 | -0.54053947 |
| 16852 | -0.08836285 | -0.597477902 |
| 17147 | -0.791090969 | -0.550206022 |
| 17378 | 0.183228598 | -0.175886455 |
| 17970 | -0.509357123 | -0.228472175 |
| 17987 | -0.15028259 | -0.349397643 |
| 18164 | -0.421645514 | -0.680760567 |
| 18331 | 0.166581854 | -0.552533199 |
| 18612 | -0.078589034 | -0.437704086 |
| 18802 | -0.653686809 | -0.482801861 |
| 18833 | -0.155334559 | -0.594449611 |
| 19233 | -0.073962024 | -0.453077077 |
| 19773 | -0.313739199 | -0.602854252 |
| 20199 | -0.174956239 | -0.354071292 |
| 20242 | 0.110685304 | -0.358429748 |
| 20489 | 0.193459742 | -0.335655311 |
| 20638 | -0.172746567 | -0.371861619 |
| 20677 | -0.078642092 | -0.357757145 |
| 21079 | -0.13938496 | -0.438500012 |
| 21731 | 0.112488178 | -0.306626875 |
| 21832 | -0.393666446 | -0.392781498 |
| 21839 | 0.063680222 | -0.38543483 |
| 22068 | nan | -0.65883407 |
| 22162 | 0.055531767 | -0.423583285 |
| 22263 | -0.076482521 | -0.375597574 |
| 22278 | 0.026406556 | -0.352708497 |
| 22325 | 0.29725608 | -0.491858973 |
| 22336 | 0.126492506 | -0.432622546 |
| 22349 | -0.159550964 | -0.388666017 |
| 22395 | 0.056639058 | -0.412475994 |
| 22632 | -1.816953663 | -0.656068715 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 22824 | -0.001992668 | -0.47110772 |
| 23383 | -0.16991519 | -0.259030243 |
| 23555 | 0.101830026 | -0.527285026 |
| 23941 | 0.039860823 | -0.529254229 |
| 24037 | -0.299923222 | -0.289038274 |
| 24682 | -0.133997272 | -0.243112325 |
| 24722 | -0.121663303 | -0.310778355 |
| 24819 | 0.10388149 | -0.145233562 |
| 24829 | nan | -0.497752235 |
| 25209 | 0.201050217 | -0.648064835 |
| 25528 | 0.100213233 | -0.65890182 |
| 25905 | -0.24556191 | -0.294676963 |
| 26273 | -0.199422188 | -0.328537241 |
| 26641 | nan | -0.30869592 |
| 26828 | 0.021034813 | -0.54808024 |
| 27072 | nan | -0.523751273 |
| 27080 | -0.481855557 | -0.220970609 |
| 27128 | -1.521593571 | -0.560708623 |
| 27910 | 0.003828185 | -0.155286867 |
| 28044 | 0.204491617 | -0.244623436 |
| 28066 | 0.045849578 | -0.343265475 |
| 28159 | nan | -0.421990002 |
| 28267 | -0.074775497 | -0.263890549 |
| 28369 | 0.112296651 | -0.626818401 |
| 28403 | -0.230997953 | -0.340113006 |
| 28671 | nan | -0.350224859 |
| 29271 | -0.008244774 | -0.267359827 |
| 29716 | 0.088417541 | -0.600697512 |
| 30158 | 0.047815487 | -0.331299565 |
| 30439 | -0.209525793 | -0.308640846 |
| 30476 | 0.1229153 | -0.306199752 |
| 30480 | 0.122295711 | -0.446819342 |
| 30503 | -0.0691524 | -0.428267453 |
| 30545 | 0.040166357 | -0.468948695 |
| 31030 | -0.173244259 | -0.232359311 |
| 32649 | 0.016709343 | -0.26240571 |
| 33094 | 0.050819159 | -0.458295893 |
| 33220 | -0.340860637 | -0.59997569 |
| 33324 | -0.503881736 | -0.492996789 |
| 33582 | -0.290892209 | -0.540007261 |
| 33642 | -0.043189933 | -0.442304986 |
| 34017 | nan | -0.433459932 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 34028 | 0.234603346 | -0.234511706 |
