
Wesleyan University

Collision Ahead: Probing a Mixing Zone in the Local Interstellar Medium

by

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*Reach me down my Tycho Brahé,—I would know him when we meet,
When I share my later science, sitting humbly at his feet;
He may know the law of all things, yet be ignorant of how
We are working to completion, working on from then till now.*

— SARAH WILLIAMS, *The Old Astronomer*

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Why?

Contents

1	Introduction	1
1.1	Solar and Stellar Winds	2
1.2	The Heliosphere	2
1.3	The Interstellar Medium	4
1.3.1	The Local Bubble and Local Interstellar Medium	4
1.3.2	Nearby Clouds	5
1.4	Colliding Clouds and the Future Path of the Sun	7
1.5	Overview	7
2	Observations and Data	9
2.1	Observing in the Ultraviolet	9
2.1.1	Ultraviolet Spectroscopy	11
2.1.2	<i>Hubble Space Telescope</i>	14
2.1.3	Goddard High Resolution Spectrograph (GHRS)	16
2.1.4	Space Telescope Imaging Spectrograph (STIS)	17
2.1.5	Mikulski Archive for Space Telescopes	20
2.1.6	Future of UV Spectroscopy	20
2.2	Target Stars and Observation Program	21
2.3	Observations	24

2.4	Data Processing	25
3	Fitting and Data Analysis	29
3.1	Flux Background	30
3.2	LISM Component Fitting	33
3.2.1	gismfit Input Files	36
3.2.2	Additional considerations for HI	38
3.3	Error Analysis	39
3.4	Fit Results	40
3.4.1	HD 73752	40
3.4.2	HD 52698	42
3.4.3	HD 57095	44
3.4.4	HD 27274	44
3.4.5	A note on collaboration	47
3.5	Final Fit Parameters	50
4	Results	52
4.1	Cloud Assignments	52
4.1.1	HD 73752	54
4.1.2	HD 52698	55
4.1.3	HD 57095	56
4.1.4	HD 27274	56
4.1.5	HD 166620	57
4.1.6	HD 2151	58
4.2	Temperature and Turbulence	58
4.2.1	HD 73752	59
4.2.2	HD 52698	61

4.2.3	HD 57095	63
4.2.4	HD 27274	64
4.3	Neutral Hydrogen Column Densities	66
4.4	Depletion	67
4.5	Heliospheric Absorption	70
5	Discussion	72
5.1	Comparison to LISM Aggregate	72
5.2	Comparison to Dynamical Model	79
5.3	Previously Known Cloud Properties	84
5.4	Do we see signs of mixing?	88
5.5	LISM towards HD 166620 and HD 2151	90
6	Conclusions	92
6.1	Conclusions	92
6.2	Future Work	93
A		97
A.1	A Searchable LISM Database	97
A.2	Getting Started	97
A.3	Tips and Tricks	99
	Bibliography	101

Chapter 1

Introduction

*I shall start with the sun, since we
believe . . . that it is the source of
energy for all phenomena observed in
the earth, and . . . for all the churning
that apparently occurs in
interplanetary space . . .*

EUGENE PARKER

When the Earth's nightly rotation points us away from the Sun, and we stare out at the tiny points of light filling the sky, every one a potential Sun of its own, we cannot see the vast expanse of space between us and the stars. To the naked eye, one star looks very much like another, with only minor differences in color and brightness, and on a clear cold night, it might feel like there is nothing but void separating us from these other worlds. But the path the light of the stars has taken to reach us is far more complicated than a straight shot through empty space.

Between our solar system and all other stars, we are surrounded by the interstellar medium (ISM), composed of warm (~ 8000 K), partially ionized clouds of low-density material. Every time we look outside our solar system, we are looking through these clouds of the ISM. These invisible clouds are not undetectable; when studied at the right wavelengths, they leave "shadows," or fingerprints of

absorption, on the emission spectra produced by the light of the stars beyond. It is the goal of this work to take these spectral shadows, and use them to characterize the clouds of plasma responsible for creating them.

1.1 Solar and Stellar Winds

Our story begins very close to home, with our own Sun. Responsible for the light and heat that enables all life, our Sun is a moderately sized, moderately cool, main-sequence star of spectral type G2V, approximately 4.6 billion years old (A. Bonanno et al. 2002). As the Sun rotates, a stream of plasma is released into space, forming the solar wind.

The solar wind varies throughout the Sun's 11-year activity cycle, as well as in response to discrete spontaneous events such as solar flares and coronal mass ejections. The solar wind comes in two speeds: the fast solar wind at about 700 km s^{-1} , and the slow solar wind at about 400 km s^{-1} .

This region dominated by the solar winds is called the *heliosphere*. The analogous structures around other stars are called *astrospheres*. Stellar winds and astrospheres will be discussed in further detail in Chapter 4.

1.2 The Heliosphere

Figure 1.1 shows an artist's rendition of our local interstellar environment, situated between our Sun and other stars, on a logarithmic distance scale. As we move away from the Sun and towards the outskirts of the Solar System, we first encounter the *termination shock*, where the solar wind speed drops suddenly. At the edges of the heliosphere, the solar wind reaches and begins to interact with the local interstellar medium (LISM) altering its shape and size, moving at a speed

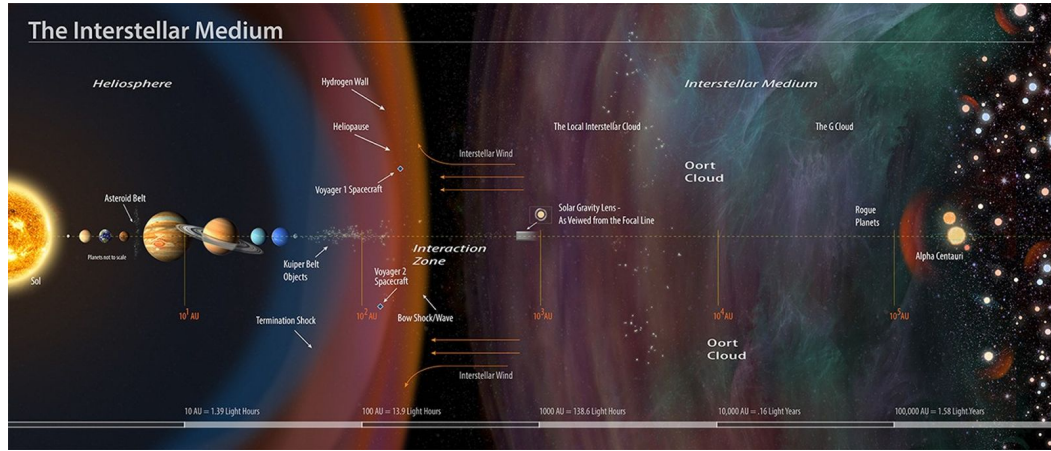


Figure 1.1 An illustration of the interstellar medium, on a logarithmic distance scale. Credit: Charles Carter/Keck Institute for Space Studies.

of about 23 km s^{-1} (D. J. McComas et al. 2012). This shift from solar wind to interstellar material is called the *heliopause*. Beyond the heliopause, we begin to truly encounter the interstellar medium. We continue on in this way for some time until the entire situation is repeated in reverse as we approach another star’s astrosphere.

The size of the heliosphere changes in relation to the balance of pressure between the LISM and the solar wind (H.-R. Müller et al. 2006; M. Opher et al. 2024). At various points in the Sun’s history, the heliosphere may have been compressed to a radius as close as the orbit of the Earth, leaving the outer planets exposed to interstellar material (M. Opher et al. 2024). Presently the heliosphere extends about 120 au in the direction of the Sun’s motion, as determined when the space probes Voyager I and II crossed the heliopause in 2012 and 2018 respectively (D. A. Gurnett et al. 2013; E. C. Stone et al. 2019). In the opposing direction, the heliosphere consists of a longer tail that may extend for thousands of au, like that created behind a boat moving through calm water (N. V. Pogorelov et al. 2025).

1.3 The Interstellar Medium

The interstellar medium (ISM) is a varied and dynamic environment occupying the space between stars, filled with gas and dust. The material in this area is refreshed and disturbed by stellar explosions, and is recycled into later generations of stars.

1.3.1 The Local Bubble and Local Interstellar Medium

The Local Bubble is a nearby cavity in the interstellar dust surrounding the Sun of about 50×100 pc (P. C. Frisch & D. G. York 1983). The plasma inside this bubble is extremely low-density with an electron volume density between $0.05 - 0.21 \text{ cm}^{-3}$, but relatively warm, with a temperature of about 6,700 K (P. C. Frisch & D. G. York 1983; P. C. Frisch et al. 2011).

The Local Bubble was likely caused by a supernova, driving material outwards. The Local Bubble is surrounded by a shell of cooler gas and dust. This shell of cooler, denser material is the site of most nearby star formation with C. Zucker et al. (2022) finding that every nearby molecular cloud (< 200 pc of the Sun) is on the boundary of the Local Bubble's shell. The ISM contains other bubbles or cavities, which may also be sites of star formation (R. Lallement et al. 2003).

Within the Local Bubble, the characteristics of the local interstellar medium (LISM) can be attributed to a few dozen clouds of material at different locations and distances, possessing their own flow velocities. J. L. Linsky et al. (2022) found significant inhomogeneities in temperature and turbulence in the clouds that make up the local environment. The aggregate properties of the nearby cluster of interstellar clouds are summarized in Table 1.1 (P. C. Frisch et al. 2011).

Table 1.1. Characteristics of Local Interstellar Clouds Outside Heliosphere

Property	Value
Temperature	$6,680 \pm 1,490$ K
Turbulent Velocity	2.24 ± 1.03 km s ⁻¹
Log mean HI column density	17.18 ± 0.70 cm ⁻²
Cloud diameter	~ 2.5 pc
Cloud mass	$0.32M_{\odot}$

Note. — Adapted from P. C. Frisch et al. (2011).

1.3.2 Nearby Clouds

Through mapping absorption lines towards nearby stars, upwards of fifteen LISM clouds have been identified within 100 pc (S. Redfield & J. L. Linsky 2008). The boundaries of these clouds are shown in Figure 1.2.

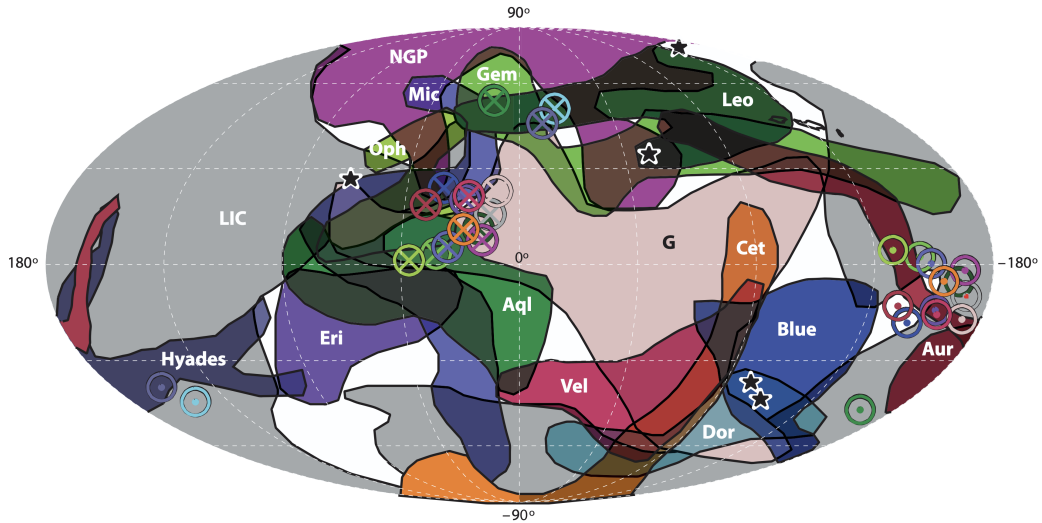


Figure 1.2 Map of all fifteen clouds identified by S. Redfield & J. L. Linsky (2008), shown in Galactic coordinates. The upwind velocity direction for each cloud is indicated with an X, and the downwind direction with a dot. Figure from P. C. Frisch et al. (2011).

Table 1.2. Existing Surveys of the LISM

Authors	Year	Number of Sight Lines	Ions Used
Nisak, A. et al.	2025	36	Mg II, Fe II, Mn II
Linsky, J. et al.	2022	28	Mg II, Fe II, H I, D I, C II, O I
Wood, B. et al.	2021	9	Mg II, Fe II, H I
Malamut, C. et al.	2014	34	Mg II, Fe II, Mn II
Redfield, S. & Linsky, J.	2008	–	all existing measurements
Redfield, S. & Linsky, J.	2004	33	D I, C II, N I, O I, Al II, Si II
Redfield, S. & Linsky, J.	2002	24	Mg II, Fe II, Ca II

The Local Interstellar Cloud (LIC) surrounds the Sun itself and takes up a tremendous portion of the visible sky. The G cloud is also highly visible, but concentrated towards the Galactic center. As the clouds may be at different distances along the line-of-sight, overlapping in this “map” does not necessarily indicate overlapping in physical space.

Since the properties of the LISM differ along different observational sight lines, it is advantageous to obtain measurements in as many different directions as possible, in order to determine a more complete map of the local region. The most straightforward technique is to observe a background star, and to examine absorption deviations in its spectrum that can be attributed to line-of-sight absorption by the LISM. This technique has been performed in multiple earlier surveys, summarized in Table 1.2, resulting in measurements for at least 130 sight lines.

A sight line typically traverses one or more clouds, with C. Malamut et al. (2014) finding an average of 1.5 cloud components per sight line.

1.4 Colliding Clouds and the Future Path of the Sun

The Sun is moving through interstellar space at a velocity of 19 pc Myr^{-1} (M. Opher et al. 2024). While initially it was thought that the Sun resided near the edge of the Local Interstellar Cloud, *in situ* measurements of the temperature and velocity of interstellar helium gas within the heliosphere showed properties that were instead much closer to the average temperature and velocity between the LIC and G (i.e., $(\text{LIC}+\text{G})/2$) than either individual cloud, indicating that the Sun is actually located in a transitional region between the two clouds (E. Möbius et al. 2004; S. Redfield & J. L. Linsky 2008). P. Swaczyna et al. (2022) showed that the LIC and G clouds appear to be in the process of colliding, and the Sun’s velocity vector is pointed further into this region.

How would we know if a given sight line traverses the collision zone? Cloud collisions are associated with higher-than-expected column densities as the light moves through a greater volume of material, broader absorption in spectral lines, and increased temperature and turbulence (P. Swaczyna et al. 2022; J. L. Linsky et al. 2022). We might also expect to see absorption at velocities intermediate to the velocities of the colliding clouds, as in the case of the interstellar helium velocity in the heliosphere (S. Redfield & J. L. Linsky 2008).

1.5 Overview

In this thesis, I will examine spectral features of the LISM towards six nearby stars, four of which fall into a projected cloud collision zone, and present an analysis of the physical properties of the LISM in this region.

In Chapter 2, I detail the observational data used in this thesis. In Chapter 3, the fitting and analysis procedure is described at length. In Chapter 4, my results for the fitting and analysis of six sight lines towards local stars are presented. In Chapter 5, I expand my interpretation of these results. In Chapter 6, I summarize my conclusions and their implications for future work. In Appendix A, a searchable database consisting of sight lines within 100 pc with analyzed or unanalyzed ISM observations is described.

Chapter 2

Observations and Data

*There is a crack, a crack in everything:
that's how the light gets in.*

LEONARD COHEN

The data used in this thesis are a set of high-resolution ultraviolet spectra obtained with *Hubble Space Telescope (HST)*. Absorption line spectroscopy allows us to determine important physical characteristics of the LISM along the line-of-sight to nearby stars, either through direct measurement (velocity, column density), or derivation (such as turbulent velocity, temperature, depletion). The UV part of the electromagnetic spectrum contains many resonance lines that are strong enough to detect LISM absorption. In order to accurately distinguish between individual velocity components (representative of distinct LISM clouds), high-resolution observations are necessary. At this moment in time, and for the foreseeable future, *HST* is the only facility capable of making these measurements.

2.1 Observing in the Ultraviolet

Life as we know it is possible on Earth partly because of the protective cocoon of Earth's atmosphere. This barrier between surface and space provides stable temperatures, air to breathe, and defense against bombardment with space debris. At certain wavelength windows corresponding to visible light and part of the

radio spectrum, Earth's atmosphere is largely transparent, allowing us to perform astronomical science observations from the surface. However, the atmosphere also

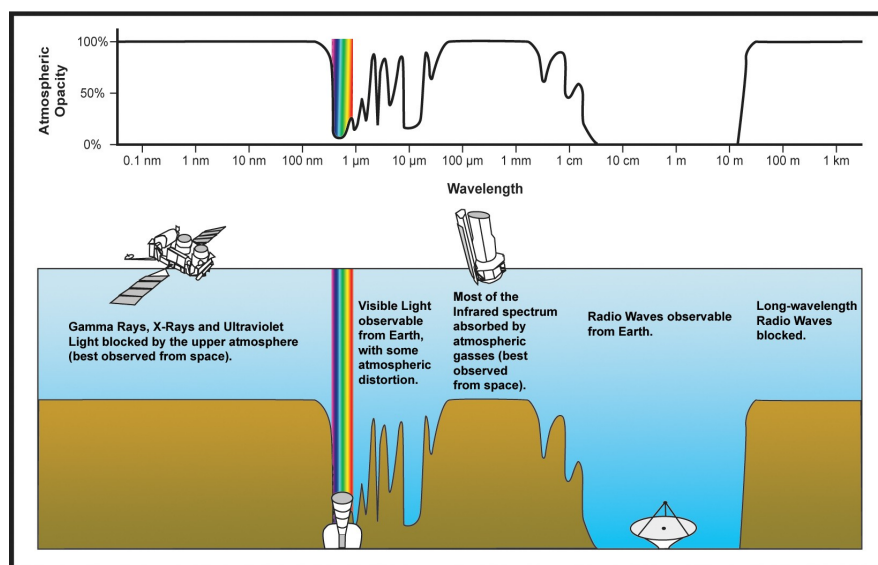


Figure 2.1 Atmospheric Electromagnetic Opacity (Image: NASA). At very short wavelengths, the atmosphere blocks nearly 100% of the light; an example of a space telescope that operates in this regime is the *Chandra X-ray Observatory*. In the visible part of the spectrum, nearly all of the light makes it through the atmosphere, allowing large optical telescopes like the Vera Rubin Observatory to operate. At the longer, infrared wavelengths, the opacity increases again, forcing observatories like the *James Webb Space Telescope* to operate in space. The atmosphere is transparent to a large part of the radio regime, allowing telescopes like the Atacama Large Millimeter/submillimeter Array to operate from the ground.

prevents certain wavelengths of light from reaching the surface. This selective transparency is illustrated in Figure 2.1. Where the atmospheric opacity is 100%, such as at very short wavelengths, light at these wavelengths is blocked. Other parts of the spectrum have somewhere between full and zero opacity, allowing some percentage of the light to penetrate the atmosphere. While this protects us from exposure to harmful X-rays and ultraviolet radiation, it also means that in order to observe at these wavelengths, we must wiggle out from Earth's atmosphere and into space. This is part of why telescopes such as *Hubble Space Telescope* and

James Webb Space Telescope could not be built to operate on Earth.

2.1.1 Ultraviolet Spectroscopy

Spectroscopy is a technique that involves spreading out light to examine its brightness and properties as a function of wavelength, creating a *spectrum*. For a hot source like a star, this spectrum is in the form of a smooth curve that peaks at a wavelength corresponding to its surface temperature. Hotter objects emit more of their light at shorter wavelengths, and vice versa. This type of continuous spectrum forms the basis for *absorption line spectroscopy*. When light from a continuous source travels through a cooler layer of gas, the light interacts with those atoms and is sometimes absorbed by them. When an atom absorbs light, an electron moves to a higher energy level; conversely, when it emits light, it loses energy and moves to a lower energy level. These electron transitions within the atom can only occur at specific energy levels, releasing or absorbing a photon of a specific wavelength. Absorption creates dips in the spectrum that occur at those very particular wavelengths, depending on the elemental composition of the gas. The wavelength of an absorption feature can therefore be used to identify the elements in the source and intervening gas (J. Tennyson 2005). We can also determine the velocity of the material through the Doppler effect, which shifts the observed wavelength.

Ultraviolet Interstellar Lines

Many of the atomic transitions that correspond to elements in the LISM occur in the ultraviolet (UV) part of the electromagnetic spectrum, as shown in Figure 2.2. Mg II h & k (2803 Å and 2796 Å) and Fe II (2586 Å and 2600 Å) are near-

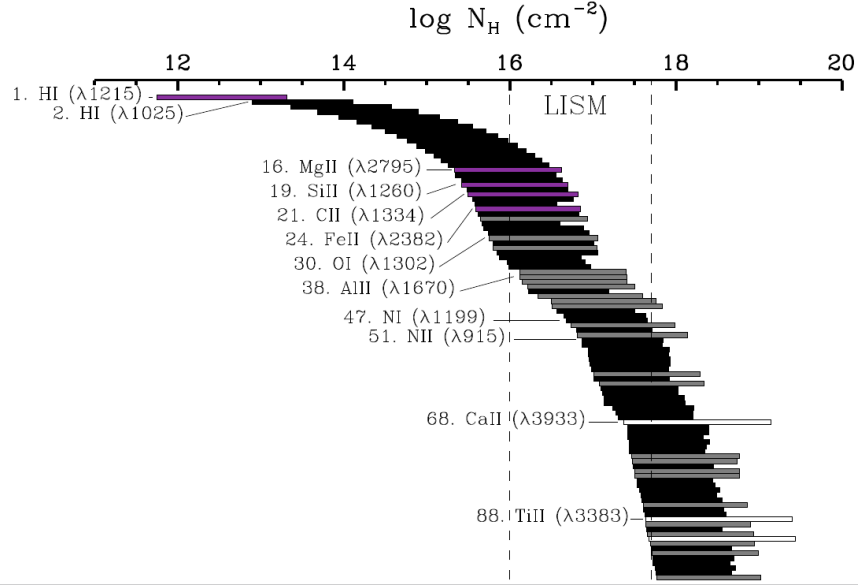


Figure 2.2 Modified from S. Redfield (2006). Arrangement of 100 strongest ground state transitions in order of increasing hydrogen column density. The dashed lines indicate the typical LISM column densities; outside this region, the transition is either not strong enough for absorption to be detected, or saturated and optically thick. In order to be detectable and useful for our analysis, the transition must fall between the two dashed lines. White bars occur in the optical (3000–10000 Å); gray bars occur in the UV (1200–3000 Å); and black in the FUV (900–1200 Å); purple bars are UV and FUV lines used in this thesis.

ultraviolet (NUV) emission lines produced in the upper chromospheres of stars. They are also both doublets (when a single transition produces two lines at a fixed wavelength difference), which means observing them gives us twice as many chances to observe the LISM. An example of a Mg II 2796 Å profile is shown in Figure 2.3, demonstrating the background stellar emission and absorption from the LISM.

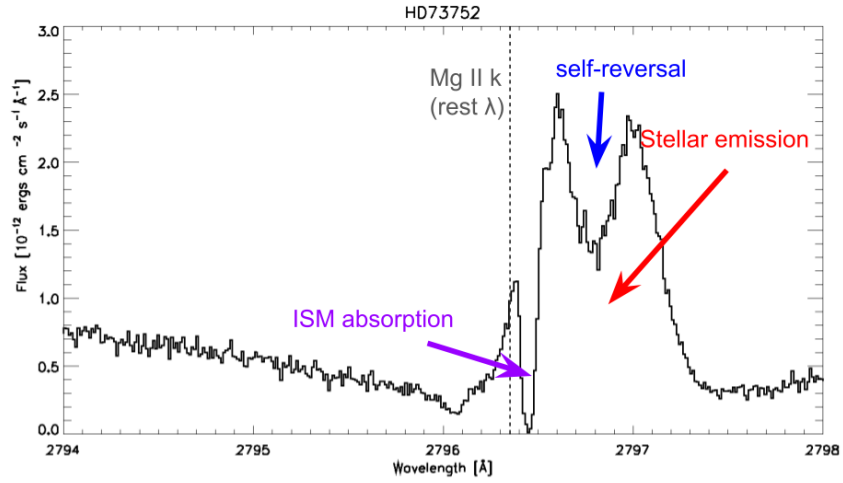


Figure 2.3 Example Mg II spectrum from HD73752. The overarching flux emission is from the star (red). When stimulated enough, Mg II can exhibit a self-reversal (absorption on itself) at its central wavelength (blue). The cloud of LISM between us and the star is responsible for the other absorption at 2796.5 Å (purple). This spectrum is redshifted (moved to longer wavelengths) as the star recedes from us. The vacuum rest wavelength is shown in dotted gray.

Si II (1260 Å) and C II (1334 Å) are far-ultraviolet (FUV) emission lines also common in stars. Hydrogen Lyman- α (1215 Å) is also produced in stellar chromospheres, and has a similar emission profile to Mg II. Ly- α is also of particular interest because it can be used to detect heliospheric and astrospheric absorption.

As already stated, most UV light is blocked by Earth's atmosphere. Therefore, in order to study these lines, we must get around the atmosphere.

2.1.2 *Hubble Space Telescope*

The challenges of observing at ultraviolet wavelengths were well-known by the middle of the twentieth century. The astrophysicist Lyman Spitzer, Jr. first began theorizing about the benefits of a telescope in space in a 1946 (then classified) military report titled “Astronomical Advantages of an Extra-Terrestrial Observatory” (C. Gainor 2020; N. Roman 2001; L. Spitzer 1990). Such a telescope could avoid the atmospheric turbulence that plagues ground-based images, while also avoiding the opaque layer of atmosphere that prevented observation of the whole spectrum. It was unclear at the time whether or not an observatory could be free-standing or connected to a space station of some kind. Advances in rocketry later meant that such a telescope could be revisited, allowing for instruments that could be serviced and replaced by astronauts.

The next few decades saw many short-lived astronomical spacecraft, such as NASA’s Orbiting Solar Observatories (OSOs) and Orbiting Astronomical Observatories (OAOs). These provided crucial technical information about the challenges of space-based astronomy, such as the need for reliable pointing and space-stable detectors (N. Roman 2001).

There was also a rapidly changing sociopolitical scene for astronomers to navigate. No longer was astronomy solely a privately funded endeavor sponsored by wealthy eccentrics or universities; in the post-World War II climate, scientists were considered highly desirable national resources, and the U.S. government was interested in funding research that could be used to establish dominance in science and space. The National Science Foundation was established in 1950, and NASA itself opened its doors in 1958, providing the first layer of infrastructure for government-funded space science (N. Roman 2001).

By the early 1970s, NASA had started to work on plans for the Large Space Telescope (LST), an observatory project that would later become the *Hubble Space Telescope*. Such a large and expensive project, however, depended on congressional support, which varied wildly throughout the planning phase. Numerous plans were drawn up to reduce the cost of the telescope, while trying to preserve its science goals. These arguments over funding and scale eventually led to the inclusion of the European Space Agency (ESA) in the project in 1977 (C. Gainor 2020). From this moment on, *HST* was an international endeavor, and construction of the telescope continued.

Due to the long timescale of the project, scientists and engineers knew that they were building an observatory whose instruments would likely be surpassed by advances in optics and detection during the mission lifetime. This meant that they were able to plan for the instruments in sequence: an initially approved spectrograph launched with *HST*, for example, could be followed by an even better replacement spectrograph whose development and construction could continue while the rest of the telescope was being built, and installed during later planned servicing missions.

Nearly fifty years after that initial report, *HST* was launched in 1990 by the space shuttle *Discovery*. *HST* is now in low-Earth orbit, about 515 km above the surface. It completes one orbit of the Earth every 95 minutes. This proximity to Earth is what allows for the telescope to be serviced by astronauts, a feature that quickly became necessary as the first images from *Hubble* were returned.

Although the first images were better than comparable ground-based images, close inspection revealed persistent optical flaws, and the problem was eventually identified as spherical aberration. Further investigation revealed that an unauthorized adjustment during the building of the null corrector resulted in a primary

mirror that was precisely ground to the wrong shape (C. Gainor 2020).

The flaw in *HST*’s mirror initially damaged public confidence in the costly, highly anticipated mission (C. Gainor 2020). Engineers, scientists, and program directors deliberated for months to determine a solution. Ultimately, the decision was made to correct the optical path to compensate for the spherical aberration by inserting an array of tiny mirrors that would unfold within the telescope to slightly redirect the light as it moved towards each instrument, much like a specialized pair of “eyeglasses” (N. Roman 2001; C. Gainor 2020). The Corrective Optics Space Telescope Axial Replacement (COSTAR) was installed during Servicing Mission 1 in 1993. Later instruments could be designed to compensate for the aberration without relying on this corrective mechanism. The adjustments that were made allowed *HST* to collect decades of high-quality data that has been responsible for fundamental advances in the field of astronomy and our understanding of the physical universe.

2.1.3 Goddard High Resolution Spectrograph (GHRS)

The High Resolution Spectrograph¹ (GHRS) was launched with *HST* and provided the bulk of early spectroscopic data from the telescope. It operated in the ultraviolet, with a spectral range of 1,150–3,200 Å. Since UV radiation is mostly blocked by Earth’s atmosphere, nearly all astronomy in this regime must be performed from space.

Unlike the imaging cameras on *HST*, GHRS was not strongly affected by the spherical aberration in *HST*’s main mirror and was able to perform science observations prior to the installation of COSTAR. Spectroscopic data from GHRS was used widely in early studies of the LISM, providing a wealth of informa-

¹with the later prefix of “Goddard”

tion about our nearest interstellar environment that was previously inaccessible. While GHRS observations are not the primary focus of this thesis, they laid the groundwork for later LISM analysis.

GHRS operated until one week before it was due to be removed and replaced in Servicing Mission 2, in 1997.

2.1.4 Space Telescope Imaging Spectrograph (STIS)

Due to the delays caused by the spherical aberration and its correction with COSTAR, the Space Telescope Imaging Spectrograph (STIS) was not installed until *HST* Servicing Mission 2, allowing it to replace GHRS in 1997. Figure 2.4 shows astronaut Steven Smith carefully removing the refrigerator-sized, 318 kg (700 pounds) spectrograph from the Space Shuttle *Discovery* prior to installing it alongside the new Near Infrared Camera and Multi-Object Spectrometer (NICMOS).

This instrument greatly expanded *HST*’s spectrographic capabilities to 1,150–10,300 Å, allowing observations from the ultraviolet to the near-infrared portion of the electromagnetic spectrum (S. Medallion & D. Welty 2023). STIS also has the ability to collect approximately 30 times more spectral data than GHRS by detecting along the entire slit, rather than a point. This was a monumental advance for studies of the LISM, because it meant that many LISM absorption lines now appear in observations of nearby stars taken for any other research purpose: the LISM is observed essentially “for free” during another proposal’s observing time. The available data for LISM studies is no longer limited to LISM-specific observations, as it was with GHRS. (To enable easy identification of suitable observations that may not yet be analyzed for the LISM, we created a database

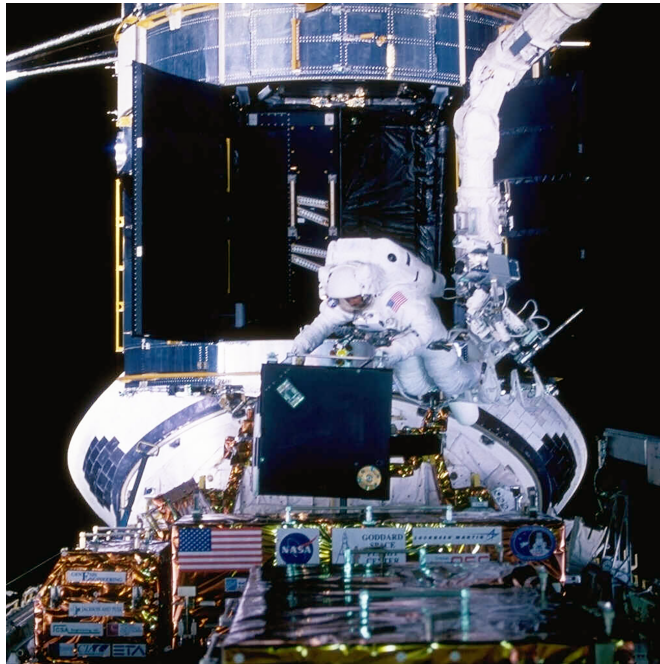


Figure 2.4 Astronaut Steven Smith removes STIS from the Space Shuttle *Discovery* prior to installation (Image: NASA).

noting which observational sight lines have and have not been analyzed, which is discussed in Appendix A in further detail.)

After 7.5 years of data collection, STIS experienced a power failure in 2004. STIS was repaired in 2009, during the fifth and final servicing mission (SM-4), and has been in operation since.

Multi-Anode Microchannel Array (MAMA) detectors

STIS contains two detectors specifically designed to operate at UV wavelengths, as well as a charge-coupled device (CCD). The Multi-Anode Microchannel Array (MAMA) detectors are specially treated with materials to make them more UV sensitive. They work by using a photocathode to convert incident photons into electrons that are funneled into an array of specially designed channels to be amplified and counted.

One detector allows for FUV observation and the other for NUV observation. Both detectors have a 25×25 arcsecond field of view (S. Medallon & D. Welty 2023).

Gratings

STIS is equipped with a number of gratings designed for observation at different wavelengths and resolutions, including ten first-order gratings for long-slit spectroscopy, four echelle gratings, and a prism setting (S. Medallon & D. Welty 2023).

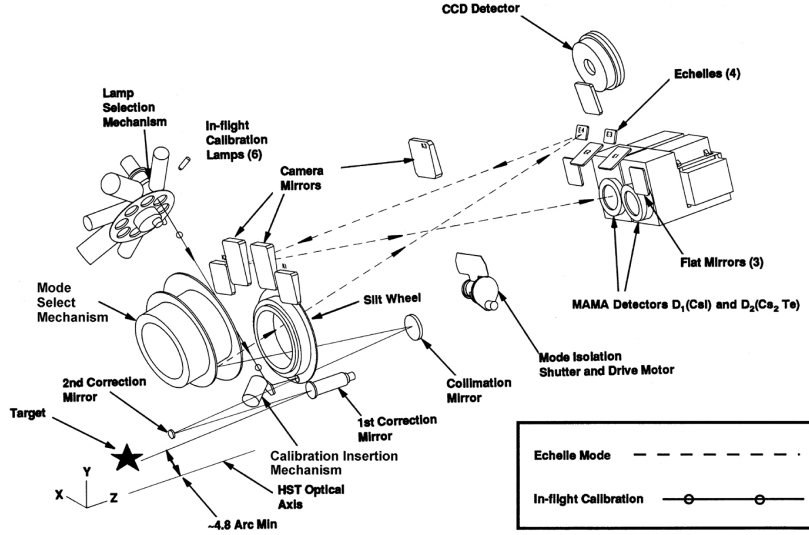


Figure 2.5 Optical path diagram for STIS (STIS Instrument Handbook, S. Medallon & D. Welty (2023)).

The data for this thesis were obtained with the high- and medium-resolution echelle gratings, E230H (spectral resolution $R = \lambda/\Delta\lambda \sim 114,000$) and E140M ($R = \lambda/\Delta\lambda \sim 45,800$), visible as the echelles in the optical path diagram in Figure 2.5. Both gratings have a spatial plate scale of $0.029''/\text{pix}$ and a spectral plate scale of $0.047''/\text{pix}$.

2.1.5 Mikulski Archive for Space Telescopes

Once data from *HST* is sent to Earth, it heads to the Space Telescope Science Institute (STScI) for processing and storage. As more space missions resulted in large datasets, it became clear that a more centralized archive would streamline data storage and access for astronomers, and in 1997 the Multimission Archive at STScI (MAST) was born. This publicly accessible archive allows scientists all over the world, regardless of institutional affiliation, to view, download, and analyze the data collected by *HST*. Astronomers aren't limited to data that they propose for themselves; archival data reanalyzed by new eyes and new ideas continues to contribute to the advancement of our scientific understanding. In 2012, the archive was renamed for U.S. Senator Barbara Mikulski, in recognition of her advocacy for space telescopes and astronomy (MAST 2026).

2.1.6 Future of UV Spectroscopy

HST is a testament to the value of moving slowly and fixing things. Every carefully selected redundancy in engineering, every future-focused decision made by an administrator, every maintenance space walk, and every vote for a budget bill worked together to lengthen the lifespan of *HST*, making it the longest-operating space telescope. At the time of this writing, *HST* is still operational, far exceeding its initial operating lifespan of fifteen years. Every year that *HST* is able to collect data provides several times more years of analysis through archival research, which since 2007 has accounted for more than half of all papers published with *HST* data (C. Gainor 2020).

HST is one of the chief accomplishments of NASA's Science Mission Directorate. The level of cooperation between NASA and ESA necessary to protect

this shared investment benefited international scientific relations. The science performed with *HST* data has revolutionized our understanding of the universe and our place in it, and *HST* proved the feasibility of a large, multi-instrument space-based observatory. *HST* paved the way for other large-scale space telescopes, like *Chandra X-ray Observatory* and *James Webb Space Telescope*, which operates primarily in the infrared. But no mission can last forever, and this Great Observatory will eventually need to be retired. Current estimates place a potential atmospheric re-entry date in the early 2030s unless *HST* receives an orbital boost.

However, at the time of this writing, there are no plans to replace the ultraviolet capacity of *HST*. As proposed NASA science funding in the U.S. continues to decline year after year, administrators will have to make difficult decisions about which missions receive priority (C. Dreier 2026). There is no other observatory currently capable of performing these observations. This uncertainty for the future of high-resolution UV spectroscopy means that now is the time to collect as many observations as we can, in order to preserve our ability to study the LISM for years to come.

2.2 Target Stars and Observation Program

The six target sight lines are all towards cool stars within 20 pc of the Sun. Four sight lines (HD 73752, HD 52698, HD 57095, and HD 27274) were selected due to their position in the projected interaction zone between the LIC and G clouds (P. Swaczyna et al. 2022). Two sight lines (HD 166620 and HD 2151) were added to my analysis later and are included here for contrast with the mixing-zone sight lines. Figure 2.6 shows the location of all target sight lines in the context

of previously analyzed LISM sight lines and current cloud boundaries for the LIC and G clouds.

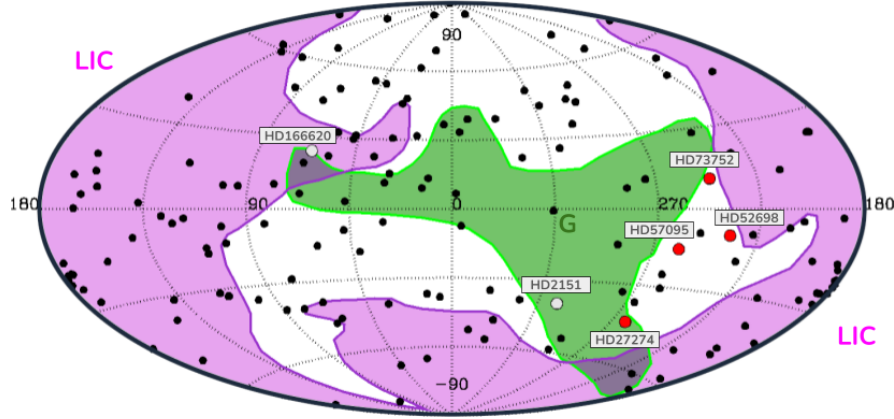


Figure 2.6 Location of existing sight lines with LISM analysis in galactic coordinates (black); new sight lines that fall in the projected LIC-G Cloud interaction zone (red); new sight lines not in interaction zone (gray). The known boundaries of the Local Interstellar Cloud (LIC) and G Cloud are shaded purple and green respectively. For clarity, other LISM clouds are not included in this figure.

Figure 2.7 shows that the four primary sight lines fall in the densest part of the projected mixing zone, where we would expect to see the greatest overlap between the two clouds. It is important to note that this projection relies on the treatment of the two clouds as rigid spheres, an assumption that is useful for modeling, but which almost certainly does not describe the actual physical shape of the interaction zone, which we would expect to show much more variation. However, this simplification allows us to identify the general region of the sky where cloud mixing could be occurring. If this region represents an overlap of multiple clouds, we might expect to see higher column densities and broader line widths as the light traverses more physical material with higher degrees of turbulence.

The basic stellar parameters are summarized in Table 2.1. All six of the stars are cool, main-sequence stars with the hottest star being HD 57095. Sight line HD 73752 is a cool star binary.

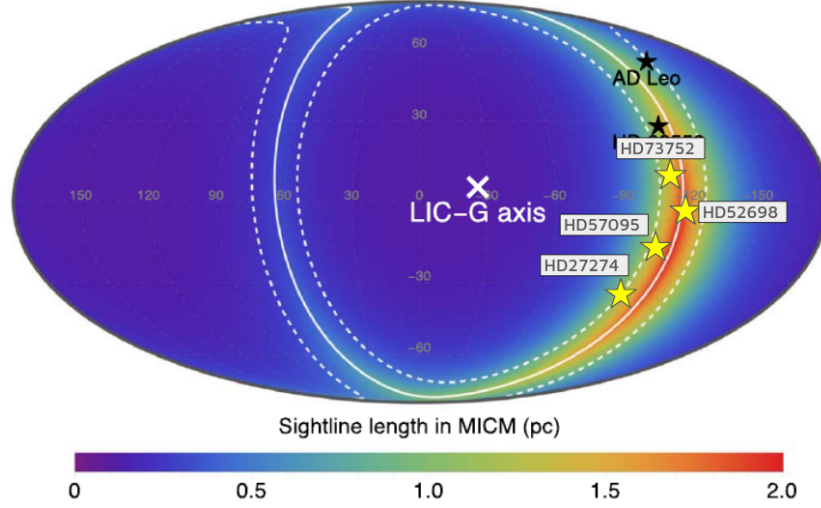


Figure 2.7 Figure modified from P. Swaczyna et al. (2022): Mixed Interstellar Cloud Medium (MICM) depth as seen from the Sun. The direction along the line connecting the centers of the LIC and G clouds is shown by a white x. Sight lines in this thesis are marked by yellow stars; greater sight line length indicates more overlap between the LIC and G colliding clouds.

Table 2.1. Stellar Parameters and Predicted Cloud Velocities

Star	l (deg)	b (deg)	Distance (pc)	Spectral Type	Stellar v_r (km s ⁻¹)	Predicted v_{LIC} (km s ⁻¹)	Predicted v_{G} (km s ⁻¹)
HD 73752	245.9	11.3	19.6	G3V+K0V	52.13	10.66	10.97
HD 52698	237.3	-9.5	14.7	K1V	12.42	15.52	18.24
HD 57095	258.3	-15.3	14.6	F5V	59.0	8.61	10.22
HD 27274	262.3	-44.4	13.0	K4.5Vk	-23.09	8.02	11.46
HD 166620	65.3	24.2	11.1	K2V	-19.32	-13.36	-16.60
HD 2151	304.8	-39.8	7.5	G0V	23.1	-4.83	-4.07

Note. — Spectral type, distances, and stellar radial velocities from SIMBAD; cloud velocity predictions from S. Redfield & J. L. Linsky (2008). Sight lines above the horizontal line are in the projected LIC-G mixing zone.

Table 2.2. HST/STIS Observations

Star	Date	Start Time	Grating	Wavelengths (Å)	Exposure Time (s)	PI
HD 73752	2024-10-08	01:09:52	E230H	2574-2846	1647	Redfield
	2024-10-08	02:28:40	E140M	1140-1735	2598	Redfield
	2024-10-08	04:03:09	E140M	1140-1735	2618	Redfield
	2024-10-08	05:37:48	E140M	1140-1735	2618	Redfield
	2024-10-08	07:12:27	E140M	1140-1735	2618	Redfield
HD 52698	2024-08-28	01:45:25	E230H	2574-2846	1651	Redfield
	2024-08-28	03:04:17	E140M	1140-1735	2298	Redfield
	2024-08-28	04:38:50	E140M	1140-1735	2622	Redfield
HD 57095	2024-08-02	13:00:46	E230H	2574-2846	1681	Redfield
	2024-08-02	14:07:38	E140M	1140-1735	2632	Redfield
	2024-08-02	15:42:14	E140M	1140-1735	2652	Redfield
HD 27274	2024-06-21	08:26:00	E230H	2574-2846	1695	Redfield
	2024-06-21	09:39:55	E140M	1140-1735	2648	Redfield
	2024-06-21	11:14:53	E140M	1140-1735	2668	Redfield
HD 166620	2025-05-18	08:15:32	E230H	2574-2846	1543	Wood
HD 2151	2025-04-18	05:10:51	E230H	2574-2846	1325	Wood

Note. — Observational parameters from MAST.

2.3 Observations

All six targets were observed by STIS with the high-resolution E230H grating to capture Mg II and Fe II in the near-UV, and by the medium-resolution E140M setting to observe the far-UV (D I, C II, O I, Si II, and Lyman α). The observational parameters are summarized in Table 2.2. The data were successfully collected in 2024–2025 with no instrumental problems noted. The wide spectral range and high resolving power of STIS made it particularly well-suited for this project.

2.4 Data Processing

All data collected by *HST* eventually becomes publicly available (sometimes after a brief proprietary period), as it is produced with the public's money. But before the data are ready for download from the public archive, it must undergo some initial reduction.

After observations are taken with STIS, they must be calibrated and processed. This process is performed by the Space Telescope Science Institute (STScI) using the calibration pipeline `calstis`. The STIS pipeline combines data from multiple exposures and calibrates them before release, resulting in science-ready output files. Initially, the data are in the form of two-dimensional echelle spectra as seen

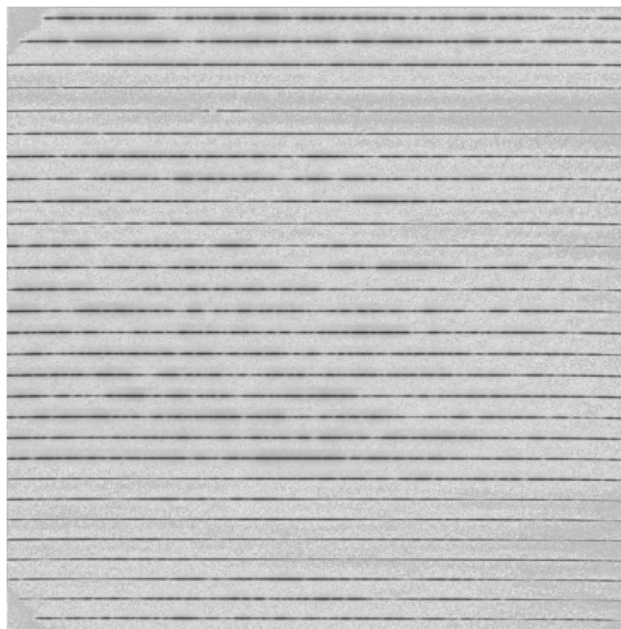


Figure 2.8 Raw exposure of β Hyi (HD2151) from the NUV-MAMA detector showing stacked echelle orders.

in Figure 2.8.