| 34065 | -0.166497079 | -0.415612131 |
| 34069 | -0.240940769 | -0.190055821 |
| 34212 | -0.088937183 | -0.648052236 |
| 34254 | 0.068538253 | -0.310576799 |
| 34285 | -0.956760374 | -0.555875427 |
| 34410 | -0.06874885 | -0.547863902 |
| 34511 | -0.077027828 | -0.386142881 |
| 34739 | -0.263232014 | -0.282347066 |
| 34961 | -0.236398022 | -0.235513074 |
| 35139 | -0.494344576 | -0.453459629 |
| 35148 | -0.198518049 | -0.497633101 |
| 35318 | -0.17401639 | -0.483131442 |
| 35718 | 0.003755699 | -0.235359353 |
| 35750 | -0.053226972 | -0.112342024 |
| 36210 | -0.063366038 | -0.292481091 |
| 36269 | -1.806782762 | -0.595897815 |
| 36491 | -0.688321596 | -0.677436649 |
| 36515 | -0.143766137 | -0.48288119 |
| 36795 | nan | -0.588061859 |
| 36849 | -0.507542424 | -0.556657477 |
| 36855 | nan | -0.319715372 |
| 36874 | -0.046171913 | -0.385286965 |
| 36993 | nan | -0.387788064 |
| 37171 | 0.058021732 | -0.29109332 |
| 37233 | -0.057958978 | -0.407074031 |
| 37419 | -0.140851434 | -0.329966487 |
| 37520 | nan | -0.369499985 |
| 37789 | -0.411521852 | -0.490636905 |
| 37853 | -0.408041056 | -0.477156109 |
| 38134 | -0.539013709 | -0.488128762 |
| 38541 | nan | -0.498230071 |
| 38625 | -0.54263023 | -0.261745282 |
| 38750 | -0.045261345 | -0.494376398 |
| 38782 | -0.025439073 | -0.414554126 |
| 38862 | -0.213787414 | -0.412902467 |
| 38926 | nan | -0.601512227 |
| 39911 | -0.677535229 | -0.426650281 |
| 40613 | -0.405469342 | -0.604584395 |
| 40761 | nan | -0.442799123 |
| 40794 | -0.088379767 | -0.45749482 |
| 41471 | -0.04579339 | -0.524908442 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 41544 | nan | -0.648189144 |
| 42356 | nan | -0.42972665 |
| 42612 | -0.012307322 | -0.401422374 |
| 42734 | nan | -0.479418724 |
| 42889 | -0.138762439 | -0.417877492 |
| 43054 | -0.022701241 | -0.481816294 |
| 43393 | -0.520396276 | -0.309511329 |
| 44075 | nan | -0.743625123 |
| 44319 | 0.112107656 | -0.407007397 |
| 44441 | nan | -0.551905617 |
| 44713 | 0.089361687 | -0.399753366 |
| 44821 | -0.082906545 | -0.122021598 |
| 44860 | -0.255572009 | -0.404687062 |
| 44896 | -0.123046322 | -0.482161374 |
| 44915 | 0.100598048 | -0.578517004 |
| 44927 | 0.1728351 | -0.506279952 |
| 45283 | -0.629722113 | -0.568837166 |
| 45514 | -0.032559116 | -0.231674168 |
| 45733 | -0.429887792 | -0.579002845 |
| 46685 | 0.07275669 | -0.206358363 |
| 46888 | 0.034743224 | -0.394371829 |
| 47048 | -0.396284893 | -0.625399946 |
| 47588 | -0.226547292 | -0.495662344 |
| 48152 | -2.050742228 | -0.56985728 |
| 48468 | 0.219784152 | -0.4593309 |
| 49285 | -0.063348298 | -0.292463351 |
| 49793 | nan | -0.460212785 |
| 49942 | nan | -0.438853866 |
| 49988 | -0.159337744 | -0.468452796 |
| 50274 | -0.302685828 | -0.211800881 |
| 50316 | -0.181561907 | -0.460676959 |
| 50671 | -0.273627129 | -0.472742181 |
| 50713 | -0.326750501 | -0.275865554 |
| 50834 | -0.316399818 | -0.595514871 |
| 50907 | 0.160608643 | -0.568506409 |
| 50941 | -0.229045654 | -0.318160707 |
| 51028 | -0.387774365 | -0.566889418 |
| 51078 | 0.280133986 | -0.368981067 |
| 51477 | nan | -0.454502369 |
| 51579 | -0.08757935 | -0.466694403 |
| 51614 | 0.175569724 | -0.463545329 |
| 51933 | -0.104839525 | -0.563954577 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 51938 | -0.074639344 | -0.383754397 |
| 52247 | -0.077244787 | -0.25635984 |
| 52325 | -0.05846673 | -0.407581783 |
| 52564 | 0.034142102 | -0.164972951 |
| 52990 | 0.09954081 | -0.399574242 |
| 53122 | -0.08178185 | -0.380896903 |
| 53311 | nan | -0.49540792 |
| 53719 | -9.44E-05 | -0.119209431 |
| 53765 | -0.27702838 | -0.556143433 |
| 53982 | 0.1437095 | -0.445405553 |
| 54043 | -0.250920885 | -0.360035938 |
| 54469 | -0.14744091 | -0.476555962 |
| 54641 | -1.136764674 | -0.625879727 |
| 54779 | -0.370916862 | -0.540031914 |
| 54924 | -0.639776854 | -0.538891906 |
| 55210 | nan | -0.248638728 |
| 55278 | 0.015536631 | -0.603578421 |
| 55592 | -0.983846276 | -0.602961329 |
| 55805 | -0.876621986 | -0.445737039 |
| 56004 | 0.146649631 | -0.452465422 |
| 56336 | -0.450196013 | -0.489311065 |
| 56389 | -0.114394196 | -0.423509249 |
| 56452 | -0.34014397 | -0.199259022 |
| 56557 | 0.010674885 | -0.268440168 |
| 56664 | -0.624251281 | -0.673366334 |
| 56830 | -0.250062753 | -0.239177805 |
| 56845 | -0.130823139 | -0.229938192 |
| 56868 | -0.150262541 | -0.379377594 |
| 57017 | nan | -0.618102793 |
| 57216 | -0.271116191 | -0.550231244 |
| 57360 | -1.370505994 | -0.609621047 |
| 58145 | -1.049602261 | -0.628717314 |
| 58153 | nan | -0.30130021 |
| 58401 | -0.54616047 | -0.205275522 |
| 58517 | 0.014357378 | -0.504757675 |
| 58576 | nan | -0.221409324 |
| 58843 | -0.725315787 | -0.58443084 |
| 58950 | nan | -0.411064772 |
| 58962 | -0.801996166 | -0.521111219 |
| 59021 | 0.058756026 | -0.460359027 |
| 59380 | nan | -0.481913685 |
| 59490 | -1.476068559 | -0.555183611 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 59532 | nan | -0.236372599 |
| 59639 | -0.097685359 | -0.146800411 |
| 59696 | -0.376111486 | -0.225226539 |
| 59699 | -0.422336124 | -0.561451176 |
| 60019 | nan | -0.537588405 |
| 60288 | 0.114629429 | -0.494485624 |
| 60462 | -0.560430067 | -0.21954512 |
| 60574 | -0.06200117 | -0.291116222 |
| 60632 | nan | -0.513810892 |
| 60729 | 0.086853471 | -0.382261582 |
| 60825 | -0.573876514 | -0.562991567 |
| 60956 | nan | -0.290625802 |
| 61619 | 0.187777806 | -0.511337247 |
| 61802 | -0.971045924 | -0.410160976 |
| 61971 | -0.284243699 | -0.303358751 |
| 62108 | nan | -0.631587381 |
| 62534 | -0.322098801 | -0.311213854 |
| 62607 | -0.422332179 | -0.271447231 |
| 62809 | nan | -0.394061073 |
| 62857 | -0.01441112 | -0.483526172 |
| 63405 | -0.179474727 | -0.65858978 |
| 63548 | nan | -0.300239486 |
| 63918 | -0.256360526 | -0.495475579 |
| 64345 | nan | -0.444595505 |
| 64408 | nan | -0.306959928 |
| 64426 | -0.408549845 | -0.517664897 |
| 64444 | -0.003708284 | -0.472823337 |
| 64459 | nan | -0.498864541 |