We are working with one-dimensional extracted spectra. There are three pri-

mary arrays we are concerned with: wavelength, flux, and error. The wavelength array gives the calibrated wavelength in units of Angstroms. The flux array for the `.fits` files gives the calibrated flux in units of $\text{ergs s}^{-1}\text{cm}^{-2}\text{\AA}^{-1}$, and the default error array gives a vector including the propagated background noise, dark noise, Poisson noise, and readnoise. The data file consists of separate rows for each echelle order, which includes a small overlap, meaning that a line of interest may appear in two echelle orders. Table 2.3 lists many of the lines of interest and their accompanying locations in the data files. For the best signal-to-noise ratio, it is preferential to select the order where the line of interest appears closer to the beginning of the wavelength array than the end. An example of a 1D spec-

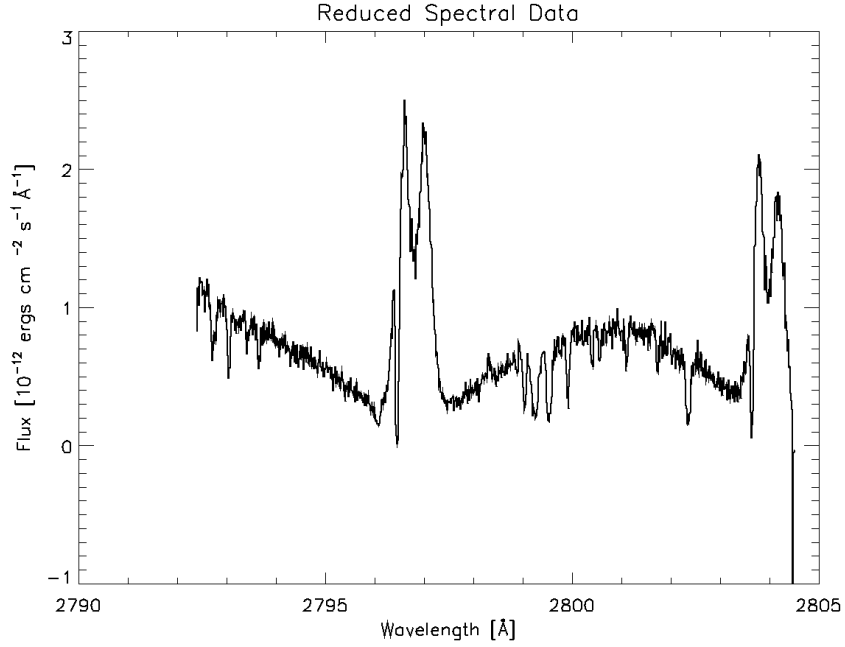


Figure 2.9 Spectrum from HD 73752 in the region of Mg II h and k.

trum where the line of interest crosses two echelle orders to accommodate both Mg II 2796 Å and 2803 Å can be seen in Figure 2.9; since the 2803 Å part of the spectrum approaches the end of the array, this means we need to splice the array

together with the next echelle order from the same observation to create a single array that includes the best data for both halves of a doublet.

The FUV observations taken with the E140M grating are lower signal and lower resolution. They were taken as a series of 2–4 observations on different orbital passes with *HST*, and must be co-added in order to boost signal before any further analysis occurs.

At this point, we are ready to fit our data.

Table 2.3. Selected LISM Lines in the Ultraviolet

Line	Rest λ (Å)	Gamma (γ) 10^8 s^{-1}	Oscillator Strength (f) 10^{-1}	Echelle Order
D I	1215.3376	6.270	2.777	36
	1215.3430	6.270	1.388	36
C II	1334.5323	2.88	1.28	25
N I	1199.5496	4.07	1.32	37
	1200.2233	4.02	0.869	37
	1200.7098	4.00	0.432	37
O I	1302.1685	5.65	0.48	27,28
Al II	1670.7886	13.9	17.4	2,3
Si II	1190.4158	40.8	2.92	38
	1193.2897	40.7	5.82	38
	1260.4221	29.5	11.8	31
	1304.3702	10.1	0.863	27
	1526.7066	11.3	1.33	11
C IV	1548.204	2.643	1.899	10
	1550.781	2.628	0.9475	9
S II	1250.578	0.463	0.0543	32
	1253.805	0.462	0.109	32
	1259.518	0.462	0.166	32
N V	1238.821	3.391	1.56	33
	1242.804	3.356	0.777	33
Si III	1206.500	24.8	16.3	36
Si IV	1393.7602	8.80	5.13	20
	1402.7729	8.62	2.54	19
Mg II	2803.5315	2.595	3.058	3,4
	2796.3553	2.625	6.155	4
Fe II	2600.1729	2.70	2.39	25
	2586.6500	2.72	0.691	26,27

Note. — Rest wavelengths, γ , and oscillator strength from D. C. Morton (2004); typical echelle order from STIS E230H/E140M

Chapter 3

Fitting and Data Analysis

*...those who can find
a tunnel with no light at the end
of it and hold it up like a telescope
to show that the darkness contains
many truths that can bring the light
to its knees.
Grief astronomer,
adjust the lens, look close. Tell us
what you see.*

ANDREA GIBSON

Our general approach for analyzing UV spectra of the LISM follows that described in S. Redfield & J. L. Linsky (2002), and used in many further studies of the LISM. A brief description follows. High resolution spectra are collected towards nearby stars at wavelengths corresponding to stellar chromospheric emission lines. The stellar background forms our continuum. Absorption from the LISM along the line-of-sight is fit using Voigt profiles, representing the convolution of a Lorentzian distribution (natural broadening) and a Gaussian distribution (thermal broadening), and may consist of multiple different velocity components corresponding to multiple LISM clouds. These absorption lines may be broadened (due to both thermal and non-thermal effects), saturated, or blended with one an-

other, increasing the difficulty of fitting. Some stellar emission profiles (such as Mg II) exhibit strong self-reversals near their line center; some lines are weaker than others; sometimes the radial velocity of the star aligns with the LISM absorption. Since absorption from the same cloud of material is expected to occur at the same velocity regardless of ion, we can use multiple measurements across the UV spectrum to constrain our fitting parameters for each component. The fitting parameters we obtain are then used to derive physical properties of the LISM, as explored in Chapter 4.

3.1 Flux Background

We begin by looking at our highest-resolution, highest-signal data: the Mg II 2796 Å lines. The four mixing zone sight lines are shown in Figure 3.1. Before we

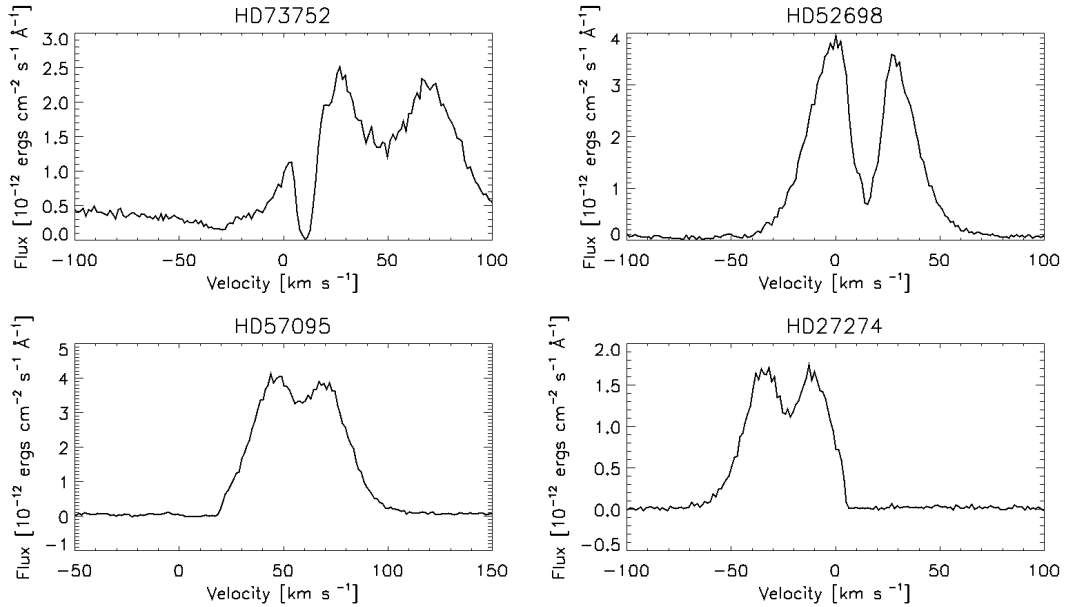


Figure 3.1 Mg II profiles for the four mixing zone sight lines, in velocity space normalized to the rest wavelength of Mg II 2796 Å.

can identify LISM absorption components, we need to establish what the under-

lying stellar emission would look like without any intervening clouds of material. This results in the creation of a *flux background*, an array of smoothed flux values. There are multiple methods for creating the flux background using the program

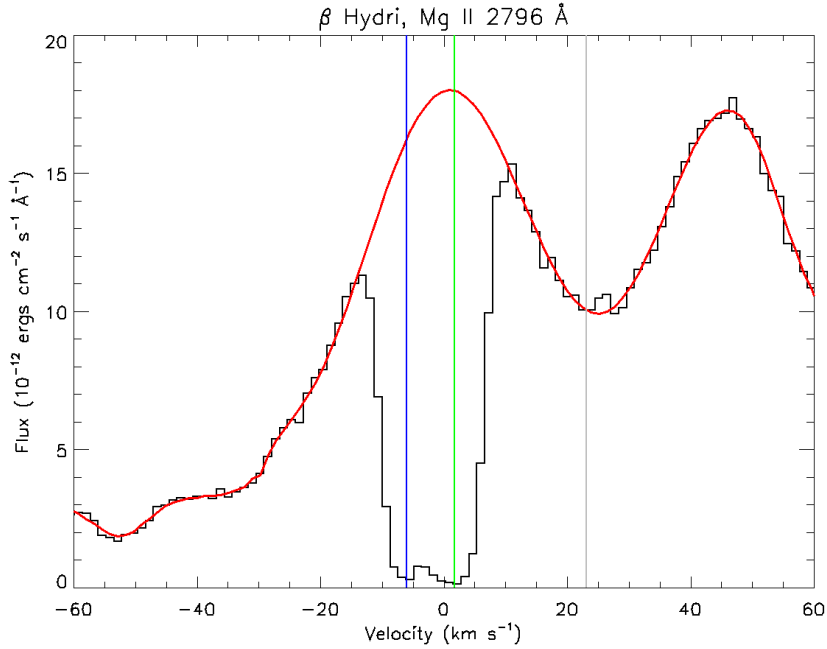


Figure 3.2 The Mg II emission line, centered at the radial velocity of β Hyi. The received flux is shown in black, transformed to velocity-space. The star’s radial velocity is represented by the gray vertical line at approximately 23 km s^{-1} . The estimated stellar continuum is overplotted in solid red. The blue and green lines denote estimated velocities of two LISM absorption components at approximately -6 and 2 km s^{-1} respectively.

`mkfb.pro` written by S. Redfield. The most straightforward technique when the LISM absorption is easily visible involves selecting regions of the profile on either side of the interstellar absorption, and fitting a polynomial that includes the intervening region. An example of this is shown in Figure 3.2.

However, if the absorption is more subtle, it may be helpful to take advantage of the relative symmetry of the emission line, and create a flux background by “flipping” the profile across the line center to more readily view the absorption,

and stitching together a smoothed composite between the unabsorbed portion and its mirrored counterpart. This technique is particularly useful when the absorption is at the wings of the emission, although it can also identify asymmetries in absorption overlapping with the self-reversal. An example of this is shown in Figure 3.3.

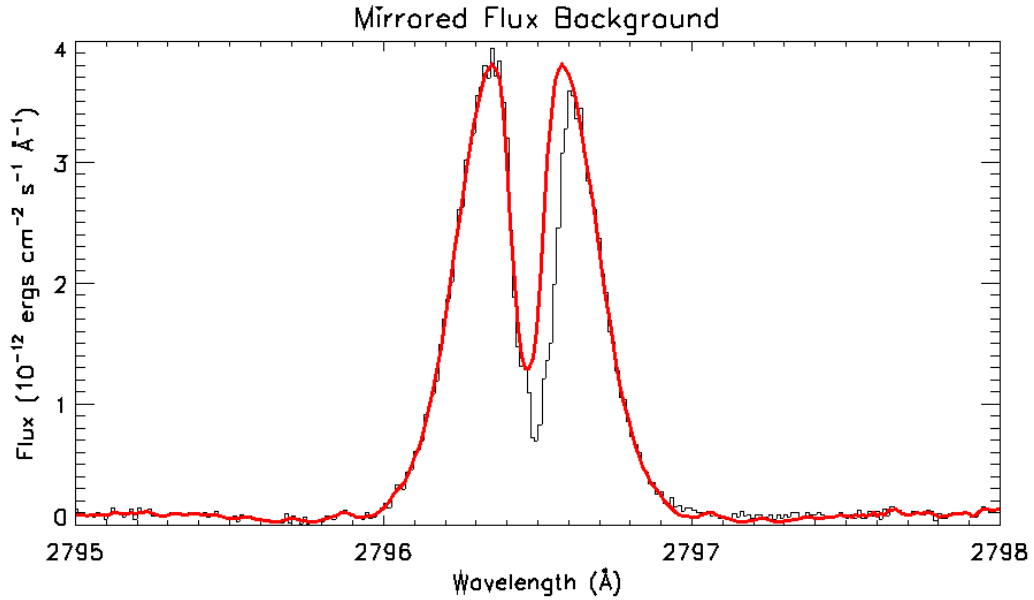


Figure 3.3 An example of a flux background for Mg II for HD52698 created using the “mirroring” or “flipping” technique. There is a deep central self-reversal that is closely aligned to the location of the LISM absorption.

All four sight lines (shown in Figure 3.1) exhibit a central self-reversal in the Mg II doublet. This self-reversal is caused by an inversion in temperature in the chromosphere of the star, causing Mg II to absorb on itself, beginning at the line center. When the LISM absorption overlaps with the self-reversal, as with HD 52698, it can be difficult to accurately distinguish the depth of the absorption relative to the depth of the self-reversal.

When creating a combined flux background for both lines in a doublet that may be separated by several Å, we also want to be careful that the background

continuum is not weighted preferentially by the fitting algorithm during the simultaneous fit. To avoid this, we multiply the values of the error in the separation region by 100 to ensure that the fitting routine properly fits to the line profiles themselves. An example of this method is shown in Figure 3.4. The creation of

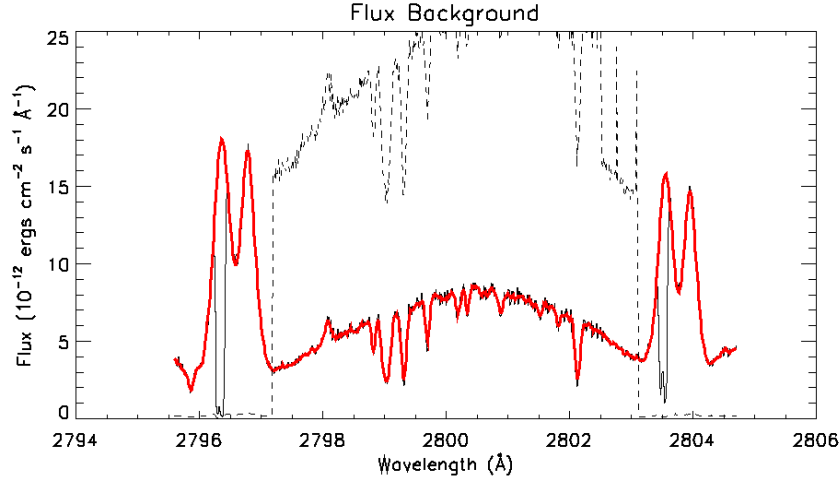


Figure 3.4 Flux background (red) for Mg II h & k for HD 73752 with absolute error values overplotted (dashed). The error values for the wavelength region between the two halves of the doublet have been artificially inflated to prevent the background continuum from dominating the fit.

the flux background is the most subjective step in the fitting process, and often requires multiple iterations, which can be compared throughout the later fitting steps. We implement other checks for consistency (fitting multiple lines, fitting doublets individually and simultaneously, evaluating how much parameters change between variations in flux background), but it is important to keep this in mind when faced with unexpected values.

3.2 LISM Component Fitting

To model the LISM absorption, we treat each absorption feature as a combination of one or more Voigt profiles dominated by their Gaussian components (as

would be expected in the optically thin regime for unsaturated absorption). A Gaussian function of the form

$$f(x) = a \exp \left(-\frac{(x - b)^2}{2c^2} \right),$$

allows us to parameterize the shape of the absorption. In this form, a corresponds to the column density parameter (or the amplitude of the Gaussian), b corresponds to the velocity parameter (or the relative offset of the centroid of the Gaussian), and c is related to the Doppler width of the line (or the width of the Gaussian).

LISM component fitting was performed with S. Redfield and B. Wood’s routine `gismfit.pro`. After a suitable flux background is loaded, this routine takes an input file of starting parameters and iterates on them to find the best fit as determined by minimizing χ^2 . The starting parameters are manually adjusted and the process is repeated until the fit matches the data well.

To guide our starting guesses, we compare the spectra for each sight line with the projected cloud velocities predicted by a kinematic model created by S. Redfield & J. L. Linsky (2008) (described in further detail in Chapter 4). Figure 3.5 shows the MgII spectrum for HD 73752 with the star’s radial velocity and predicted velocities of nearby clouds overplotted. The close alignment in velocity between the visible absorption feature and the predicted cloud velocities (dashed and solid lines near 10 km s^{-1}) is a strong indicator that one or more of these clouds is the source of the absorption. However, there may be absorption at velocities that do not correspond to any predicted clouds; or there may be no immediately apparent absorption. The model is only a starting place, but it does not constrain our fits.

These starting guesses for cloud velocities are entered into the input file for

`gismfit.pro`, along with information about the specific atom from Table 2.3.

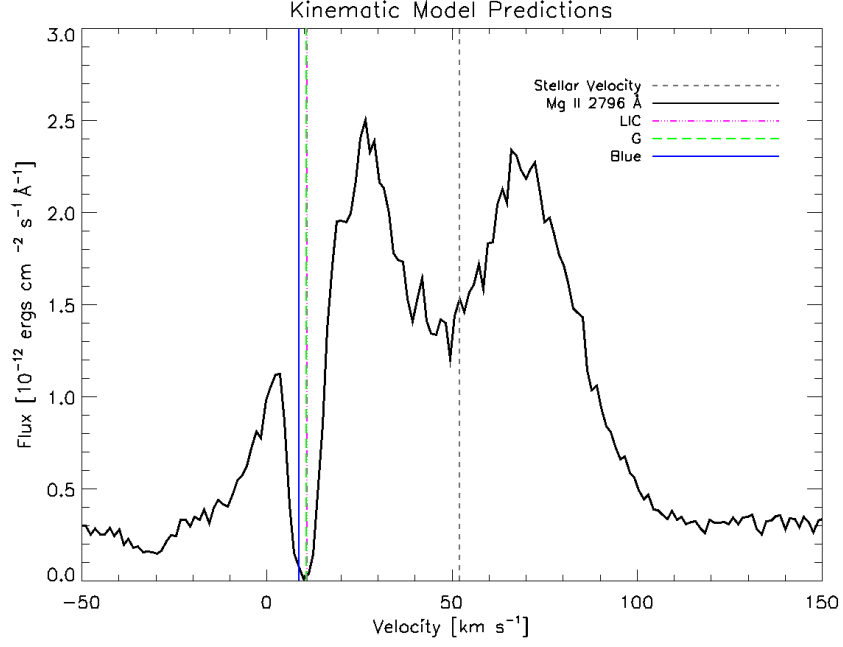


Figure 3.5 The Mg II 2796 Å spectrum for HD 73752. The stellar radial velocity aligns with the central self-reversal (gray dashed line), and the predicted velocities for the LIC, G, and Blue clouds are plotted with vertical lines. In this case, all three clouds have predicted velocities (10.67, 10.97, and 8.63 km s⁻¹, respectively) that are quite close to each other, and align well with the absorption feature, making it particularly difficult to distinguish between the LIC and G clouds.

3.2.1 gismfit Input Files

The input file provides information about the species of interest and starting parameters. An annotated example of an input file is shown in Figure 3.6. Initially,

```

1 /path/to/desired/text/log/filename.fit ; text description
2 /path/to/desired/output/arrays/filename.dat ; IDL arrays of fit
3 2796. ; minimum wavelength for plot
4 2798. ; maximum wavelength for plot
5 y ; y/n specify flux range to plot
5a 0 ; minimum flux to plot
5b 3E-12 ; maximum flux to plot
6 0 ; background level
7 2796.5 ; minimum wavelength for ISM fit
8 2797.0 ; maximum wavelength for ISM fit
9 y ; y/n line spread function to consider
9a /path/to/line/spread/function.dat ; filename of LSF
10 0 ; number of emission features to fit to the data
11 1 ; number of absorption features to fit to the data
   ; gamma and oscillator strength (f) for component 1
11a 2.625E+08 6.155E-01
   ; log abundance (H=12), depletion, rest wavelength for component 1
11b 7.58 0. 2796.3543 0.0001
   ; guess for central wavelength, width, log column density for
   component 1
11c 2796.458 3.0 13.0
12 y ; n/y freeze any parameters
12a n ; freeze column density
12b n ; freeze central wavelength
12c n ; freeze Doppler parameter
13 y ; y/n run Monte Carlo error estimation
13a 100 ; number of Monte Carlo runs
14 y ; y/n create a log file

```

Figure 3.6 A sample input file for fitting a single absorption feature in a Mg II profile. All wavelengths are given in Angstroms.

we fit each sight line with one absorption component. Then, we add additional

components as supported by f-testing. If there is difficulty in determining good starting guesses (i.e., `gismfit` will not run or converge), an alternative program (`gismforce.pro`) can be used with the same input file to display a fit that matches the starting guesses exactly. This allows for fine-tuning of the starting guesses.

For doublets like Mg II and Fe II, we improve our results by fitting each half of the doublet independently, and then simultaneously, resulting in three independent measurements. We then take a weighted mean of the three to arrive at our final fitting parameters. An example of a satisfactory fit is shown in Figure 3.7. This is a two component fit where each component (dashed lines) has a physically reasonable Doppler parameter and column density, the differences between the data and the total fit (red solid line) are minimized, and the parameters were consistent with the other individual and the simultaneous fit.

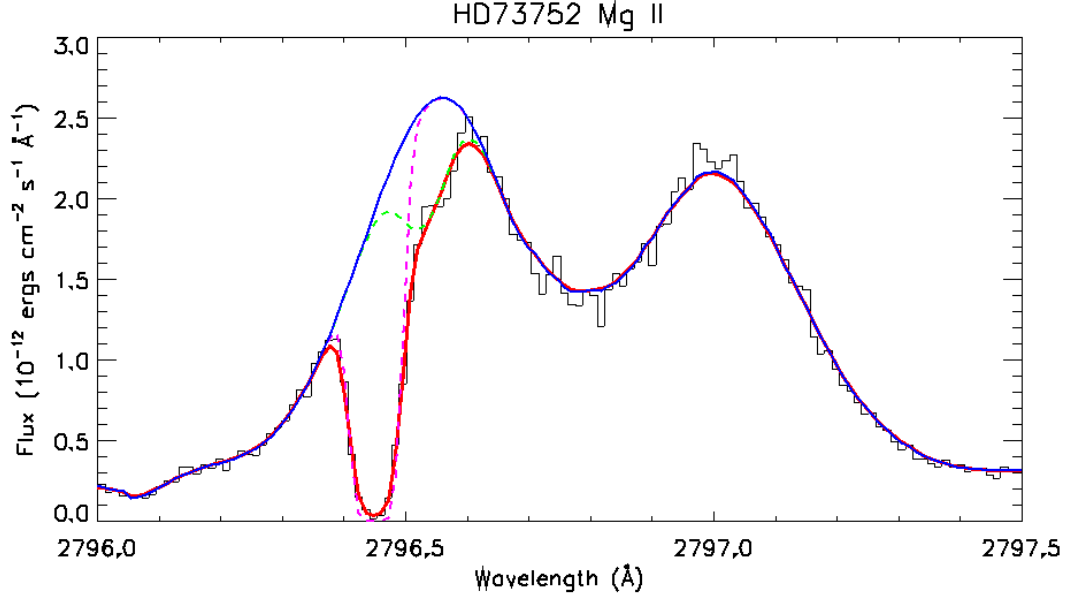


Figure 3.7 Fit for HD 73752 using `gismfit`. The flux background is shown in blue, individual fitting components are shown with dashed lines, and the total fit is shown in solid red, which closely matches the data.

For the lower-resolution, lower-signal FUV data, we sometimes need to use

Table 3.1. Weighted Mean of LISM Parameters in the Aggregate

Ion	Doppler Parameter Weighted Mean	Standard Deviation	Column Density Weighted Mean	Standard Deviation
D I	7.65	0.67	13.01	0.25
C II	3.64	0.81	13.82	0.60
O I	3.24	0.70	14.00	0.44
Mg II	2.79	0.55	12.45	0.33
Si II	2.70	0.34	13.08	0.34
Fe II	2.13	0.25	12.45	0.24

Note. — Adapted from Table 10 in S. Redfield & J. L. Linsky (2004).

our knowledge of the LISM conditions obtained with the NUV data to arrive at a fit that is self-consistent. This may include freezing the velocity difference Δv between LISM components; freezing the ratio of the column densities or b -values; or in severe cases, sacrificing some of the interpretable information by freezing parameters to match the LISM aggregate. The LISM aggregate parameters were obtained via S. Redfield & J. L. Linsky (2004) and are summarized in Table 3.1.

3.2.2 Additional considerations for HI

Fitting for HI Lyman- α (1216 Å) is more involved than the other species involved in this study. The data for Lyman- α are contaminated by geocoronal emission from Earth’s hydrogen envelope, as detailed in Figure 3.8. This emission occurs at the center of a very broad, saturated absorption feature. Before fitting, the geocoronal emission must be subtracted off. In order to reconstruct the flux background from the remaining data, it is helpful to consider the shape of the stellar continuum created for Mg II as a starting place. The creation of the flux background for Lyman- α is further complicated by the possibility of excess absorption from the interaction of the solar and stellar winds with the LISM at

their interface. This phenomenon is discussed in further detail in Chapter 4.

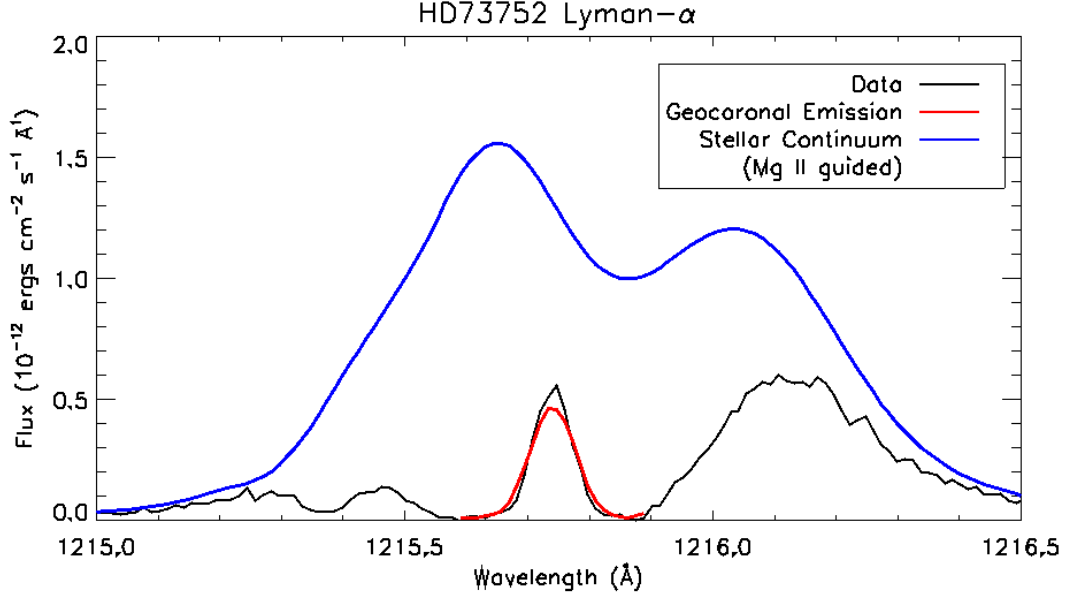


Figure 3.8 The Lyman- α profile for HD 73752. The stellar flux background, courtesy of B. Wood, is shown in blue. There is substantial broad absorption, primarily from the LISM. The geocoronal emission appears at the center of the absorption, and is highlighted in red, and must be removed before fitting the profile. There is also DI emission (and its own associated LISM absorption) around 1215.3 Å. If LISM fitting alone cannot account for the entirety of the absorption, the presence of astrospheric or heliospheric absorption may be considered.

3.3 Error Analysis

We expect that the systematic errors will outweigh the random errors throughout our analysis. To correct for instrumental broadening, the program `gismfit` takes into account the line spread function of STIS at the time the data was collected, and convolves it with the fit before final comparison with the data. This, combined with oversampling, allows us to gain sub-pixel resolution on the order of 0.3 km s⁻¹. As already stated, the flux background represents a systematic source of error in our fits. However, we aim to mitigate systematic sources of

error through the simultaneous fitting of the Mg II and Fe II doublets, which can reveal inconsistencies in the choice of stellar flux background that can then be corrected. To further reduce the systematic error on the fitting parameters, we use a Monte Carlo methodology to better estimate the errors. This process takes the fitted parameters from the actual dataset that were determined through χ^2 minimization, and randomly varies them to create a series of synthetic data sets. Then the χ^2 minimization is repeated on the synthetic datasets to determine the best-fit Monte Carlo parameters. The simulated error is determined by analyzing the distribution of the Monte Carlo parameters around the original parameters from the actual data set (W. Press et al. 2007). Ideally, we use 100 runs, but in cases where the fit has higher error, sometimes the Monte Carlo modeling will only converge with a lower number of runs, resulting in higher uncertainty in the final value.

3.4 Fit Results

I detected two velocity components in each sight line, corresponding to two interstellar clouds. This is consistent with the findings of S. Redfield & J. L. Linsky (2004) and C. Malamut et al. (2014) for sight lines towards stars at distances less than 20 pc. The fitting process is described in greater detail for each of the sight lines in the following subsections, and the final fit parameters are summarized in a table at the end of the chapter.

3.4.1 HD 73752

The data showed clear interstellar absorption at two velocities corresponding to nearby clouds (angular separation $\leq 20^\circ$). While the spectra for the first

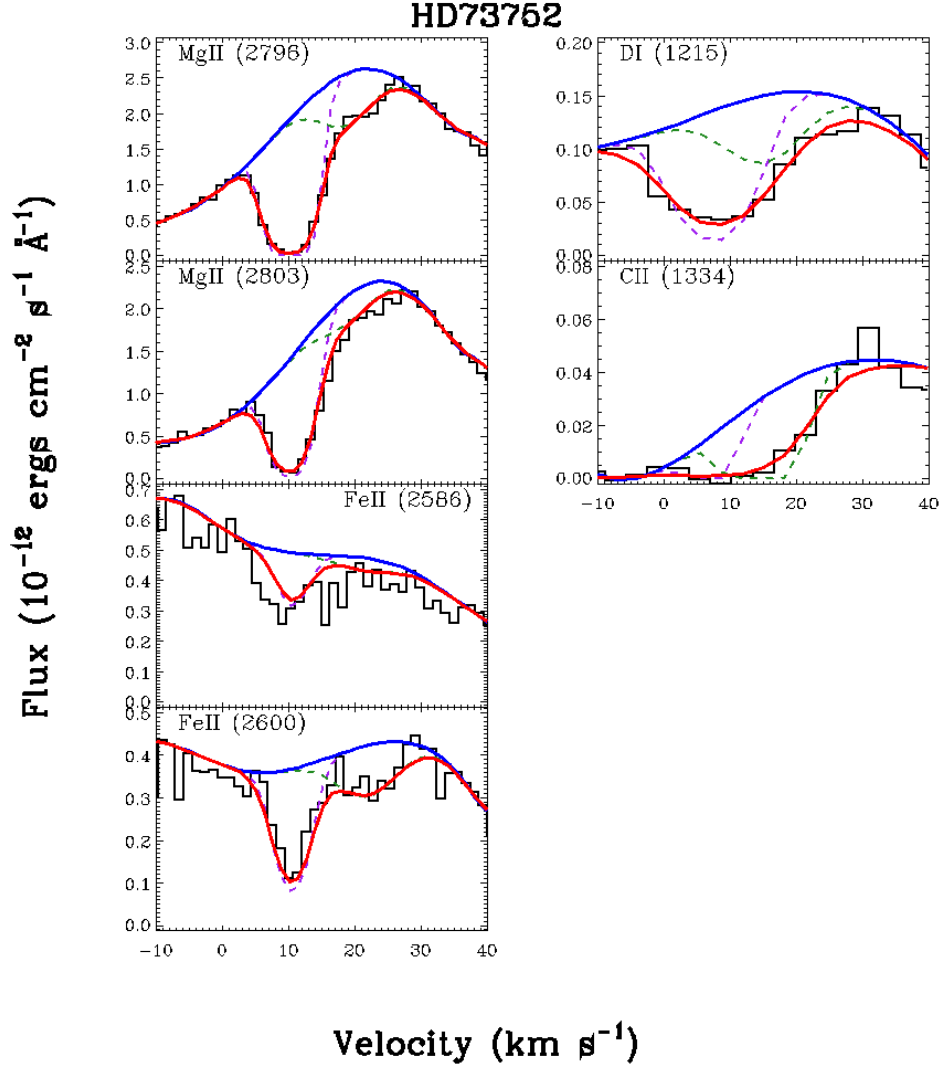


Figure 3.9 Final fits for HD 73752. The stellar emission estimate (“flux background”) is shown in solid blue; individual absorption components are shown with dashed lines; and the sum of the absorption components is in solid red. For Mg II and Fe II doublets, the simultaneous fits (where parameters are forced to be self-consistent between both halves of the doublet) are shown.

component were saturated in Mg II, the Fe II observations were not fully saturated, as shown in Figure 3.9, allowing us to obtain a column density. The central velocities for the two components in Mg II were identified at 10.346 ± 0.073 and $18.1 \pm 1.3 \text{ km s}^{-1}$, as shown in the top two panels of Figure 3.9.

Fitting the Fe II profiles presented a minor oddity: while very good fits were achieved when fitting the 2600 Å and 2586 Å lines separately, the central velocity of each absorption component was offset by approximately $2\text{--}4 \text{ km s}^{-1}$ between the two halves of the doublet. A satisfactory simultaneous fit was still achieved, with central velocities of 10.6 ± 1.1 and $21.7 \pm 2.2 \text{ km s}^{-1}$, but this is responsible for the slight visual discrepancy between the data and the fit for the 2586 Å line as seen in the third panel of Figure 3.9, and reflected in the higher uncertainty for the second component in particular. The final reported values for Mg II and Fe II parameters are the weighted mean of the two individual fits for each half of the doublet and the simultaneous fit.

The D I and C II fits for this sight line were fairly uncomplicated, and are shown in the right panels of Figure 3.9. Although the data is lower resolution than the NUV data and the absorption is blended, two components at velocities consistent with the Mg II velocities were detected.

3.4.2 HD 52698

This sight line was more challenging to fit, as the interstellar absorption lies closer to the center of the self-reversal. Use of the “mirroring” technique identified asymmetries in the Mg II profile that guided the creation of the flux background, as was seen in Figure 3.3. Once the flux background was created, the fits for Mg II were straightforward, and two components were identified at 15.10 ± 0.19

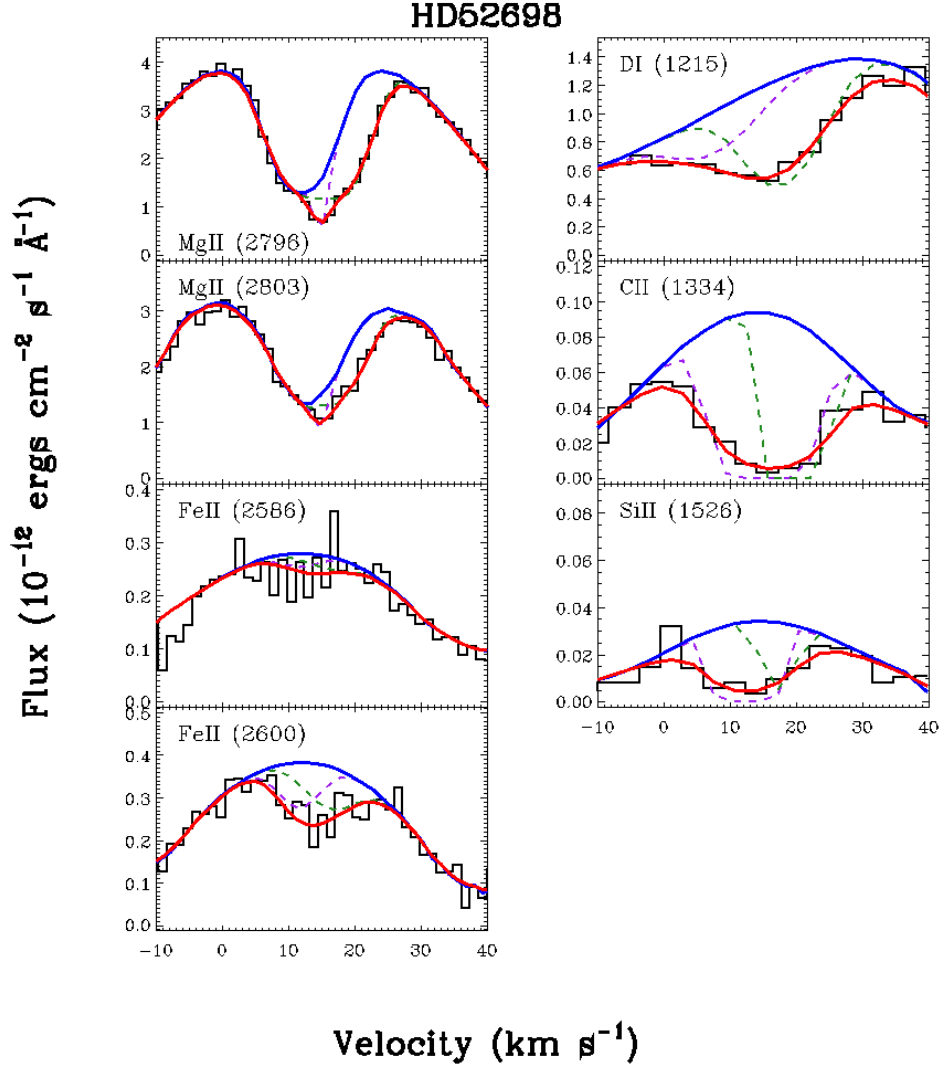


Figure 3.10 Final fits for HD 52698. The stellar emission estimate (“flux background”) is shown in solid blue; individual absorption components are shown with dashed lines; and the sum of the absorption components is in solid red. For Mg II and Fe II doublets, the simultaneous fits (where parameters are forced to be self-consistent between both halves of the doublet) are shown.

and $19.88 \pm 0.32 \text{ km s}^{-1}$ respectively, as seen in the first two panels of Figure 3.10.

For Fe II 2586 Å, there was considerable uncertainty in determining the central velocity of the components due to high noise and blended lines, as seen in the third panel of Figure 3.10. This is reflected in the final weighted fit velocities of 13.1 ± 1.6 and $19.9 \pm 3.9 \text{ km s}^{-1}$.

This sight line had detectable LISM absorption for three FUV ions as well, shown in the right panels of Figure 3.10. The profiles for C II, Si II and D I were fit with two components that agreed well with the velocities for Mg II, with the exception of component 1 in D I, which was centered at $7.0 \pm 3.3 \text{ km s}^{-1}$.

3.4.3 HD 57095

The interstellar absorption for HD 57095 is far from the line center, near the bluer wing of the emission. To create the Mg II flux background, the “mirroring” technique was used. This allowed for the detection of two components in Mg II at velocities of 6.15 ± 0.58 and $15.92 \pm 0.32 \text{ km s}^{-1}$. While the signal for Fe II is low, using the velocities associated with the Mg II observations as a starting place allowed us to detect similarly spaced absorption components in Fe II at 7.5 ± 1.7 and $14.6 \pm 1.0 \text{ km s}^{-1}$, as shown in Figure 3.11.

Unfortunately, we were unable to obtain an adequate D I fit for this sight line, which would prevent us from analyzing most of the physical properties of the LISM.

3.4.4 HD 27274

The interstellar absorption for HD 27274 is also far from the line center, in the redder wing of the emission. For Mg II, this merited a mirrored flux background.

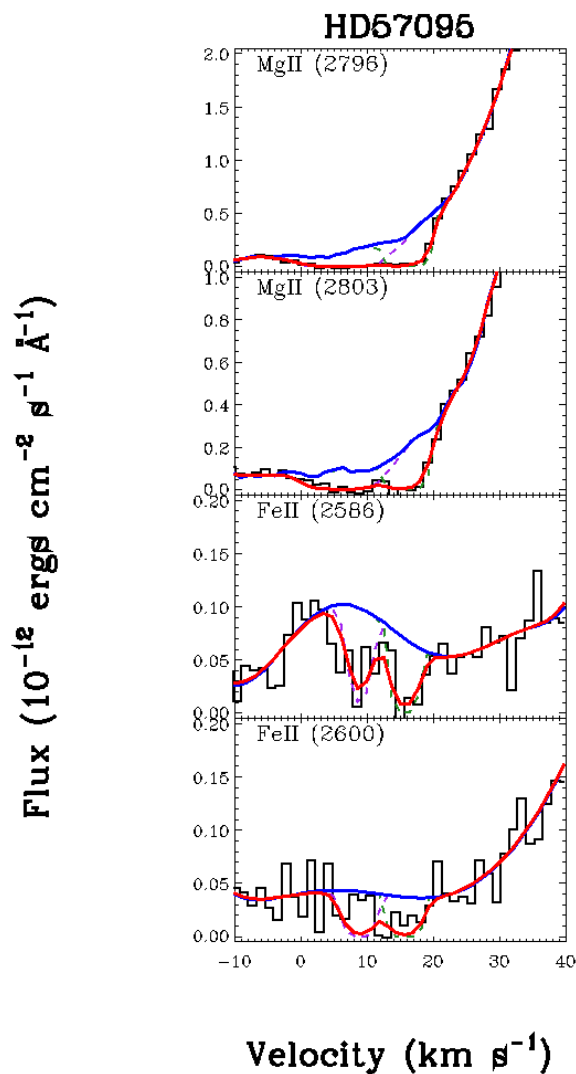


Figure 3.11 Final fits for HD 57095. The stellar emission estimate (“flux background”) is shown in solid blue; individual absorption components are shown with dashed lines; and the sum of the absorption components is in solid red. For Mg II and Fe II doublets, the simultaneous fits (where parameters are forced to be self-consistent between both halves of the doublet) are shown.

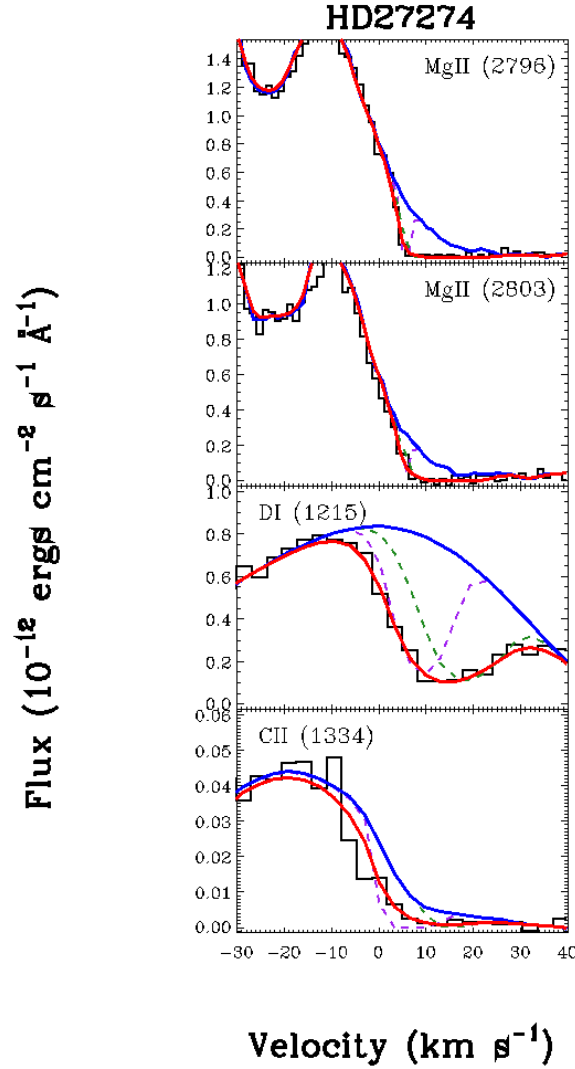


Figure 3.12 Final fits for HD 27274. The stellar emission estimate (“flux background”) is shown in solid blue; individual absorption components are shown with dashed lines; and the sum of the absorption components is in solid red. For Mg II doublet, the simultaneous fits (where parameters are forced to be self-consistent between both halves of the doublet) are shown.

Flipping a profile also helps us to identify if potential LISM absorption is too far removed from the line center to analyze. Due to low signal and considerable distance from the line center, there was no discernible Fe II absorption detected. In order to fit the C II absorption, the width of the second component had to be fixed to the LISM aggregate value.

As seen in Figure 3.12, we were able to detect two velocity components for Mg II at 7.1 ± 1.6 and 16.18 ± 0.73 km s⁻¹. These were consistent with the FUV fits for DI and C II, shown in the bottom two panels of Figure 3.12.

3.4.5 A note on collaboration

Early in my analysis of the four mixing zone sight lines, I was offered the opportunity to perform a very similar analysis for Brian Wood, a frequent collaborator of my advisor with expertise in stellar winds and astrospheres. I modeled the NUV LISM absorption for two additional sight lines not in the mixing zone. Later, B. Wood analyzed the H I Lyman- α absorption for the four mixing zone sight lines used in this thesis, and included in the table of final fit parameters at the end of the chapter.

Lyman- α Fits

The Lyman- α fits for all four mixing zones are shown in Figure 3.13, which was provided by B. Wood. With the wide, saturated absorption that is characteristic of these profiles, achieving a self-consistent fit requires fewer free parameters. It becomes very difficult, for example, to uniquely distribute the total absorption width between two or more components under these circumstances. B. Wood made the assumptions that the velocity separation and ratio between column

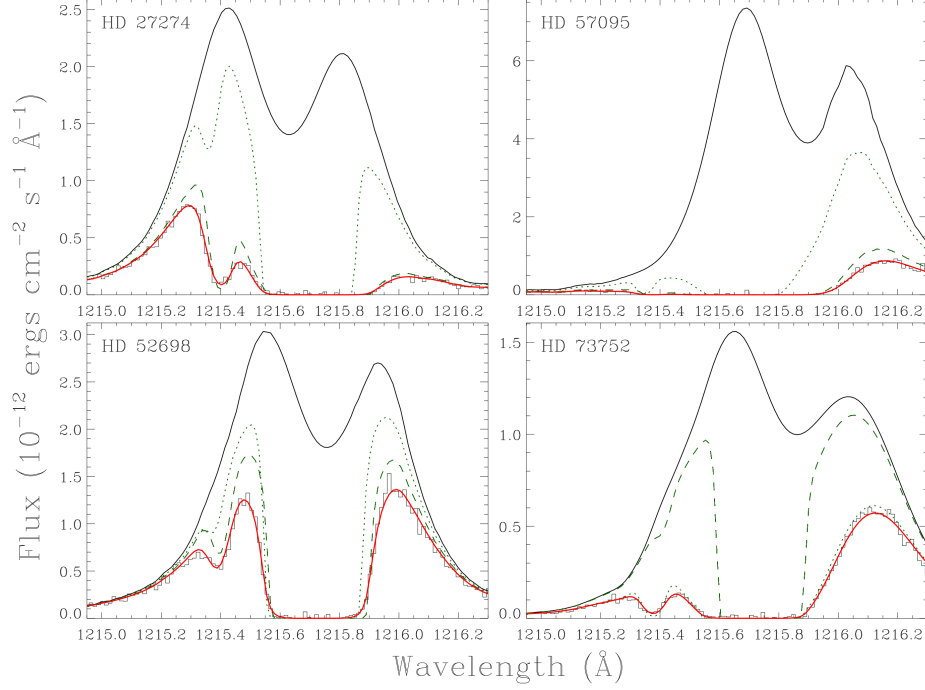


Figure 3.13 Figure provided by B. Wood. Ly- α stellar emission profiles with geocoronal contamination removed for each of four mixing zone sight lines. Stellar continuum is shown in solid black line; data in histogram mode; dashed/dotted lines for each fitted LISM component; and red solid line for the total summed fit across components, which matches the data well.

density measurements for the two components would be the same between Mg II (or in the case of HD 57095, Fe II) and H I, and that both components for each sight line had an equivalent Doppler width parameter. The H I Doppler parameters provided us with a light species for HD 57095 that we could use to determine temperature and turbulence. B. Wood also assessed a velocity correction based on the location of the geocoronal emission.