| 64673 | 0.109006278 | -0.400108774 |
| 64698 | -0.181325657 | -0.42044071 |
| 64706 | -0.235420775 | -0.134535827 |
| 64747 | nan | -0.367853775 |
| 64792 | 0.26415322 | -0.454961833 |
| 64920 | nan | -0.169716327 |
| 64924 | -0.158155288 | -0.327270341 |
| 66238 | -0.135543135 | -0.304658188 |
| 66814 | nan | -0.233861376 |
| 67371 | 0.389362241 | -0.359752811 |
| 67534 | nan | -0.620844076 |
| 67784 | -0.040927699 | -0.570042751 |
| 67863 | -1.293572825 | -0.402687877 |
| 68273 | -0.250078503 | -0.269193556 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 68464 | -1.967372681 | -0.536487734 |
| 68468 | 0.026613054 | -0.432501998 |
| 68727 | -0.459671561 | -0.668786613 |
| 68796 | nan | -0.480990388 |
| 69220 | -0.239133955 | -0.368249008 |
| 69645 | -0.126884672 | -0.465999725 |
| 69780 | -0.253814129 | -0.472929181 |
| 69796 | -0.065997387 | -0.495112439 |
| 70140 | -0.22049392 | -0.419608973 |
| 70182 | 0.008289329 | -0.490825724 |
| 70330 | 0.133718803 | -0.39539625 |
| 70681 | -1.126325471 | -0.425440524 |
| 70829 | -0.443532745 | -0.322647798 |
| 70922 | -0.457510702 | -0.466625755 |
| 71019 | -0.040005792 | -0.259120844 |
| 71284 | -0.215915415 | -0.695030468 |
| 71470 | -0.581182569 | -0.730297621 |
| 71735 | -0.291162883 | -0.320277935 |
| 71844 | -0.446694577 | -0.58580963 |
| 72479 | nan | -0.144509321 |
| 72673 | -0.540610222 | -0.639725274 |
| 72688 | -0.021182432 | -0.120297485 |
| 72797 | nan | -0.233996456 |
| 73385 | nan | -0.501116573 |
| 73444 | nan | -0.633525609 |
| 73650 | -0.036475212 | -0.505590264 |
| 74033 | nan | -0.532700565 |
| 74067 | nan | -0.642752426 |
| 74079 | -0.243100978 | -0.48221603 |
| 74234 | -1.433155787 | -0.29227084 |
| 74235 | -1.627358229 | -0.336473282 |
| 74389 | 0.062432829 | -0.366682223 |
| 74500 | 0.081772286 | -0.427342766 |
| 74537 | -0.082787965 | -0.191903017 |
| 74831 | -0.237803836 | -0.446918889 |
| 75023 | 0.234294323 | -0.57482073 |
| 75181 | -0.286158964 | -0.365274016 |
| 75206 | 0.431264536 | -0.527850516 |
| 75487 | -0.443678984 | -0.542794037 |
| 76226 | -0.517211057 | -0.676326109 |
| 76394 | -0.103291613 | -0.472406665 |
| 76899 | nan | -0.426277704 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 76976 | nan | -0.423178947 |
| 76984 | 0.091649867 | -0.357465186 |
| 77358 | 0.060132797 | -0.308982255 |
| 77439 | -0.315601351 | -0.604716404 |
| 77536 | 0.195997806 | -0.703117247 |
| 77637 | nan | -0.547318451 |
| 77641 | 0.144979783 | -0.254135269 |
| 78267 | nan | -0.418144727 |
| 78330 | -0.207116239 | -0.426231292 |
| 78425 | 0.012939656 | -0.376175396 |
| 78551 | -0.106823015 | -0.265938068 |
| 78556 | -0.085700869 | -0.394815922 |
| 78640 | nan | -0.63241096 |
| 78917 | -0.619177166 | -0.328292218 |
| 78955 | 0.214563453 | -0.354551599 |
| 79073 | 0.142923066 | -0.396191987 |
| 79137 | 0.213033766 | -0.106081287 |
| 79138 | -0.27217545 | -0.551290503 |
| 79576 | -0.526519738 | -0.33563479 |