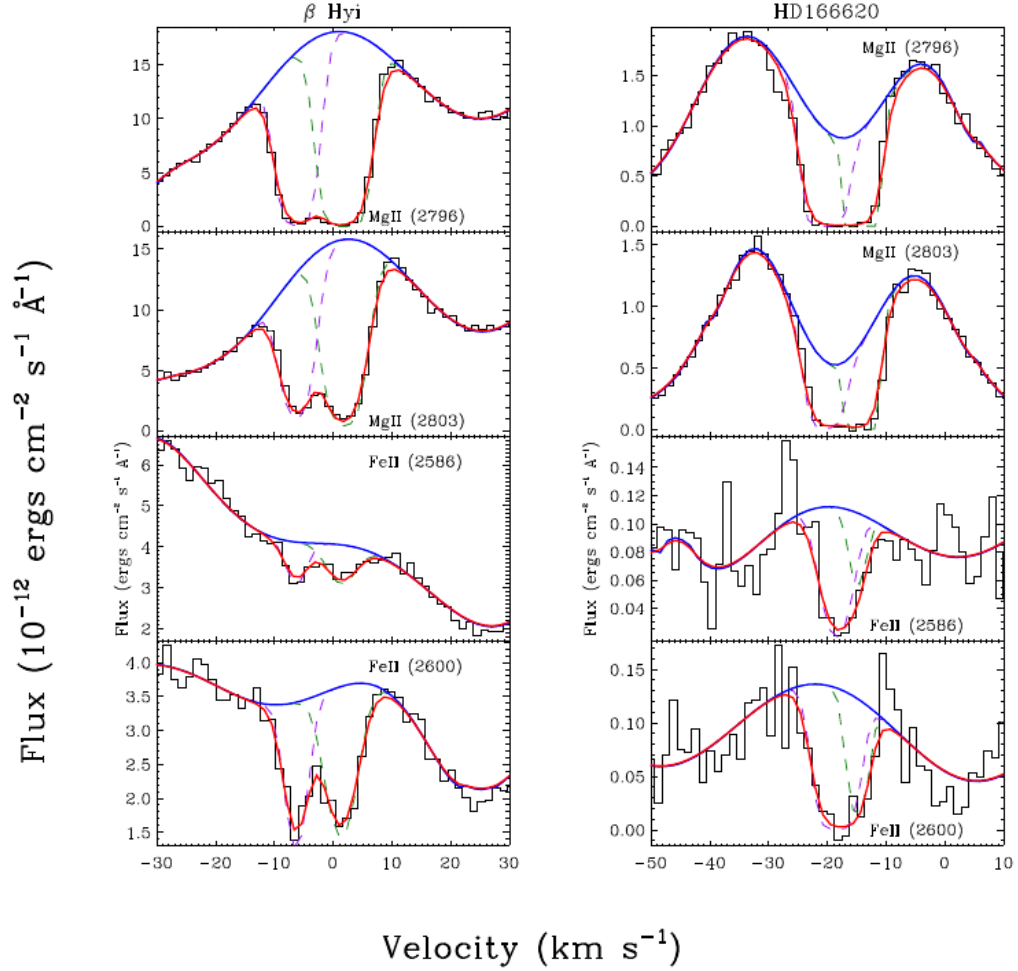


Figure 3.14 Final fits for HD 2151 (left) and HD 166620 (right). The stellar emission estimate (“flux background”) is shown in solid blue; individual absorption components are shown with dashed lines; and the sum of the absorption components is in solid red. For MgII and FeII doublets, the simultaneous fits (where parameters are forced to be self-consistent between both halves of the doublet) are shown.

HD 2151

This was the first of two sight lines I analyzed for B. Wood. Also known as β Hyi, HD 2151 exhibits two well-separated absorption components in both Mg II and Fe II as seen in Figure 3.14. Fitting this sight line was extremely straightforward, with close agreement between the velocities for each component across ions.

HD 166620

For this sight line, I again modeled two absorption components in both Mg II and Fe II. Although the components were blended and saturated in Mg II, the unsaturated Fe II eventually allowed for a consistent fit between the two ions, as seen in Figure 3.14. The results from this sight line appeared in B. E. Wood et al. (2026). HD 166620 has the distinction of being the first star with UV spectra confirmed to be experiencing a Grand Magnetic Minimum.

3.5 Final Fit Parameters

The final fit parameters are summarized in Table 3.2. For Mg II and Fe II, the reported value is a weighted mean of the two individual and the simultaneous fits.

Now that we have analyzed the data and extracted fit parameters for the absorption, we can use them to determine the physical properties of the LISM, which will begin in the next chapter.

Table 3.2. Fit Parameters

HD	Atom	Comp.	v (km s ⁻¹)	b (km s ⁻¹)	log N log(cm ⁻²)
73752	D I	1	7.57 ± 0.83	6.6 ± 1.9	13.47 ± 0.12
		2	14.9 ± 5.6	7.9 ± 2.1	12.94 ± 0.48
	H I	1	9.43 ± 0.31	11.87 ± 0.47	18.34 ± 0.01
		2	17.08 ± 0.31	11.87 ± 0.47	17.26 ± 0.01
	C II	1	9.6 ± 1.5	3.0 ± 1.3	14.05 ± 0.71
		2	17.4 ± 1.5	4.9 ± 1.8	14.18 ± 0.56
	Mg II	1	10.346 ± 0.073	2.97 ± 0.26	12.987 ^{+0.015} _{-0.016}
		2	18.1 ± 1.3	6.11 ± 0.77	11.91 ^{+0.23} _{-0.52}
	Fe II	1	10.6 ± 1.1	2.91 ± 0.65	12.67 ^{+0.15} _{-0.24}
		2	21.7 ± 2.2	5.3 ± 1.2	12.28 ± 0.43
52698	D I	1	7.0 ± 3.3	8.8 ± 2.2	12.78 ± 0.17
		2	17.7 ± 1.1	7.4 ± 1.7	13.14 ± 0.14
	H I	1	10.18 ± 0.10	12.932 ± 0.057	17.45 ± 0.01
		2	14.88 ± 0.10	12.932 ± 0.057	17.73 ± 0.01
	C II	1	15.0 ± 1.5	5.7 ± 1.1	14.32 ± 0.25
		2	19.6 ± 1.5	2.82 ± 0.90	14.74 ± 0.70
	Si II	1	12.3 ± 1.2	3.2 ± 1.2	14.35 ± 0.31
		2	17.2 ± 1.2	2.8 ± 2.0	13.22 ± 0.81
	Mg II	1	15.10 ± 0.19	1.36 ± 0.44	11.796 ^{+0.054} _{-0.062}
		2	19.88 ± 0.32	3.56 ± 0.29	12.076 ^{+0.035} _{-0.039}
	Fe II	1	13.1 ± 1.6	5.25 ± 0.46	12.54 ^{+0.13} _{-0.19}
		2	19.9 ± 3.9	1.7 ± 3.1	11.73 ± 0.45
57095	H I	1	2.22 ± 0.74	8.8 ± 1.9	18.17 ± 0.01
		2	9.37 ± 0.74	8.8 ± 1.9	18.73 ± 0.01
	Mg II	1	6.15 ± 0.58	4.1 ± 1.8	13.2 ± 1.8
		2	15.92 ± 0.32	1.72 ± 0.31	13.76 ^{+0.21} _{-0.44}
	Fe II	1	7.5 ± 1.7	2.17 ± 0.53	12.24 ± 0.74
		2	14.6 ± 1.0	2.6 ± 1.0	12.8 ± 1.1
27274	D I	1	9.3 ± 2.1	6.5 ± 2.0	13.35 ± 0.22
		2	17.9 ± 2.4	9.2 ± 1.7	13.52 ± 0.16
	H I	1	6.18 ± 0.26	12.50 ± 0.48	17.52 ± 0.01
		2	15.31 ± 0.26	12.50 ± 0.48	18.37 ± 0.01
	C II	1	6.6 ± 5.4	2.5 ± 1.3	15.8 ± 1.3
		2	15.6 ± 5.4	(3.64)	(13.82)
	Mg II	1	7.1 ± 1.6	1.63 ± 0.74	12.45 ± 0.51
		2	16.18 ± 0.73	3.6 ± 1.3	13.3 ± 2.4
166620	Mg II	1	-20.44 ± 0.70	2.64 ± 0.17	12.98 ± 0.13
		2	-14.19 ± 0.46	1.66 ± 0.18	13.92 ± 0.28
	Fe II	1	-18.47 ± 0.10	3.25 ± 0.51	13.245 ^{+0.053} _{-0.060}
		2	-14.81 ± 0.27	1.61 ± 0.50	12.744 ± 0.067
2151	Mg II	1	-6.04 ± 0.29	2.85 ± 0.17	12.765 ^{+0.063} _{-0.074}
		2	1.923 ± 0.090	3.38 ± 0.36	12.98 ^{+0.20} _{-0.39}
	Fe II	1	-6.27 ± 0.11	2.33 ± 0.32	12.398 ± 0.021
		2	1.42 ± 0.13	3.36 ± 0.28	12.532 ^{+0.017} _{-0.018}

Note. — Parentheses indicate values where parameters were fixed/not independent. H I parameters provided by B. Wood.

Chapter 4

Results

*There are certain calculations I should
like to make with you,
To be sure that your deductions will be
logical and true;*

SARAH WILLIAMS

The parameters obtained by fitting the absorption features in Chapter 3 now allow us to derive information about the physical conditions of the plasma responsible for the absorption. Observing across many ions allows us several independent measurements of the same cloud of material. This chapter describes the process and results of calculating cloud assignments, temperature and turbulence, neutral hydrogen column densities, elemental depletion, and heliospheric absorption.

4.1 Cloud Assignments

Now that we have identified and characterized LISM absorption for each of our stars, we can attempt to identify exactly which cloud of interstellar material is responsible for the absorption. Redfield and Linsky (2008) created a dynamical model¹ of fifteen clouds of LISM within 15 pc of the Sun using high-resolution spectra from GHRS and STIS sampled along 157 lines of sight, with a total of

¹see <http://lism.wesleyan.edu/LISMdynamics.html>.

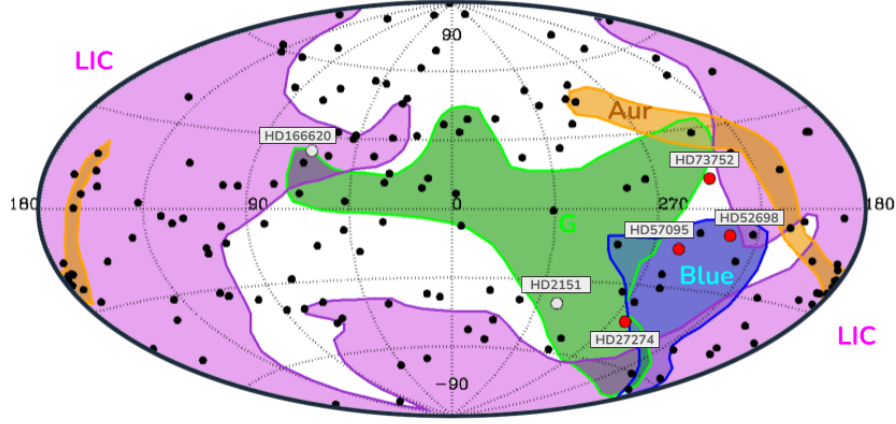


Figure 4.1 Cloud boundaries from S. Redfield & J. L. Linsky (2008) in galactic coordinates. The mixing zone sight lines are marked by red circles and appear close to the boundaries of the LIC, G, Blue, and Aur clouds; and the sight lines analyzed for B. Wood are marked in gray. Earlier sight lines with LISM analysis are indicated by black dots.

270 velocity components. This model allows for prediction of projected radial and transverse velocities for each nearby cloud at a given set of coordinates, as well as identifying which LISM clouds are traversed or close to the sight line. To further contextualize our sight lines, Figure 4.1 shows the model’s current boundaries for the LIC, G, Blue, and Aur clouds. The predictions from this model for all six sight lines are included in Table 4.1.

As the number of observed sight lines does not completely fill the sky, it is possible that the cloud boundaries predicted by the model may vary, and that a “nearby” cloud ($< 20^\circ$) could actually be responsible for the absorption. For each sight line, the weighted mean velocity across all observed ions was used as the velocity for a given component.

Table 4.1. Dynamical Model Comparison

HD	l (deg)	b (deg)	Dist. (pc)	Predicted Clouds Traversed	Predicted Near ($< 20^\circ$)	Assigned Clouds
73752	245.9	11.3	19.6	...	LIC, G, Blue, Gem, Cet, Aur	LIC/G, Aur
52698	237.3	-9.5	14.7	Blue	LIC	LIC, G
57095	258.3	-15.3	14.6	Blue	G, Dor, Cet, Vel	Blue, Unassigned
27274	262.3	-44.4	13.0	G, Dor,	LIC, Blue, Cet, Vel	Blue, Unassigned
166620	65.3	24.2	11.1	LIC, Mic	G, NGP, Aql, Oph	LIC, Mic
2151	304.8	-39.8	7.5	G, Vel	LIC, Dor, Cet	G, Dor

Note. — Stellar parameters from SIMBAD. Dynamical model predictions from <http://lism.wesleyan.edu/>.

4.1.1 HD 73752

While the kinematic model did not predict that this sight line traversed any known clouds, the data showed clear interstellar absorption at two velocities corresponding to nearby clouds ($< 20^\circ$). As shown in Figure 4.2, the first component is very close in velocity (10.324 km s^{-1}) to both the LIC and G cloud (10.67 and 10.97 km s^{-1} respectively), whose predicted boundaries are within 5° of the sight line. The second component is very close in velocity to the Aur cloud, which is within 12° of the sight line.

Due to the very close predicted velocities of the LIC and G cloud, attributing the first component to either cloud alone is difficult. The sight line is slightly closer to the boundary of the G cloud, but the observed velocity is a closer match to the LIC. With the spectral resolution of our observations, it is not possible to distinguish between either cloud. The absorption could be caused by one, or the other, or both.

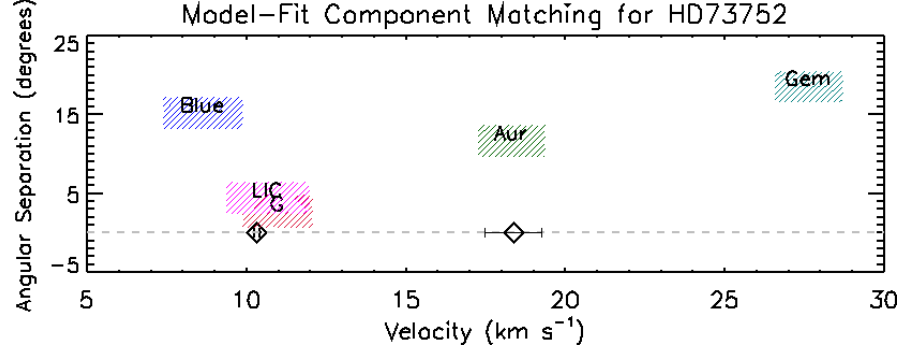


Figure 4.2 Comparison of observed velocities (diamonds, with 1σ error bars) with kinematic model predictions in velocity (diagonal hatching with width equal to 1σ error) and separation from line of sight. An angular separation of 0° indicates that the model predicts that the sight line traverses that cloud.

4.1.2 HD 52698

Although the kinematic model predicted that this sight line traversed the Blue cloud, the velocity of the first component more closely matched the nearby LIC ($\theta = 4.6^\circ$). As shown in Figure 4.3, the G and Aur clouds are also nearby. The G cloud is likely responsible for this component, as the difference in their velocities is not statistically significant ($\sigma = 1.4$).

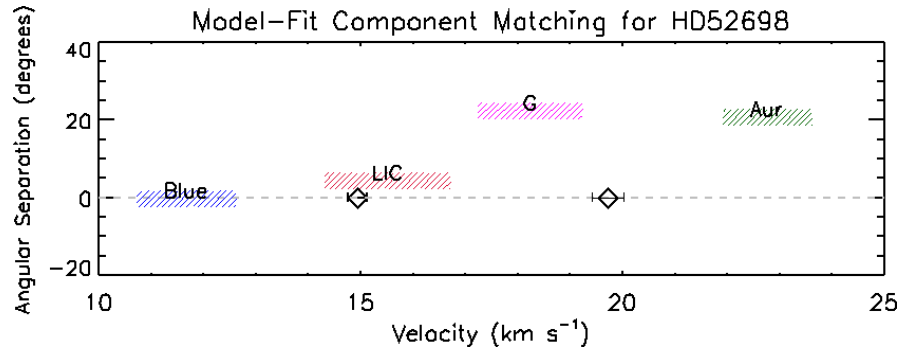


Figure 4.3 As Figure 4.2. Comparison of observed velocities with kinematic model predictions. A velocity component at approximately 15 km s^{-1} is within 1σ of the predicted velocity of the nearby LIC. Another velocity component at approximately 20 km s^{-1} is close in velocity to the G cloud, although it is further away from the sight line.

4.1.3 HD 57095

This sight line was also predicted to cross the Blue cloud, as shown in Figure 4.4. For the first component, it does appear to correspond to the Blue cloud ($\sigma = 2.1$). However, the second component is less straightforward. The observed velocity has relatively small uncertainty ($15.79 \pm 0.30 \text{ km s}^{-1}$), but there are no clouds within 40° of separation predicted by the model that have velocities within 4 km s^{-1} of the observed component. I am unable to identify a known cloud for component 2.

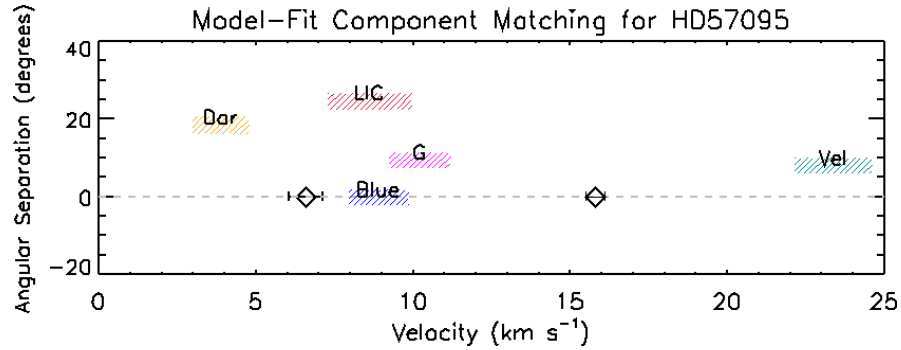


Figure 4.4 As Figure 4.2. Comparison of observed velocities with kinematic model predictions. An observed velocity component at approximately 7 km s^{-1} is close to predictions of the LIC, Blue, and Dor clouds. A second velocity component at approximately 15 km s^{-1} is not close to any predicted clouds.

4.1.4 HD 27274

This sight line was predicted to cross the G and Dor clouds. However, as shown in Figure 4.5, the nearby LIC and Blue cloud are much closer matches to the observed velocity. As the predicted boundaries of the Blue cloud bring it much closer to the sight line, I identify the Blue cloud as the most likely absorber. Like HD 57095, the second component does not appear to correspond to any known nearby clouds. The implications of this are discussed further in Chapter 5.

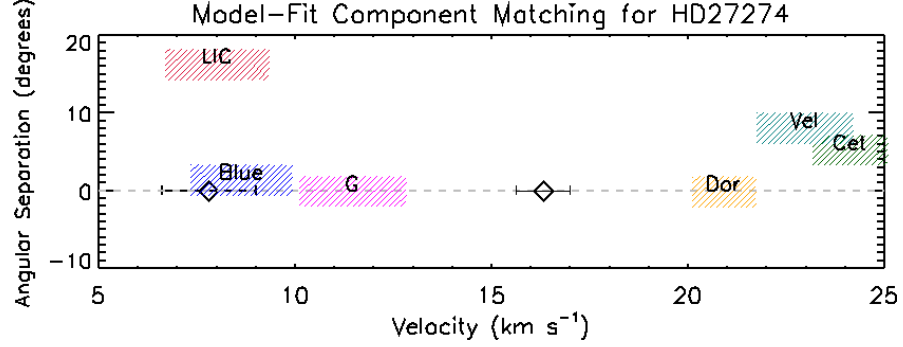


Figure 4.5 As Figure 4.2. Comparison of observed velocities with kinematic model predictions. A velocity component at approximately 8 km s^{-1} is within 1σ of the LIC and Blue clouds. A second velocity component at approximately 16 km s^{-1} is not within 3σ of any nearby clouds.

4.1.5 HD 166620

This sight line did not fall in the projected mixing zone. Rather, it was predicted to cross the LIC and Mic clouds. As shown in Figure 4.6, the model predictions align well with the observed data, and the first and second velocity components correspond to the Mic cloud and LIC respectively.

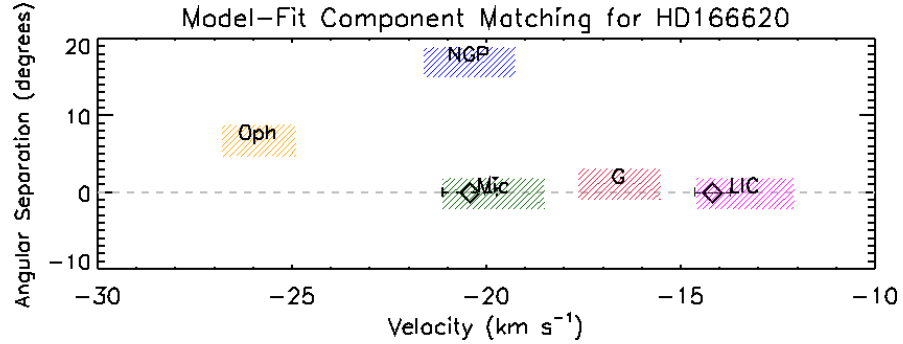


Figure 4.6 As Figure 4.2. Comparison of observed velocities with kinematic model predictions. An observed velocity component at approximately -20 km s^{-1} overlaps with the Mic cloud, and a second velocity component at approximately -14 km s^{-1} corresponds to the LIC.

4.1.6 HD 2151

This sight line was also not in the projected LIC-G mixing zone. Rather, it was predicted to traverse the G and Vel clouds. The first component does have a velocity consistent with the G cloud ($\sigma = 1.3$). However, the second component appears to more closely match the velocity of the nearby Dor cloud.

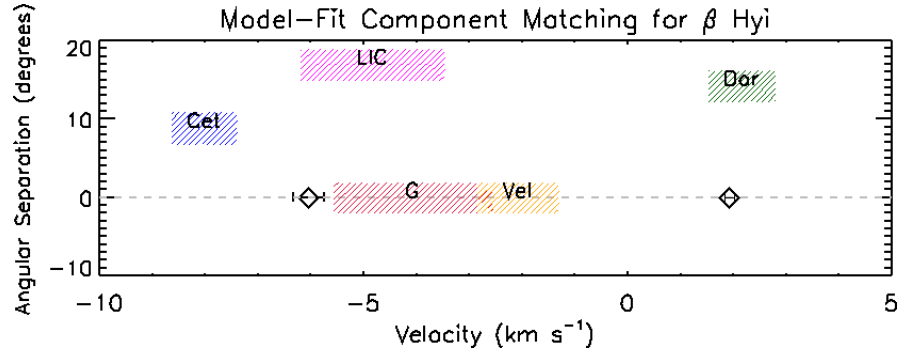


Figure 4.7 As Figure 4.2. Comparison of observed velocities with kinematic model predictions. An observed velocity component at approximately -6 km s^{-1} is close to the predictions for the LIC and G cloud. A second velocity component at approximately 2 km s^{-1} is aligned with the predicted velocity of the nearby Dor cloud.