| 79715 | -0.162470635 | -0.461585687 |
| 79792 | -0.078826298 | -0.417941351 |
| 80013 | 0.033409436 | -0.355705616 |
| 80043 | -0.363797829 | -0.152912881 |
| 80114 | nan | -0.438928047 |
| 80221 | -0.550807207 | -0.33992226 |
| 80337 | -0.031779637 | -0.42089469 |
| 80423 | nan | -0.695403015 |
| 80587 | -0.354971703 | -0.484086756 |
| 80686 | -0.243847083 | -0.622962136 |
| 80700 | -0.082315866 | -0.261430919 |
| 80722 | -0.140227617 | -0.549342669 |
| 80837 | nan | -0.641630245 |
| 81041 | -0.228653058 | -0.457768111 |
| 81269 | 0.064808363 | -0.404306689 |
| 81300 | -0.081786577 | -0.220901629 |
| 81461 | -0.386512896 | -0.555627949 |
| 81520 | -0.632859406 | -0.551974458 |
| 81580 | -0.412242201 | -0.581357253 |
| 81603 | -0.004591885 | -0.333706938 |
| 81749 | 0.072308497 | -0.246806556 |
| 81952 | 0.309895041 | -0.329220011 |
| 82062 | -0.446356222 | -0.585471275 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 82265 | 0.172605714 | -0.206509338 |
| 82588 | -0.185042196 | -0.274157248 |
| 82621 | 0.252868953 | -0.3362461 |
| 83204 | -0.212526909 | -0.491641962 |
| 83229 | -0.362089044 | -0.471204097 |
| 83241 | -0.233895443 | -0.523010495 |
| 83276 | -0.053688458 | -0.452803511 |
| 83301 | 0.068303586 | -0.620811466 |
| 83489 | -0.1572147 | -0.426329753 |
| 83562 | -0.226413239 | -0.415528292 |
| 83601 | 0.110156643 | -0.488958409 |
| 83867 | -0.038768641 | -0.507883694 |
| 84255 | -0.629209515 | -0.368324568 |
| 84551 | nan | -0.537365356 |
| 84636 | 0.222755806 | -0.496359247 |
| 84781 | -0.072025694 | -0.291140747 |
| 84803 | 0.040822385 | -0.428292667 |
| 84905 | nan | -0.500068828 |
| 84907 | -0.082546892 | -0.211661944 |
| 84988 | -0.372191701 | -0.411306754 |
| 85007 | -0.433519096 | -0.522634149 |
| 85042 | -0.158261185 | -0.337376238 |
| 85320 | 0.075364616 | -0.163750437 |
| 85474 | 0.762129949 | -0.486985103 |
| 85757 | nan | -0.396272558 |
| 85963 | -0.408897645 | -0.648012698 |
| 85969 | 0.046340774 | -0.422774278 |
| 86013 | -0.3816187 | -0.500733752 |
| 86193 | 0.049829607 | -0.319285446 |
| 86516 | -0.074838593 | -0.383953645 |
| 86694 | -2.021032217 | -0.55014727 |
| 86731 | 0.180112646 | -0.439002406 |
| 86796 | nan | -0.312340954 |
| 87101 | -2.106985363 | -0.596100416 |
| 87154 | 0.143258381 | -0.285856671 |
| 87443 | 0.13336111 | -0.355753943 |
| 87523 | -0.203595844 | -0.522710897 |
| 87533 | 0.118355986 | -0.500759066 |
| 87539 | -0.371684272 | -0.520799325 |
| 87679 | 0.090562535 | -0.208552518 |
| 87769 | 0.129866233 | -0.31924882 |
| 87841 | 0.06722205 | -0.421893003 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 88010 | -1.285107473 | -0.444222525 |
| 88622 | nan | -0.439296046 |
| 88631 | 0.286215841 | -0.292899212 |
| 88945 | 0.143009462 | -0.40610559 |
| 89036 | -0.038689576 | -0.477804628 |
| 89076 | 0.032881547 | -0.336233506 |
| 89105 | 0.0906649 | -0.318450153 |
| 89207 | 0.056548895 | -0.382566157 |
| 89554 | -1.694491141 | -0.533606194 |
| 89583 | -0.229371615 | -0.288486668 |
| 89589 | -0.077852823 | -0.506967875 |
| 89733 | -0.14636319 | -0.395478243 |
| 89881 | 0.132035092 | -0.27707996 |
| 89952 | -0.320527314 | -0.619642367 |
| 90004 | -0.04195942 | -0.281074473 |
| 90151 | 0.173683712 | -0.15543134 |
| 90261 | -0.921631454 | -0.560746507 |
| 90365 | -0.231839251 | -0.250954303 |
| 90442 | -0.245109979 | -0.464225031 |
| 90485 | 0.427897608 | -0.491217444 |
| 90539 | -0.175529932 | -0.214644985 |
| 90896 | 0.170793405 | -0.318321648 |
| 91089 | -0.13675557 | -0.535870623 |
| 91095 | -0.221239081 | -0.500354133 |
| 91360 | nan | -0.170314588 |
| 91438 | -0.428110377 | -0.417225429 |
| 91471 | 0.003247768 | -0.135867284 |
| 91582 | 0.027036737 | -0.252078316 |
| 92270 | -0.085346184 | -0.574461237 |
| 92288 | -0.203722001 | -0.592837053 |
| 92781 | -0.372918551 | -0.422033604 |
| 92864 | 0.116327727 | -0.522787325 |
| 92880 | -0.006889301 | -0.466004353 |
| 92973 | -0.257022543 | -0.486137595 |
| 93185 | -0.386886857 | -0.49600191 |
| 93186 | nan | -0.475453616 |
| 93377 | -0.116845977 | -0.38596103 |
| 93507 | -0.491385103 | -0.690500156 |
| 93889 | 0.039384531 | -0.419730522 |
| 93966 | 0.140772268 | -0.308342785 |
| 94347 | -0.430372451 | -0.589487503 |
| 94645 | 0.078967626 | -0.540147427 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 94678 | -0.083754927 | -0.492869979 |
| 95106 | -0.27444429 | -0.403559343 |
| 95262 | -0.24082276 | -0.509937813 |
| 95447 | 0.344278957 | -0.264836096 |
| 96124 | -0.131907985 | -0.321023037 |
| 96160 | -0.035541579 | -0.384656632 |
| 96258 | -0.077772399 | -0.606887452 |
| 96425 | -0.001293162 | -0.240408214 |
| 96536 | 0.125221517 | -0.583893535 |
| 96854 | -3.06E-05 | -0.319145651 |
| 96881 | -0.214616297 | -0.503731349 |
| 97024 | -0.063180735 | -0.322295787 |
| 97213 | 0.160600302 | -0.39851475 |
| 97358 | -0.033713223 | -0.282828276 |
| 97676 | 0.050639113 | -0.33847594 |
| 97779 | 0.057078611 | -0.462036441 |
| 98020 | -1.681323313 | -0.440438365 |
| 98355 | nan | -0.6900158 |
| 98416 | -0.031405235 | -0.400520287 |
| 98532 | -0.861075931 | -0.590190984 |
| 98565 | -0.162547577 | -0.65166263 |
| 98767 | 0.170211045 | -0.318904008 |
| 98785 | 0.307685445 | -0.461429608 |
| 98964 | 0.051167335 | -0.217947718 |
| 99100 | -0.141668903 | -0.420783955 |
| 99139 | -0.19862759 | -0.347742643 |
| 99174 | 0.069227455 | -0.409887597 |
| 99224 | nan | -0.293020566 |
| 99240 | 0.178834442 | -0.29028061 |
| 99551 | -0.127604396 | -0.476719449 |
| 99799 | -0.146436477 | -0.455551529 |
| 100394 | -0.283978617 | -0.60309367 |
| 100405 | -0.342561938 | -0.301676991 |
| 100412 | -0.182679988 | -0.56179504 |
| 100568 | nan | -0.508922455 |
| 100792 | nan | -0.601762623 |
| 100942 | 0.169405941 | -0.349709111 |
| 100970 | 0.091393897 | -0.427721156 |
| 101346 | -0.342766251 | -0.591881303 |
| 101399 | 0.056910529 | -0.362204524 |
| 101857 | -0.001405236 | -0.330520289 |