4.2 Temperature and Turbulence

The temperature (T) and turbulence (ξ) of each absorbing cloud can be calculated using the Doppler parameter b_D when measured across multiple ions with differing atomic masses m_a . For the best results, it is necessary to use species with a wide difference in mass, such as the very light D I and a significantly heavier ion like Fe II or Mg II.

The relationship between the Doppler parameter, temperature, and turbulent velocity is described by

$$b_D = \sqrt{\frac{2kT_K}{m_a}} + \xi, \quad (4.1)$$

Table 4.2. Temperature and Turbulence

HD No.	Comp. No.	Central Velocity v (km s ⁻¹)	Temperature T (K)	Turbulent Velocity ξ (km s ⁻¹)	Assigned Cloud
73752	1	10.324 ± 0.072	8100^{+1300}_{-1200}	$1.89^{+0.68}_{-0.90}$	LIC/G
73752	2	18.38 ± 0.92	6700^{+1600}_{-1500}	$5.3^{+1.2}_{-1.3}$	Aur
52698	1	14.98 ± 0.18	9700^{+1000}_{-1400}	≤ 5.4	LIC
52698	2	19.56 ± 0.29	9840^{+320}_{-350}	$2.2^{+0.9}_{-1.3}$	G
57095	1	6.29 ± 0.55	4600^{+2300}_{-1900}	$1.96^{+0.61}_{-0.71}$	Blue
57095	2	15.80 ± 0.30	4000^{+2400}_{-2100}	≤ 1.69	Unassigned
27274	1	7.8 ± 1.2	9200^{+1400}_{-1300}	≤ 2.0	Blue
27274	2	16.31 ± 0.69	9100^{+900}_{-1000}	≤ 4.2	Unassigned

Note. — Velocities are the weighted mean across all ions. Upper limits on ξ are 1σ .

where b_D is the Doppler parameter, k is the Boltzmann constant, T_K is the temperature of the cloud, m_a is the atomic mass, and ξ is the turbulent velocity. The best fit curve is highly influenced by the widths of the lightest species used, which for all sight lines was the H I width provided by B. Wood. This is expected, because the lightest atoms are the most affected by thermal broadening, before turbulent broadening takes over for even slightly heavier atoms.

S. Redfield & J. L. Linsky (2008) found that average LISM warm cloud temperature was 6680 ± 1490 K, and the typical turbulent velocity was 2.24 ± 1.03 km s⁻¹. The temperature and turbulence for the four mixing zone sight lines are summarized in Table 4.2, and plots showing the best fit for temperature and turbulence appear in Figures 4.8–4.15.

4.2.1 HD 73752

This sight line was measured with three medium-resolution light ions and two high-resolution heavy ions. The C II widths have larger uncertainties, but this is expected due to the frequent saturation of C II absorption. Component

1, shown in Figure 4.8, has a substantial overlap region of possible temperature and turbulence even before the addition of the H I region, which narrows the best fit region substantially. The final solution is consistent with the LISM aggregate ($< 1\sigma$) for both temperature and turbulence. Component 2 (Figure 4.9), is also

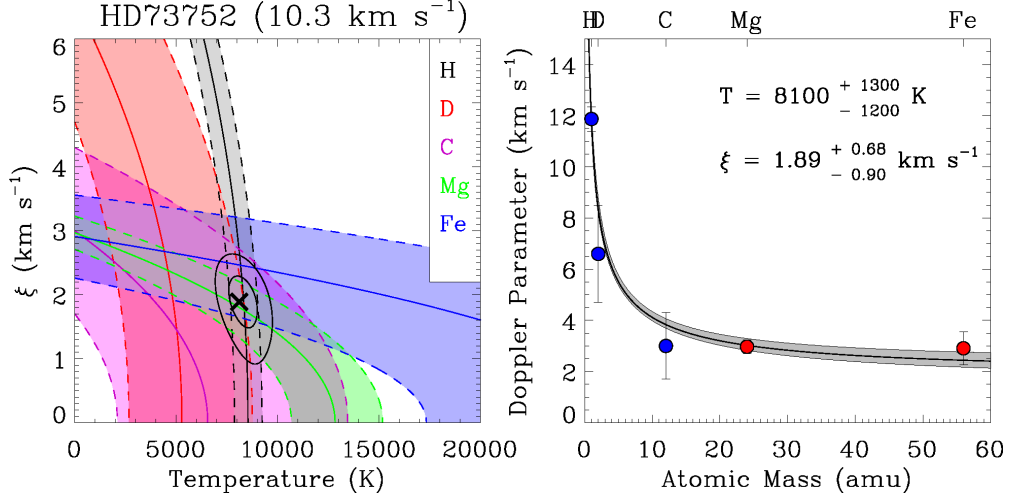


Figure 4.8 Best fit for temperature and turbulence for HD 73752, component 1. Each plot is labeled with the sight line and the velocity component used in the determination. The left plot shows the determination of the best-fit temperature and turbulence (solid cross) given the observed Doppler parameter and mass for each of the color coded listed ions, with $\pm 1\sigma$ error bars for each curve shown in dashed lines. The solid contours indicate the ± 1 and $\pm 2\sigma$ errors on the best fit value. The right plot shows the observed Doppler parameter as a function of atomic mass with $\pm 1\sigma$ error bars. Blue symbols indicate mid-resolution data (E140M) and red symbols indicate high-resolution data (E230H). The best-fit curve is shown with a solid line, and the shading represents a possible range of $\pm 1\sigma$ from the fits in the left panel.

consistent with the LISM aggregate in temperature ($< 1\sigma$) and turbulence ($< 2\sigma$).

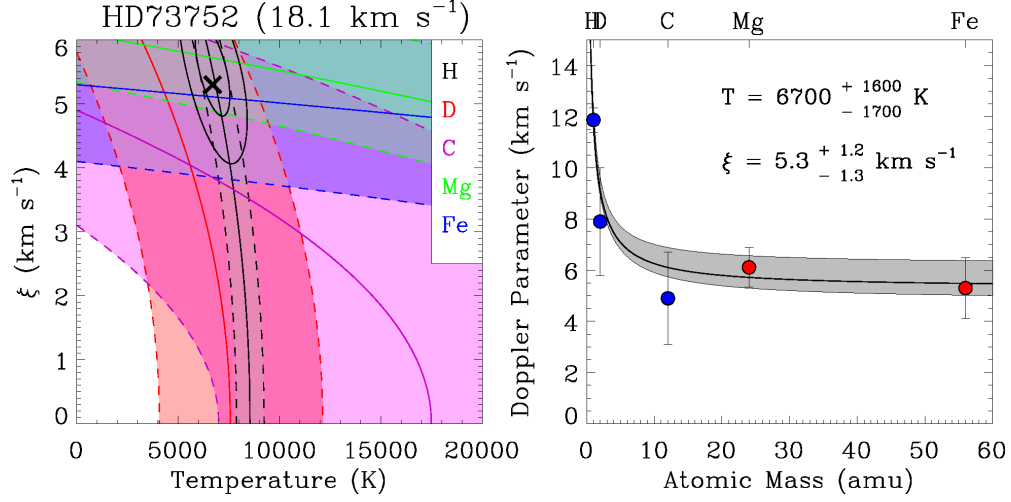


Figure 4.9 As 4.8. Best fit for temperature and turbulence for HD 73752, component 2.

4.2.2 HD 52698

This sight line was measured with four medium-resolution light ions, and two high-resolution heavy ions. Component 1, shown in 4.10, has larger uncertainty in the best fit solution. This is in large part due to the surprisingly narrow Mg II absorption, narrower than the heavier Si II and Fe II absorption. The 1σ contours around the X in the left panel indicate almost no overlap with the heavy Mg II and Fe II contours. The temperature is consistent with the LISM aggregate ($< 2\sigma$), as is the turbulent velocity ($< 1\sigma$). Component 2 has a much wider region of overlap before the inclusion of H I, which dominates the best fit determination. The temperature is consistent with the LISM aggregate ($< 3\sigma$) and the turbulence is nearly identical ($<< 1\sigma$).

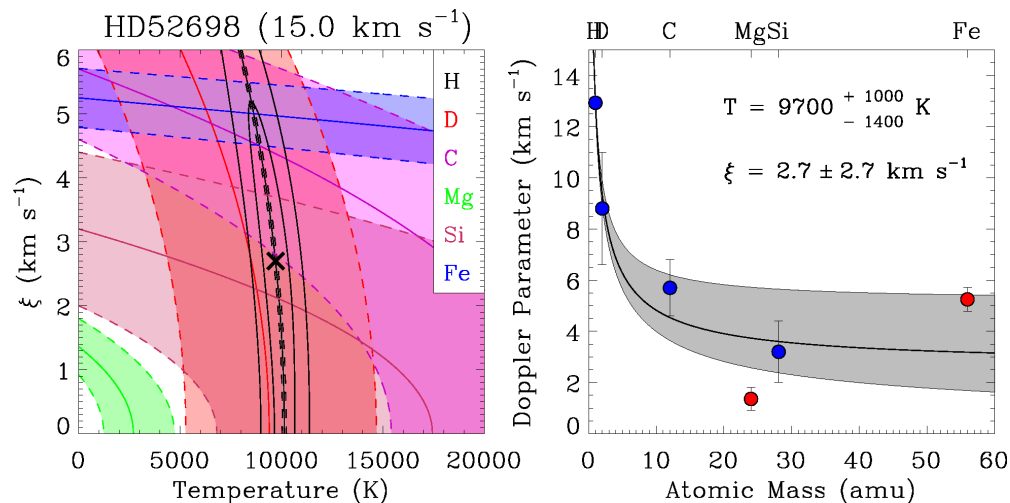


Figure 4.10 As Figure 4.8. Best fit for temperature and turbulence for HD 52698, component 1.

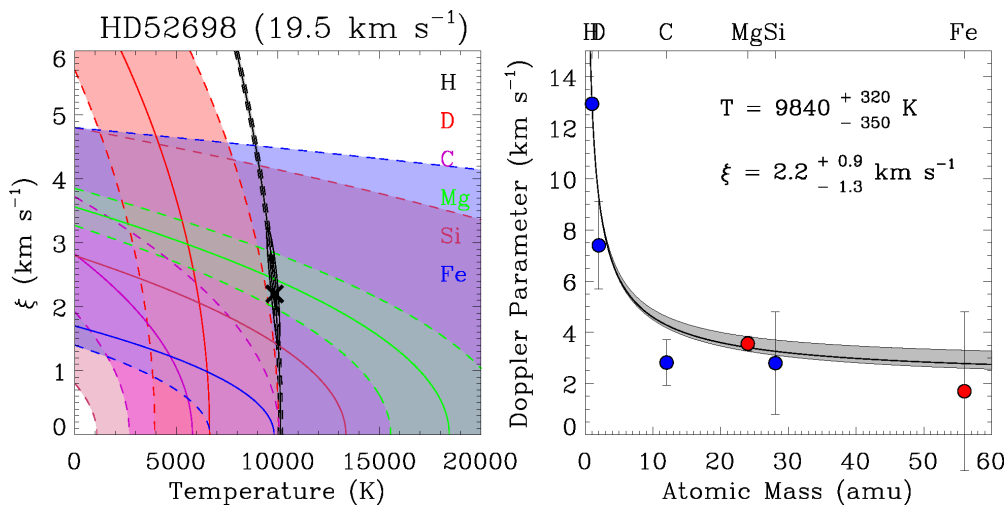


Figure 4.11 As Figure 4.8. Best fit for temperature and turbulence for HD 52698, component 2.

4.2.3 HD 57095

This sight line only has measurements from the two high-resolution heavy ions, and the light, mid-resolution H I. This is still more than enough to solve the equation, strictly speaking, but additional measurements offer consistency checks that are absent here. The best-fit determinations for this sight line are entirely driven by the H I fits provided by B. Wood. Component 1, shown in Figure

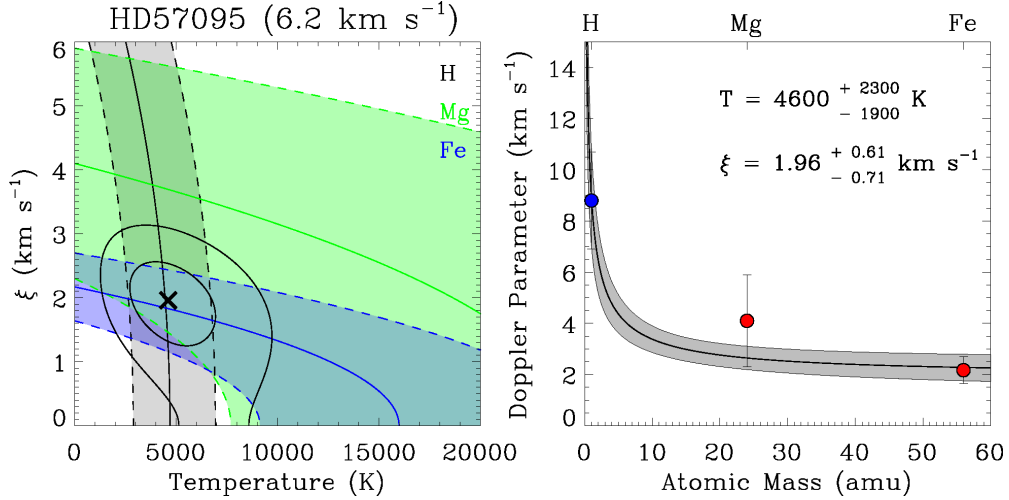


Figure 4.12 As Figure 4.8. Best fit for temperature and turbulence for HD 57095, component 1.

4.12, prioritizes the lower-uncertainty Fe II width for the heavy atom, rather than Mg II. Although Mg II is usually the higher signal data with better fits, for this observation, the Mg II components were more blended than the Fe II components. Component 2, shown in Figure 4.13, indicates that the broadening in this component could be entirely explained by thermal broadening. The temperature and turbulence for both components are consistent with the LISM aggregate ($< 1\sigma$).

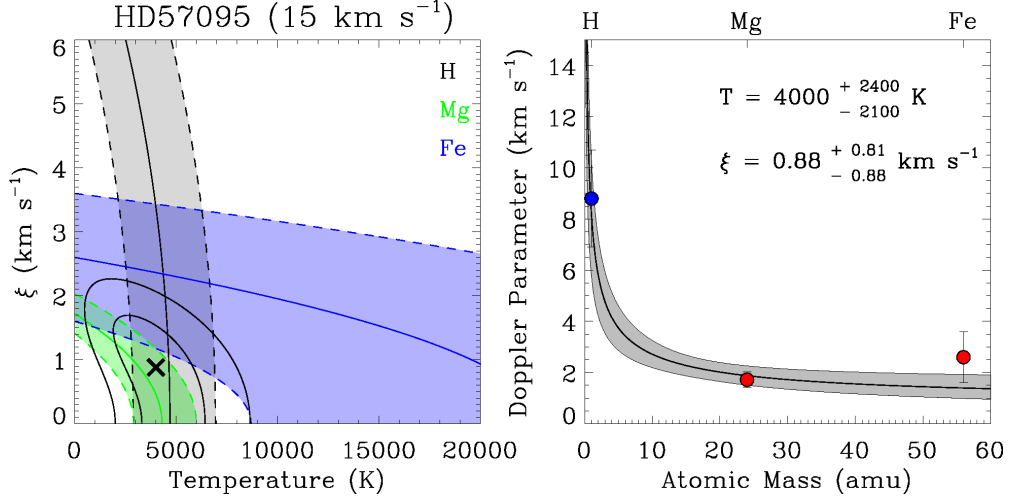


Figure 4.13 As Figure 4.8. Best fit for temperature and turbulence for HD 57095, component 2.

4.2.4 HD 27274

This sight line has three mid-resolution light measurements and only one high-resolution heavy measurement (Fe II was not detectable). The lack of heavier atomic data (which would be more influenced by turbulence) could explain why both components are consistent with a purely thermal broadening scenario. Component 1, shown in Figure 4.14, has a more narrow DI width than component 2, which is especially apparent when compared to H I. Because the two components were assumed to have equivalent H I widths during the spectral fitting, it is possible that this assumption impacts the quality of this fit more than the others. The temperature and turbulence are consistent with the LISM aggregate ($< 2\sigma$). Component 2 shows higher uncertainty in the best-fit curve (Figure 4.15); it is worth noting that the absorption in the Mg II profiles was in the wings, with the higher-velocity component very far from the line center. The temperature and turbulence are consistent with the LISM aggregate ($< 2\sigma$).

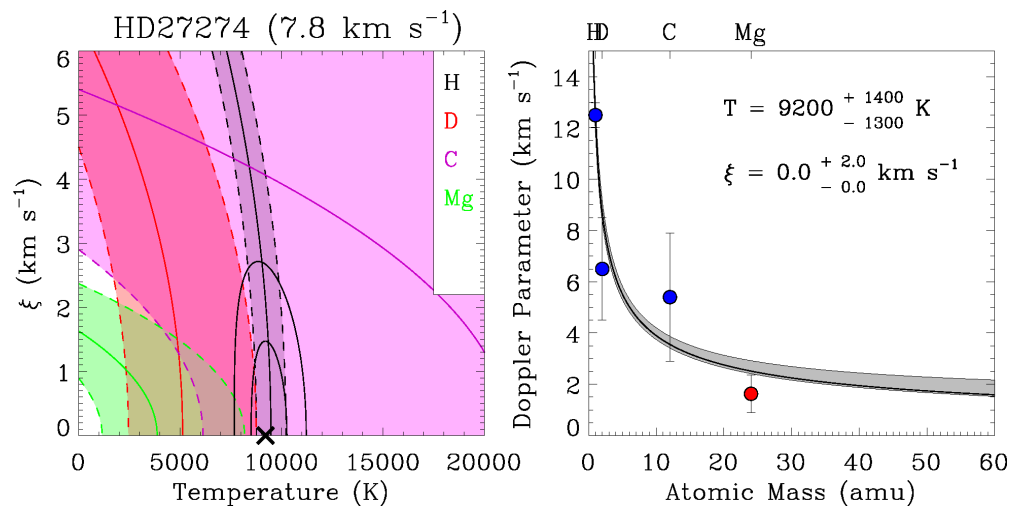


Figure 4.14 As Figure 4.8. Best fit for temperature and turbulence for HD 27274, component 1.

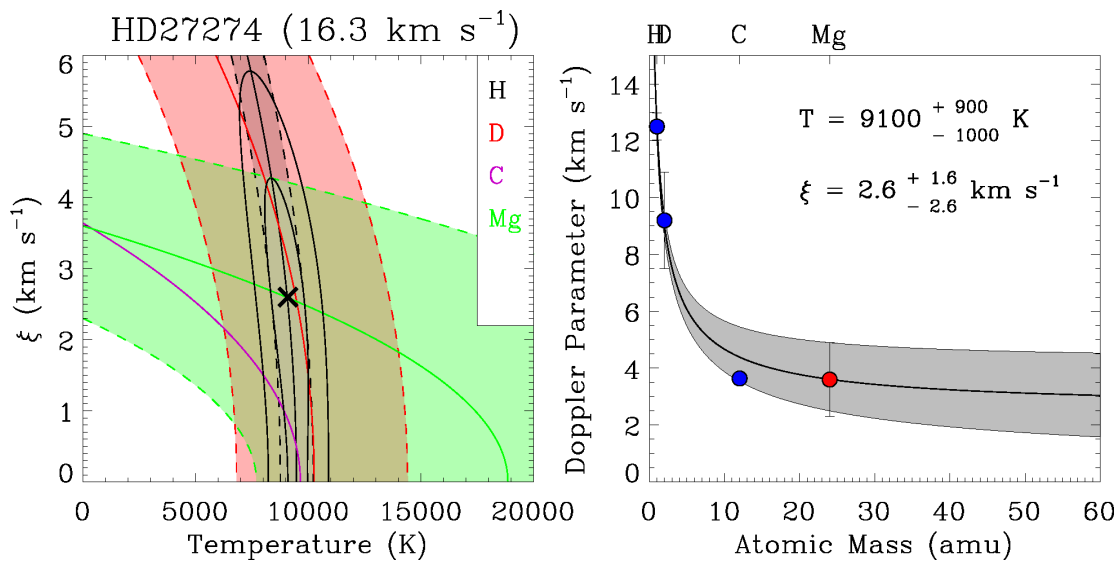


Figure 4.15 As Figure 4.8. Best fit for temperature and turbulence for HD 27274, component 2.

Overall, all eight components are within 3σ of the LISM aggregate values for temperature and turbulence determined by S. Redfield & J. L. Linsky (2008). Comparisons to individual LISM clouds will be made in Chapter 5.

4.3 Neutral Hydrogen Column Densities

Deuterium, or *heavy hydrogen*, (D I) is an isotope of hydrogen with one proton and one neutron, in contrast to the much more common isotope of neutral hydrogen (H I), which has a single proton and no neutrons. Almost all of the deuterium in the universe was created during or shortly after the Big Bang. Deuterium is destroyed during stellar fusion; therefore, the present-day ratio of D I/H I must be lower than the primordial value.

Due to the known local abundance ratio between deuterium (D I) and neutral hydrogen (H I) in the Local Bubble determined by B. E. Wood et al. (2004), it is very easy to convert a D I column density to an estimate of the H I column density. We use the abundance ratio

$$\frac{D}{H} = (1.56 \pm 0.04) \times 10^{-5},$$

to arrive at the column density for H I. This constancy of this ratio implies a common history for the gas inside the Local Bubble, consistent with the creation of the Local Bubble from a supernova (J. L. Linsky et al. 2006). Values for the H I column density are listed in 4.4. We can then compare these results to existing measurements of the average H I column density across other samples. Deuterium always appears at a short wavelength offset from neutral hydrogen, which means that it is conveniently included in observations of the whole Ly- α profile. Deuterium is also unaffected by the charge exchange that produces

Table 4.3. Comparison of H I Column Densities

HD	Comp.	DI (log N cm $^{-2}$)	From DI (log $N(\text{H})$ cm $^{-2}$)	From B. Wood (log $N(\text{H})$ cm $^{-2}$)
73752	1	13.47 ± 0.12	18.30 ± 0.03	18.34 ± 0.01
	2	12.94 ± 0.48	17.76 ± 0.05	17.26 ± 0.01
52698	1	12.78 ± 0.17	17.60 ± 0.03	17.45 ± 0.01
	2	13.14 ± 0.14	17.96 ± 0.03	17.73 ± 0.01
57095	1	...	...	18.17 ± 0.01
	2	...	...	18.73 ± 0.01
27274	1	13.35 ± 0.22	18.17 ± 0.03	17.52 ± 0.01
	2	13.52 ± 0.16	18.34 ± 0.03	18.37 ± 0.01

Note. — Neutral hydrogen column densities obtained by conversion from log $N(\text{DI})$ and by direct measurement from H I fitting. HD 57095 did not have a reliable DI column density to convert.

the “hydrogen wall” between the LISM and the heliosphere/astrospheres, which means that DI can provide valuable information for fitting the LISM absorption in H I.

Additionally, thanks to the column density measurements for H I provided by B. Wood, we have a second measurement of the column density. These results are compared in Table 4.3. I again note that the H I column densities were assumed to match the ratio of column densities between interstellar components detected in Mg II in order to produce consistent fits, a constraint which was not implemented for DI, which makes the values converted from D/H more independent. To account for these differences, subsequent calculations will be performed for both sets of values for comparison.