| 102018 | 0.221932216 | -0.407182837 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 102046 | -0.790527245 | -0.569642298 |
| 102200 | -0.404541257 | -0.43365631 |
| 102264 | -0.331300293 | -0.330415345 |
| 102548 | -0.213547238 | -0.30266229 |
| 102580 | 0.066129274 | -0.252985778 |
| 102610 | -0.176134115 | -0.415249167 |
| 102762 | -0.04144809 | -0.460563143 |
| 102793 | nan | -0.460864096 |
| 102838 | -0.11200453 | -0.421119583 |
| 103458 | -0.503718655 | -0.502833707 |
| 103498 | -0.774012693 | -0.543127745 |
| 103572 | -0.432598761 | -0.501713813 |
| 103609 | 0.00381839 | -0.185296663 |
| 103654 | 0.042603826 | -0.516511227 |
| 103682 | 0.165636566 | -0.383478486 |
| 103692 | 0.085829359 | -0.423285693 |
| 103735 | -0.032430945 | -0.351545998 |
| 103773 | -0.15320119 | -0.422316243 |
| 103881 | -0.351494782 | -0.590609835 |
| 103896 | -0.40862949 | -0.557744543 |
| 103990 | 0.313249638 | -0.405865414 |
| 104045 | -0.060792539 | -0.439907592 |
| 104075 | 0.034200499 | -0.454914554 |
| 104152 | 0.134222701 | -0.424892352 |
| 104294 | -0.138061687 | -0.567176739 |
| 104560 | -0.389101884 | -0.418216936 |
| 104659 | -0.941244797 | -0.60035985 |
| 104672 | 0.064732706 | -0.474382347 |
| 104766 | -0.02577352 | -0.564888572 |
| 104922 | 0.042212824 | -0.336902229 |
| 105083 | 0.082319082 | -0.556795971 |
| 105214 | 0.071183912 | -0.427931141 |
| 105521 | 0.164615795 | -0.414499258 |
| 105541 | 0.014133183 | -0.35498187 |
| 105606 | 0.234658712 | -0.284456341 |
| 105790 | -0.140005635 | -0.279120688 |
| 105858 | -0.527983204 | -0.547098256 |
| 106006 | 0.014968121 | -0.434146932 |
| 106560 | -0.424778832 | -0.413893884 |
| 106678 | 0.024994066 | -0.344120987 |
| 106701 | 0.090608552 | -0.318506501 |
| 106931 | -0.118422282 | -0.247537334 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 106951 | -0.023926429 | -0.353041481 |
| 107607 | -0.474044418 | -0.50315947 |
| 107618 | -0.21784377 | -0.376958822 |
| 107708 | -0.215340587 | -0.414455639 |
| 107857 | -0.341705731 | -0.280820783 |
| 107877 | -0.11536408 | -0.574479132 |
| 107975 | -0.310691336 | -0.529806388 |
| 108068 | -0.280647961 | -0.409763014 |
| 108095 | -0.432263899 | -0.611378951 |
| 108158 | 0.026200436 | -0.302914616 |
| 108288 | -0.196854335 | -0.455969388 |
| 108468 | -0.145315929 | -0.444430981 |
| 108473 | 0.029865299 | -0.449249753 |
| 108598 | -0.572895854 | -0.212010906 |
| 108736 | -0.290682073 | -0.559797125 |
| 109012 | 0.01652971 | -0.282585342 |
| 109086 | -0.079595916 | -0.548710969 |
| 109110 | 0.121589072 | -0.38752598 |
| 109144 | -0.109774045 | -0.598889097 |
| 109207 | 0.125161795 | -0.223953258 |
| 109214 | -0.051146803 | -0.470261855 |
| 109266 | -0.232532709 | -0.481647761 |
| 109378 | 0.097298534 | -0.271816519 |
| 109381 | 0.064119487 | -0.334995565 |
| 109450 | nan | -0.44709474 |
| 109650 | -0.179339285 | -0.448454337 |
| 109795 | 0.088342418 | -0.460772635 |
| 109821 | -0.241654482 | -0.450769535 |
| 110028 | 0.088974031 | -0.390141021 |