4.4 Depletion

After determining the H I column density, we can determine whether a given element is depleted. Depletion occurs when an element in a gaseous form con-

denses onto dust grains, making it invisible to our UV spectrograph. In order for depletion to occur, temperatures must be low enough and conditions must be calm enough for the gas to condense. There must also be dust grains for the gas to adhere to.

The depletion is calculated using solar abundances from M. Asplund et al. (2021), using the relationship

$$D(X) = \log \left(\frac{X}{H} \right) - \log \left(\frac{X}{H} \right)_{\odot}, \quad (4.2)$$

and the column densities for each element X . A sharp-eyed reader will note that for Fe, Equation 4.2 is the same as the formula for computing metallicity (Z). Values for depletion are listed in Table 4.4. A more negative value means that there is significantly less of a given element present relative to its solar abundance. We expect to see greater depletion for heavier elements with higher condensation temperatures. Depletion depends on having an accurate H I column density.

An example of the relationship between depletion and 50% condensation temperature (the temperature at which 50% of an element leaves the gas phase to become solid) is shown in Figure 4.16. This is generally followed for the depletion values I derived, with the exception of HD 52698. The Si in component 1 does not appear depleted. This could be due to high temperatures; or a lack of dust grains for the Si to adhere to, possibly due to destruction by high turbulence; or it could indicate an inaccurate H I column density. A singular explanation for the lack of depletion is not immediately apparent.

Table 4.4. Elemental Depletion

HD	Comp.	$D(\text{C})$	$D(\text{Si})$	$D(\text{Mg})$	$D(\text{Fe})$
73752	1	-0.70 ± 0.73	...	-0.86 ± 0.26	-1.08 ± 0.36
	2	-0.04 ± 0.60	...	-1.40 ± 0.56	-1.03 ± 0.49
52698	1	0.26 ± 0.37	1.24 ± 0.40	-1.36 ± 0.28	-0.52 ± 0.34
	2	0.32 ± 0.72	-0.25 ± 0.82	-1.44 ± 0.27	-1.69 ± 0.50
57095	1	...	...	...	...
	2	...	...	...	...
27274	1	1.17 ± 1.3	...	-1.27 ± 0.55	...
	2	...	...	-0.4 ± 2.4	...
73752	1	-0.75 ± 0.73	...	-0.90 ± 0.26	-1.13 ± 0.36
	2	0.46 ± 0.59	...	-0.90 ± 0.56	-0.44 ± 0.49
52698	1	0.41 ± 0.37	1.39 ± 0.40	-1.20 ± 0.27	-0.37 ± 0.33
	2	0.55 ± 0.72	-0.02 ± 0.82	-1.20 ± 0.27	-1.56 ± 0.50
57095	1	...	...	-0.52 ± 1.8	-1.39 ± 0.76
	2	...	...	-0.51 ± 0.50	-1.4 ± 1.1
27274	1	1.8 ± 1.3	...	-0.62 ± 0.55	...
	2	...	...	-0.6 ± 2.4	...

Note. — Neutral hydrogen column densities obtained by conversion from $\log N(\text{DI})$ (above horizontal line) and by direct measurement from B. Wood (below horizontal line). HD 57095 did not have a reliable DI column density, preventing subsequent derivation of the elemental depletion.

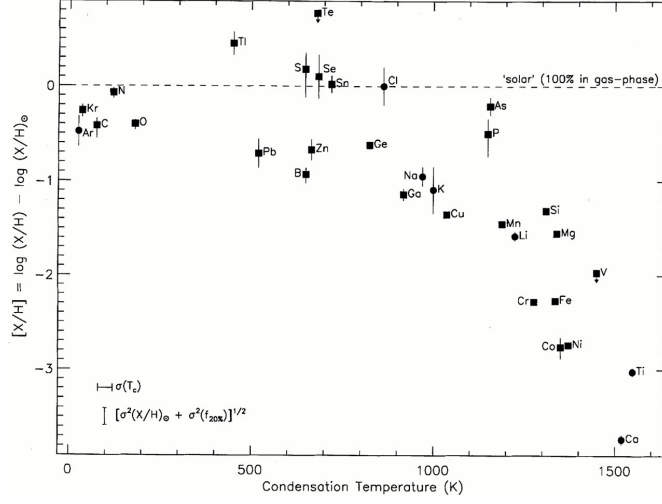


Figure 4.16 Figure from B. D. Savage & K. R. Sembach (1996). Depletion as a function of 50% condensation temperature. Heavier elements tend to have higher condensation temperatures, and subsequently exhibit more (i.e., more negative) depletion.

4.5 Heliospheric Absorption

When the hot, fully ionized solar wind hits the cooler, partially ionized LISM, charge exchange occurs, and hot neutral hydrogen is created at the interface as the solar wind picks up free electrons but maintains its temperature (G. P. Zank et al. 2013). This sudden increase in HI is called the *hydrogen wall*, and can create an absorption feature in spectra of nearby stars. The same process is also occurring with the stellar winds around other stars. Observing another star from within the solar system can therefore traverse multiple possible sources of HI: first, the heliosphere produced by the Sun’s solar wind; next, the clouds of interstellar material between us and the star, and finally the potential astrosphere surrounding the target star (B. E. Wood et al. 2005).

By analyzing the properties of the nearby DI feature, which is not part of the hydrogen wall, but should have similar LISM absorption features, we are able

to determine if the LISM alone can account for all of the absorption in the H I line. The heliosphere will create a small amount of excess redder absorption as it moves away from us along the line of sight, and an astrosphere will create a small amount of excess bluer absorption due to the stellar winds moving towards us along the line of sight.

Brian Wood's analysis of the Lyman- α absorption did not detect heliospheric or astrospheric absorption along any of the four mixing zone sight lines.

We have completed our derivation of the physical properties of the LISM plasma for each of the sight lines. In Chapter 5, we will consider these properties in their larger context, and discuss their implications.

Chapter 5

Discussion

*into the sky of this
the one world
we all belong to
where everything
sooner or later
is a part of everything else*

MARY OLIVER

We now have a pile of information to sift through: fits to spectra, comparisons to models, and newly derived physical properties. In this chapter, I consider all of these factors collectively in order to evaluate the region as a whole, and assess our motivating question: do we see indications of mixing?

5.1 Comparison to LISM Aggregate

We must first ask whether or not the parameters obtained by my fits are physically reasonable. The large sample of LISM components analyzed in S. Redfield & J. L. Linsky (2002) and S. Redfield & J. L. Linsky (2004) provides a basis for our comparison. The LISM aggregate sample I used for comparison contained 113 Mg II components and 64 Fe II components.

For the central velocities of the absorption, this comparison is straightfor-

ward. The range of central velocities of the mixing zone sample is clearly within the spread of detectable velocities for this method, as shown in Figure 5.1. It is unsurprising that the detected velocities are clustered around $10\text{--}20\text{ km s}^{-1}$ because we are observing in the same part of the sky and trying to detect material that is part of the same cloud(s).

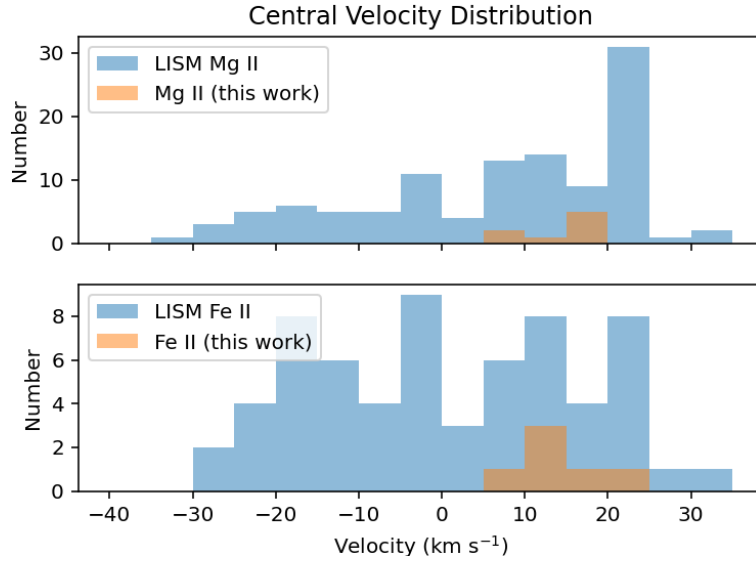


Figure 5.1 Histograms comparing the LISM aggregate (blue) distribution of the central velocity parameter for Mg II and Fe II from S. Redfield & J. L. Linsky (2002) with the values determined by this study (orange).

Evaluating the Doppler parameters necessitates a more careful consideration, as the width of the absorption is a critical part of determining temperature and turbulence. The number of components used in the fit plays a crucial role in the overall width of the LISM absorption features: one very wide component could also be approximated as two medium width components, or three very narrow components. This is why, as discussed in Chapter 3, we use statistical f-testing in order to determine whether adding an additional component improves the overall quality of the fit enough to justify its increased complexity.

When the components are very clearly separated from each other and far from the wings of the emission, it is easier to be confident in the appropriate width of each component. However, when multiple components are blended, it can be difficult to disentangle their respective widths and determine how much of the absorption width can be attributed to each component. I allowed the width of each component to vary as a free parameter. The Doppler parameter distributions for Mg II and Fe II are shown in Figure 5.2. While most of the components are clustered near the center of the distribution, there are three components that fall on the broader end of the distribution, but not outside of the previously observed range.

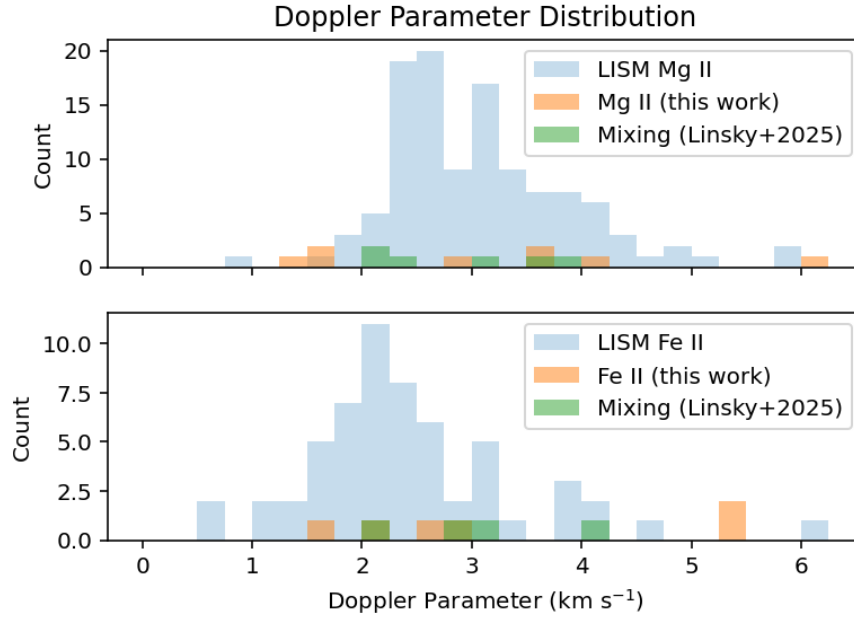


Figure 5.2 Histograms comparing the LISM aggregate (blue) distribution of the Doppler parameters for Mg II and Fe II from S. Redfield & J. L. Linsky (2002) and the LIC/G cloud mixing sight lines (green) from J. L. Linsky & S. Redfield (2025) (parameters from B. E. Wood et al. (2000); J. Zachary et al. (2018); C. Malamut et al. (2014); A. H. Nisak et al. (2025); S. Redfield & J. L. Linsky (2002)) with the values determined by this study (orange).

We expect ions of heavier mass to be less susceptible to thermal broadening

than turbulent broadening, and physically the heavier ions should show a consistent decrease in line widths when compared to their lighter counterparts. In order to assess this, I compared the Doppler parameters for Mg II and Fe II for each cloud component in Figure 5.3. This figure considers the extreme limiting cases of exclusively thermal broadening, represented by the solid line, and exclusively turbulent broadening, represented by the dashed line. The area between these two lines is the physically permissible zone for the ratio $\left(\frac{b_{\text{FeII}}}{b_{\text{MgII}}}\right)$; and indeed, for the three mixing zone sight lines where both Mg II and Fe II are observed, most of the cloud components lie within $\pm 1\sigma$ of the allowed zone. This offers a reassuring check on the validity of these fits as physically possible. However, there

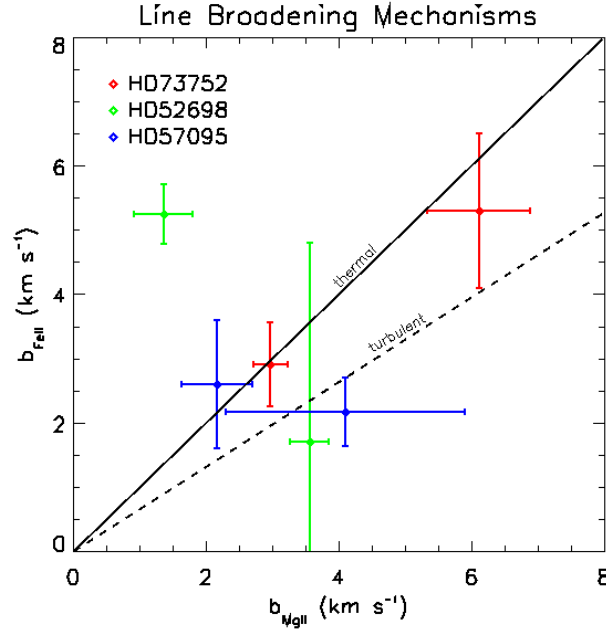


Figure 5.3 Comparison between Mg II and Fe II Doppler parameters for the same clouds (indicated by color). The solid line indicates the limit for purely thermal broadening; the dashed line indicates the limit for purely turbulent broadening. The allowed zone for the ratio of Doppler parameters is between these two lines. All of the components lie within $\pm 1\sigma$ of the allowed zone, with the exception of one component in HD 52698.

is one component (HD 52698, component 1) that falls outside the allowed zone established by the limiting cases of exclusively thermal or exclusively turbulent broadening. This is concerning, as it may indicate a problem with the fit.

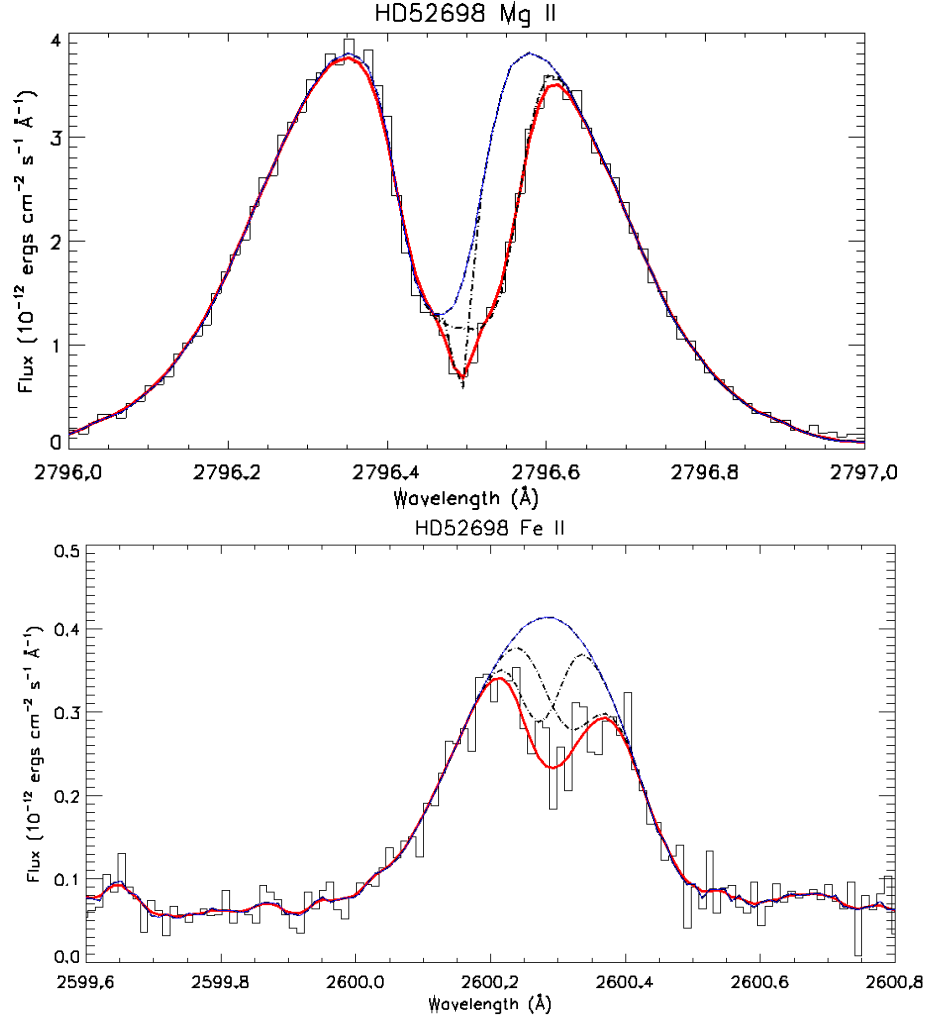


Figure 5.4 Fits from HD 52698. The data is plotted in histogram mode; the flux background is shown in solid blue; individual components of the fit are shown in dot-dash; and the combined fit is shown in solid red.

Revisiting the fits in Figure 5.4, we see that this was a case where the width of the Mg II absorption was unusually narrow when compared to the Fe II absorption, and where the absorption occurred near the central self-reversal. Interestingly, for

the second component in this sight line there are also discrepancies in the line widths. Overall, the Fe II data was considerably noisier and lower in signal than the Mg II data for this line, and the components are very blended, meaning that it may not be possible to achieve a better fit than this with the current data.

The Mg II and Fe II column density parameters are shown in Figure 5.5 and all appear to be well within the observed distribution for the LISM aggregate. How-

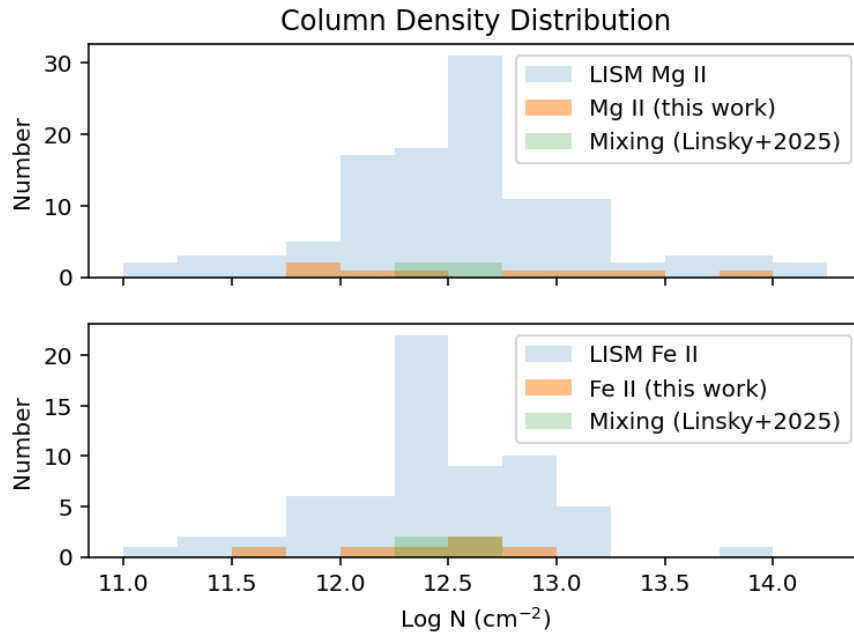


Figure 5.5 Histograms comparing the LISM aggregate (blue) distribution of the column density parameters for Mg II and Fe II from S. Redfield & J. L. Linsky (2002) and the LIC/G cloud mixing sight lines (green) from J. L. Linsky & S. Redfield (2025) (parameters from B. E. Wood et al. (2000); J. Zachary et al. (2018); C. Malamut et al. (2014); A. H. Nisak et al. (2025); S. Redfield & J. L. Linsky (2002)) with the values determined by this study (orange).

ever, J. L. Linsky & S. Redfield (2025) noted that some sight lines in the vicinity of the LIC and G clouds appeared to have anomalously high neutral hydrogen column densities. They provided summary statistics of HI column density for all observed sight lines within and at the edges of these clouds, and identified a

subset that were higher than the mean by several times the typical measurement error.

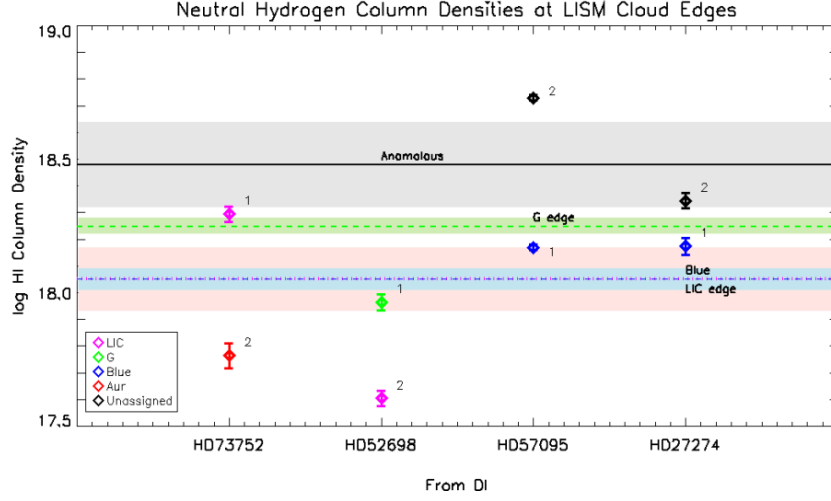


Figure 5.6 Column densities converted from DI, plotted with $\pm 1\sigma$ error. Weighted mean column densities for Blue cloud, G cloud edge, LIC edge, and anomalous sight lines computed from J. L. Linsky & S. Redfield (2025), plotted with $\pm 1\sigma$ statistical uncertainty. Note that the Blue cloud has a mean value nearly identical to the LIC edge, but with much less variation.

When I make compare my column density values with the values typical of the G cloud edge and LIC edge, the two unassigned components appear consistent with the anomalous values noted in J. L. Linsky & S. Redfield (2025). Additionally, the component in HD 73752 that has a velocity consistent with both the LIC and G clouds is also higher than the typical column density associated with the edge of the LIC, and more in line with the column density average at the G cloud edge.

One possible cause of high neutral hydrogen column densities suggested by J. L. Linsky & S. Redfield (2025) was the overlap of multiple clouds (particularly the LIC and G clouds), as suggested in P. Swaczyna et al. (2022). This situation was one of the primary motivations for the data collection used in this thesis—the

mixing zone sight lines were selected due to their location nearly perpendicular to the LIC/G axis, where the overlapping material would be greatest. When the sight line traverses material from multiple clouds simultaneously (as in a collision or mixing zone), it literally encounters more material per cm^2 than a sight line traversing a single cloud at a time. Another possible origin is a shell left over from the most recent supernova explosion in the vicinity. These two components and these potential explanations deserve particular attention as we continue our comparison with the dynamical model and the previously known cloud properties.