| 110035 | -0.213513169 | -0.502628222 |
| 110084 | -0.114820427 | -0.243935479 |
| 110102 | -0.149566125 | -0.458681177 |
| 110109 | -0.204842831 | -0.413957884 |
| 110341 | -0.221055946 | -0.640170999 |
| 110454 | -0.055882839 | -0.394997891 |
| 110468 | -0.564337001 | -0.183452053 |
| 110512 | -0.224908663 | -0.444023715 |
| 110712 | -0.015643004 | -0.424758057 |
| 110843 | 0.151311227 | -0.307803826 |
| 111274 | 0.034815377 | -0.324299676 |
| 111312 | -0.144584748 | -0.2636998 |
| 111517 | -0.041716088 | -0.330831141 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 111565 | -0.299837367 | -0.348952419 |
| 111648 | -0.263737629 | -0.242852681 |
| 111746 | -0.360046518 | -0.439161571 |
| 111978 | 0.075432533 | -0.21368252 |
| 112151 | -0.308652966 | -0.347768018 |
| 112201 | 0.091248942 | -0.32786611 |
| 112243 | -0.114355596 | -0.333470648 |
| 113044 | -0.012668814 | -0.631783867 |
| 113113 | -0.061669652 | -0.300784704 |
| 113137 | 0.135142948 | -0.413972104 |
| 113174 | 0.1888935 | -0.580221553 |
| 113357 | 0.129650872 | -0.32946418 |
| 113386 | 0.010747088 | -0.398367965 |
| 113421 | 0.187318614 | -0.291796438 |
| 113454 | -0.242437214 | -0.361552267 |
| 113543 | -0.212742772 | -0.621857824 |
| 113677 | 0.040179759 | -0.268935294 |
| 113688 | -0.187688838 | -0.48680389 |
| 113777 | -0.074693247 | -0.173808299 |
| 114040 | 0.078296258 | -0.300818794 |
| 114333 | -0.066827901 | -0.395942954 |
| 114450 | -0.061227326 | -0.410342379 |
| 114460 | -0.108773232 | -0.287888285 |
| 114576 | 0.043933104 | -0.395181949 |
| 114584 | -0.097309652 | -0.356424705 |
| 114590 | 0.216750168 | -0.352364884 |
| 114615 | -0.052406735 | -0.391521787 |
| 114702 | -0.392603585 | -0.601718637 |
| 114709 | -0.186262448 | -0.4853775 |
| 114743 | 0.000554908 | -0.288560144 |
| 114761 | -0.702368639 | -0.651483691 |
| 114962 | -1.675541532 | -0.584656584 |
| 115286 | 0.030797076 | -0.418317977 |
| 115411 | -0.417236187 | -0.326351239 |
| 115577 | -0.050969103 | -0.420084155 |
| 115662 | 0.027395911 | -0.381719141 |
| 115792 | 0.150834492 | -0.578280561 |
| 115803 | 0.021946124 | -0.587168929 |
| 115861 | 0.144745965 | -0.344369087 |
| 115917 | -0.4001567 | -0.519271753 |
| 116033 | -0.180197294 | -0.569312346 |
| 116410 | -0.3545862 | -0.323701253 |

| HIP | NLTE K | NLTE Correction |
|---|---|---|
| 116421 | -0.178366728 | -0.427481781 |
| 116478 | -0.037217528 | -0.316332581 |
| 116740 | 0.164313469 | -0.344801583 |
| 116906 | -0.207455482 | -0.576570535 |
| 117320 | 0.129997019 | -0.359118033 |
| 117364 | -0.069064706 | -0.398179758 |
| 117526 | 0.157955684 | -0.251159369 |
| 117627 | -0.096955045 | -0.276070098 |
| 117880 | 0.047936394 | -0.521178658 |
| 117902 | 0.067417446 | -0.321697606 |
| 117961 | 0.10600892 | -0.333106132 |
| 118010 | -0.045754986 | -0.454870039 |
| 118115 | -0.018064164 | -0.387179217 |
| 118141 | -0.249129567 | -0.61824462 |
| 118143 | -0.054729709 | -0.303844761 |