5.2 Comparison to Dynamical Model

Next, we consider whether or not my fitting parameters are consistent with the dynamical model. For 75% of the mixing zone sample, I was able to identify one or more clouds within 20° of the sight line that could be plausibly attributed to the observed LISM absorption on the basis of the central velocity. When compared to the previously modeled cloud boundaries as seen in Figure 5.7, these seem very plausible. Two of the eight components (HD 52698 1–LIC; HD 57095 1–Blue) directly match the model’s predictions. Four more (HD 73752 1–G/LIC; HD 73752 2–Aur; HD 52698 2–G; HD 27274 1–Blue) have absorption consistent with clouds within 20° of the model’s predictions, indicating that previously established clouds cover slightly more area in this region than previously known. Notably, only two of the eight observed components (HD 57095 2; HD 27274 2) in the mixing zone sample were unable to be assigned to a known absorber. This is consistent with the approximately 20% of components in S. Redfield & J. L. Linsky (2008) that were unassigned. They also note that the G cloud is surrounded by many smaller clouds with likely interactions, including the Blue cloud. We know that the G,

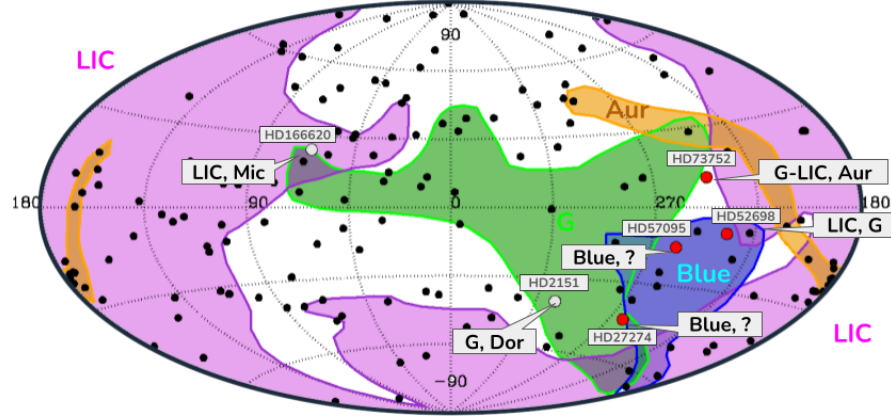


Figure 5.7 Location of sight lines in galactic coordinates with cloud boundaries for LIC, G, Blue, and Aur clouds represented with shaded regions. Sight lines are labeled with the clouds responsible for their observed absorption.

LIC, and Blue clouds are the closest interstellar clouds, because we are able to detect their absorption along sight lines to stars that are less than 3 pc away from the Sun, but there are several additional clouds whose minimum distance is also within the range of stellar distances (< 20 pc) in this sample.

Of the two components identified in the previous section as having anomalously high HI column densities, both were unable to be assigned a single absorbing cloud (HD 57095 2 and HD 27274 2). Revisiting the model comparisons for the unidentified components in Table 5.1, I note that component 2 in HD 57095 appears halfway between the predicted velocities for the G and the Vel clouds; and component 2 in HD 27274 appears halfway between the velocities for the G and the Dor clouds.

When considering the cloud boundaries for the Dor and Vel clouds from the dynamical model as seen in Figure 5.8, it seems plausible that these components are due to mixing between the G cloud and these two other clouds. HD 57095 is right on the edge of the Blue, G, and Vel clouds. HD 27274 is solidly in the middle of the Dor and G clouds (and was predicted to traverse both clouds), and riding

Table 5.1. Nearby Cloud Velocities for Unidentified Absorption Components

HD	Comp.	v_{obs} (km s ⁻¹)	v_{G} (km s ⁻¹)	Other Cloud	v_{other} (km s ⁻¹)	$(v_{\text{G}} + v_{\text{other}})/2$ (km s ⁻¹)
57095	2	15.80 ± 0.30	10.22 ± 0.97	Vel	23.37 ± 1.22	16.80
27274	2	16.31 ± 0.69	11.46 ± 1.36	Dor	20.91 ± 0.81	16.18

Note. — Observed velocity is the weighted mean across all ions for the sight line.

the border of the Blue cloud. While component 2 in HD 27274 was not within 3σ

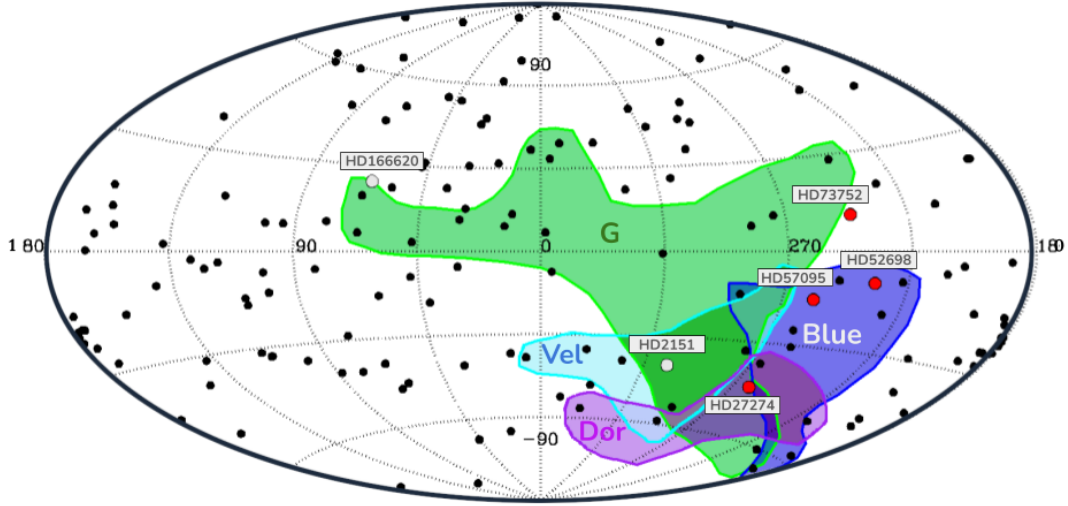


Figure 5.8 Cloud boundary map for G cloud and small, nearby neighboring clouds: Blue, Vel, and Dor. LISM sight lines from S. Redfield & J. L. Linsky (2008) are plotted in black. Sight lines used in this thesis plotted in larger circles. The four clouds nearly overlap in the vicinity of HD 27274. HD 57095 appears within the boundaries of the Blue cloud, and adjacent to the overlapping boundaries of the G and Vel clouds.

of any of the dynamical model predictions, its velocity is centered between the G and the nearby Dor cloud, and could represent an intermediate flow between them. Similarly, component 2 in HD 57095 is centered between the velocities of the G and Vel clouds. Taking this into account along with their locations, this leads me

to believe that the two unassigned components can be assigned to “subclouds” created by the mixing between two or more clouds.

To gain a better picture of how these cloud assignments physically correspond with the known LISM cloud distribution, I consider the maximum distance to the nearest cloud boundary. This is determined by taking the distance to the closest star for which a particular cloud was detected along the line of sight (S. Redfield & J. L. Linsky 2008). Figure 5.9 shows the distance to each of the clouds identified in this thesis, represented by a horizontal band of color. The approximate maximum size of each cloud is estimated by dividing the maximum HI column density reported in S. Redfield & J. L. Linsky (2008) by the appropriate cloud volume density cited in J. L. Linsky et al. (2022). Each sight line is also plotted by distance, with a black diamond point representing each component where a cloud is detected. A red diamond represents the cloud combinations where an intermediate velocity is detected. A solid line connects detected clouds along a sight line that happen to neighbor each other in the plot; the vertical dashed lines are to emphasize that clouds plotted in between the detected clouds are not necessarily themselves traversed.

Since the clouds differ substantially in morphology, size, and orientation, this is a very simplistic reduction, but it can help to visualize how the absorbing material accumulates along the line of sight. What this tells us, for example, is that the sight line to the nearest star in our sample (HD 2151) shows absorption from both the G and Dor clouds within 7.5 pc. Since the G cloud is known to begin within 2 pc of the Sun, the sight line from the Sun to the star likely crosses the G cloud first, followed by the Dor cloud, whose previous estimate of closest distance was around 12 pc. This also implies that the Dor cloud boundary extends closer to the Sun than previously detected.

Table 5.2. Summary of Cloud Properties

Cloud Name	$\langle T \rangle$ (K)	$\langle \xi \rangle$ (km s ⁻¹)	$\langle D(\text{Fe}) \rangle$	$\langle D(\text{Mg}) \rangle$	Morphology
LIC	7500 ± 1300	1.62 ± 0.75	-1.12 ± 0.10	-0.97 ± 0.23	Compact
G	5500 ± 400	2.2 ± 1.1	-0.54 ± 0.11	-0.36 ± 0.35	Compact
Blue	3900 ± 2300	2.64 ± 0.16	-0.84 ± 0.27	-0.51 ± 0.49	Compact
Aur	(6710)	(1.2)	(-1.13)	(-0.79)	Filamentary
Dor	(7000)	(5.5)	(-0.80)	(-0.65)	Compact
Vel	(10600)	(3.5)	...	(-0.03)	Compact

Note. — Adapted from Table 18 in S. Redfield & J. L. Linsky (2008). Parentheses indicate that the values result from just a single physical measurement, rather than a mean.

5.3 Previously Known Cloud Properties

Finally, we consider whether or not the derived cloud properties for each component are consistent with other observations for the same LISM clouds. A summary of previous observations of the six main clouds identified in the mixing zone sight lines is shown in Table 5.2.

While Chapter 4 established that all temperatures and turbulent velocities were consistent with the LISM aggregate, we now consider whether or not they are consistent with the individual clouds. Figure 5.10 provides a comparison of the calculated cloud temperatures with previous measurements.

Beginning with the LIC, we see that component 1 of HD 52698 appears consistent within 1σ of the quoted value. The first mixed-cloud component, HD 73752 component 1, also appears consistent with the temperature of the LIC.

There are four components ascribed to either the G cloud or interactions with the G cloud. The LIC-G mixed component in HD 52698 is closer to the temperature of the LIC than the cooler G cloud. The one component assigned solely to the

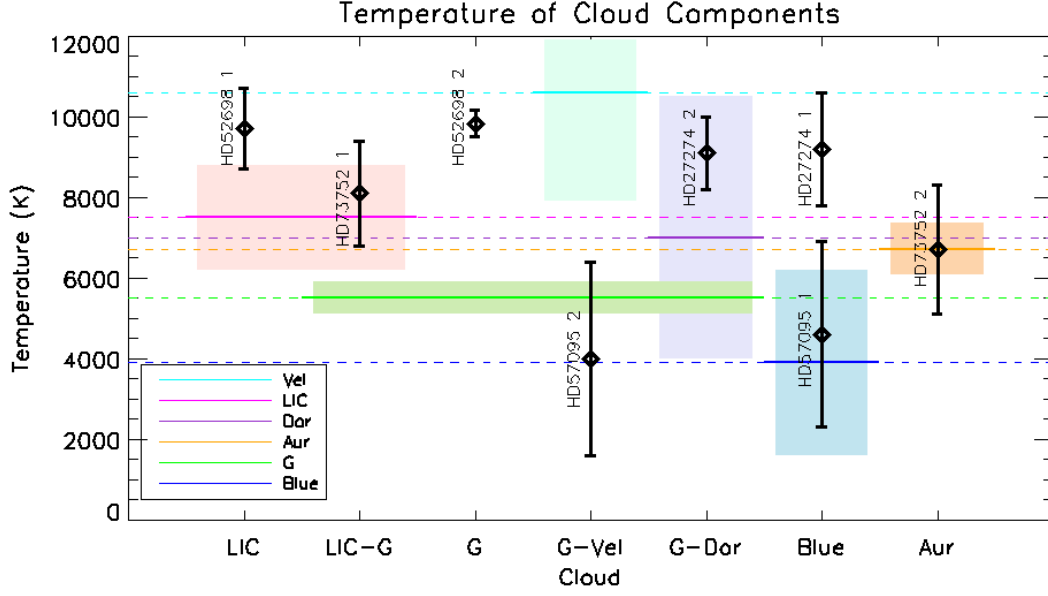


Figure 5.10 A comparison of the summary cloud temperatures from S. Redfield & J. L. Linsky (2008) with the derived values in this thesis. The shaded regions represent the $\pm 1\sigma$ error region on the summary cloud temperature (see also Table 5.2). Since the summary statistics for the Aur, Dor, and Vel clouds only used one sight line, the $\pm 1\sigma$ error was set equal to the error for the single temperature calculation reported in S. Redfield & J. L. Linsky (2008).

G cloud, HD 52698 component 2, is higher than the temperature of the G cloud by 8σ . The G-Vel mixed component 2 in HD 57095 shows a temperature consistent with the G cloud, but not the Vel cloud. The G-Dor mixed component 2 in HD 27274 is consistent with the temperature of the Dor cloud, and significantly higher than the temperature of the G cloud ($> 3\sigma$).

For the two components assigned to the Blue cloud, component 1 in HD 57095 is squarely within the average temperature. Component 1 in HD 27274, however, is about 2σ hotter than the average temperature.

The final component, HD 73752 component 2, is very consistent with the temperature of the Aur cloud to which it was assigned.

J. L. Linsky et al. (2022) noted that the inhomogeneities in temperature and

turbulence characteristic to the LISM do not show a trend with regard to stellar distance, implying that the temperature and turbulent velocities represent the clouds themselves, and not the background star. It is possible that for the components in the same sight line as cloud mixing components, the constraint of equal Doppler parameters between components in HI is having an undue influence on the cloud temperature calculations for the non-mixing component. The cloud mixing components have higher than expected HI column densities, and could also reasonably be expected to have broader line widths than expected. This could be impacting HD 27274, but is not applicable to the high temperature calculated for the G cloud along HD 52698. However, I consider the sight line to HD 52698 to be in a transitional region nearby a collision, which could conceivably have temperatures that begin to approach the other cloud involved in the collision. Overall, I consider these temperatures to be consistent with the cloud assignments we have determined.

We can also compare the elemental depletions with the elemental depletion noted by S. Redfield & J. L. Linsky (2008) for each cloud, as listed in table 5.3. Using the elemental depletions calculated from the D/H ratio and from B. Wood's Lyman- α fits, only two values are more than 2σ away from the cloud averages: component 1 of HD 52698 is less depleted in Fe than expected (i.e., more of the Fe is in the gas phase than expected); and component 2 of HD 52698 is slightly more depleted in Fe than expected. I note that component 1 also exhibited an inconsistent b_{Dop} parameter, and component 2 had a higher than expected cloud temperature. Depletion is difficult to interpret further without more information about the dust grain conditions in a given cloud.

Table 5.3. Comparison to Average Cloud Depletion

HD	Comp.	$D_{\text{obs}}(\text{Fe})$	$D_{\text{obs}}(\text{Mg})$	Cloud	$\langle D_{\text{cloud}}(\text{Fe}) \rangle$	$\langle D_{\text{cloud}}(\text{Mg}) \rangle$
73752	1	-1.08 ± 0.36	-0.86 ± 0.26	LIC	-1.12 ± 0.10	-0.97 ± 0.23
	1	-1.08 ± 0.36	-0.86 ± 0.26	G	-0.54 ± 0.11	-0.36 ± 0.35
	2	-1.03 ± 0.49	-1.40 ± 0.56	Aur	(-1.13)	(-0.79)
52698	1	-0.52 ± 0.34	-1.36 ± 0.28	LIC	-1.12 ± 0.10	-0.97 ± 0.23
	2	-1.69 ± 0.51	-1.44 ± 0.27	G	-0.54 ± 0.11	-0.36 ± 0.35
27274	1	...	-1.27 ± 0.55	Blue	...	-0.51 ± 0.49
	2	...	-0.4 ± 2.4	G	...	-0.36 ± 0.35
	2	...	-0.4 ± 2.4	Dor	...	(-0.65)
73752	1	-1.13 ± 0.36	-0.90 ± 0.26	LIC	-1.12 ± 0.10	-0.97 ± 0.23
	1	-1.13 ± 0.36	-0.90 ± 0.26	G	-0.54 ± 0.11	-0.36 ± 0.35
	2	-0.44 ± 0.49	-0.90 ± 0.56	Aur	(-1.13)	(-0.79)
52698	1	-0.37 ± 0.33	-1.20 ± 0.27	LIC	-1.12 ± 0.10	-0.97 ± 0.23
	2	-1.56 ± 0.50	-1.20 ± 0.27	G	-0.54 ± 0.11	-0.36 ± 0.35
57095	1	-1.39 ± 0.76	-0.52 ± 1.8	Blue	-0.84 ± 0.27	-0.51 ± 0.49
	2	-1.4 ± 1.1	-0.51 ± 0.50	G	-0.54 ± 0.11	-0.36 ± 0.35
	2	-1.4 ± 1.1	-0.51 ± 0.50	Vel	...	(-0.03)
27274	1	...	-0.62 ± 0.55	Blue	...	-0.51 ± 0.49
	2	...	-0.6 ± 2.4	G	...	-0.36 ± 0.35
	2	...	-0.6 ± 2.4	Dor	...	(-0.65)

Note. — Elemental depletion calculated using HI column densities from DI (above horizontal line) and from B. Wood (below horizontal line). Average depletion from cloud average in S. Redfield & J. L. Linsky (2008). For mixed cloud components, the depletion is compared separately for each individual cloud. Parentheses indicate value comes from a cloud with only one physical measurement. Note that the direct HI column densities were constrained to match the ratio of the column densities measured in Mg II between components.

Table 5.4. Evidence for Interstellar Cloud Mixing

HD	Comp.	Anomalous $\log N(\text{HI})$	Intermediate Velocities	Unusual Depletion	Inconsistent b_{Dop}	Mixing?
73752	1	—	✓	—	—	LIC-G
	2	—	—	—	—	No
52698	1	—	—	Fe	✓	Transition?
	2	—	—	Fe	—	No
57095	1	—	—	—	—	No
	2	✓	✓	—	—	G-Vel
27274	1	—	—	—	—	No
	2	✓	✓	—	—	G-Dor

Note. — Threshold for unusual depletion is $\geq 2\sigma$ deviation from average value for assigned cloud.

5.4 Do we see signs of mixing?

We now address our central question: is there physical evidence provided by these sight lines to support the LIC-G mixing zone proposed by P. Swaczyna et al. (2022)? A summary of the evidence for mixing for each sightline is shown in Table 5.4.

The clearest evidence in favor of mixing is that HD 73752 shows very clear absorption at precisely the right velocity to attribute it to either the LIC or G cloud, or both. This indicates that prior nearby observations (those that fed into the kinematic model) had velocity vectors that pointed to a situation where at this set of coordinates both clouds were predicting to be moving at nearly the exact same speed in the radial direction. I consider this to be a sign of the plasma between the two clouds reaching an equilibrium velocity. This component also exhibited a higher than expected HI column density, a further sign of cloud mixing. In conjunction, the nearby sight line HD 52698 also lends support to a cloud collision, as its two absorbers separately appear at velocities consistent with

the LIC and G clouds. Both components in HD 52698 also have temperatures close to the known temperature of the LIC. However, as these two components do not have atypically high HI column densities, I place this sight line as “near” the mixing in a transitional region, and not totally within the mixing zone.

For the two unassigned components, I do not see evidence of LIC-G mixing. However, taking into consideration the following points:

1. Both sight lines fall along the borders of the Blue and G clouds, with absorption from the Blue cloud detected;
2. both unidentified components have velocities that are not consistent with the LIC or G cloud predictions alone;
3. that the G cloud is noted to be particularly prone to interaction with other clouds, even being referred to as the “Ring of Fire” (S. Redfield & J. L. Linsky 2008);
4. and as established in Section 5.1, both components have anomalously high HI column densities, indicative of possible cloud mixing;

I believe that the two unassigned components are due to clouds that are mixing, but not with the LIC. Rather, I believe that the G cloud is mixing with several smaller clouds in the region. HD 57095 has absorption consistent with a velocity halfway between the G and Vel clouds, with a temperature consistent with the G cloud. HD 27274 has absorption consistent with a velocity halfway between the G and Dor clouds, with a temperature consistent with the Dor cloud.

This means that for three of the four mixing zone sight lines, I see evidence of cloud mixing between the G cloud and another cloud. All other components were

assigned to individual clouds predicted by the kinematic model. My final cloud assignments appear in Figure 5.11.

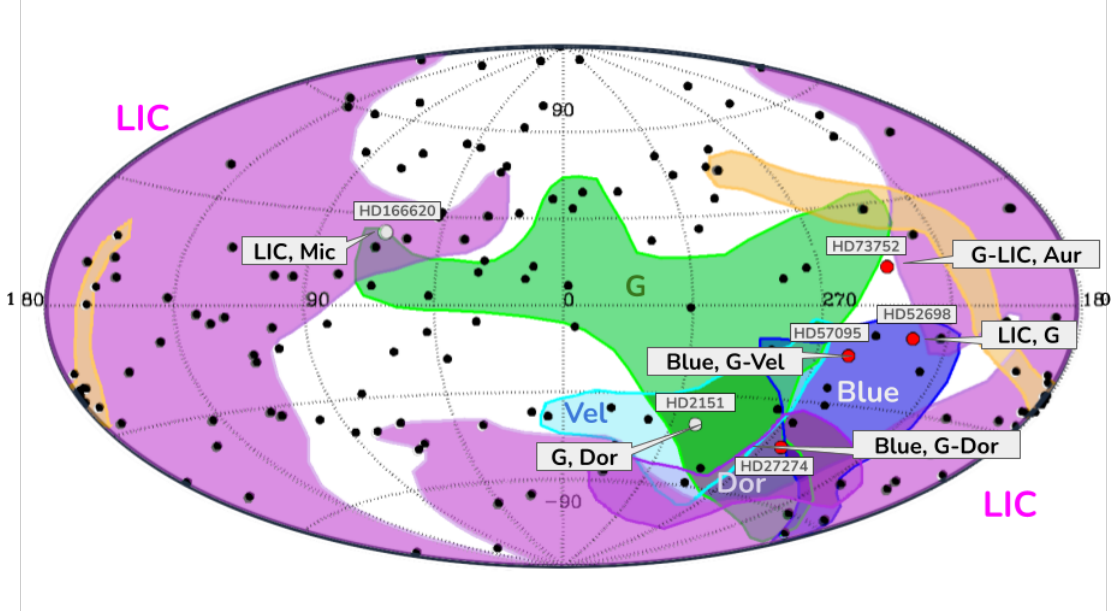


Figure 5.11 Final Cloud Assignments.

5.5 LISM towards HD 166620 and HD 2151

My analysis towards these two sight lines, performed for B. Wood, was limited to Mg II and Fe II fit parameters and cloud assignments. Both sight lines were fit with two components whose central velocities were in good agreement with predictions made by the kinematic model. The absorption in HD 166620 was saturated in Mg II and blended in Fe II, which made it more difficult to achieve a stable central velocity, but ultimately a satisfactory fit was obtained.

The NUV LISM fit parameters and flux background are also useful for fitting the hydrogen Lyman- α profile. Because so much of the Lyman- α profile is absorbed, it is very difficult to approximate the stellar continuum background as done with the methods described in Chapter 3. Rather, the Mg II flux background

provides a strong starting point for the shape of the stellar profile. The LISM fits for HD 166620 were used to inform B. Wood’s analysis of the star’s Lyman- α profile through providing a reasonable shape for the continuum, and by identifying the extent of the absorption that could be attributed to LISM (rather than astrospheres or the heliosphere). The LISM fits I performed appeared in B. E. Wood et al. (2026), whose primary purpose was confirming that HD 166620 appears to be experiencing a magnetic grand minimum like that of the Sun’s Maunder minimum in the 17th century, and establishing the extent of the astrosphere surrounding τ Ceti.

The absorption components for HD 2151 were more clearly separated, and showed close agreement with the fitting parameters and model predictions for both ions. While there are no plans at present to work further with this sight line, it was an excellent chance to practice the fitting process on a very straightforward sight line, and will find a home in a future paper.

Chapter 6

Conclusions

Your reward will be the widening of the horizon as you climb. And if you achieve that reward you will ask no other.

CECILIA PAYNE-GAPOSCHKIN

6.1 Conclusions

I initially set out to analyze just four sight lines in the heart of the projected mixing zone, expecting to find some assortment of clear indicators involving the LIC and G clouds. Instead, I found that only one of these sight lines showed clear evidence of LIC-G mixing (although another provided signs of a transitional zone), and the remaining two sight lines implicated the G cloud in further cloud collisions with the nearby Dor and Vel clouds. This supports the idea of the LIC-G colliding clouds model, but restricts the spatial extent of the interaction. This also supports S. Redfield & J. L. Linsky (2008)’s description of the G-cloud boundary as particularly active and prone to creating distinct smaller clouds. My detection of absorption from the Dor cloud at a distance of only 7.5 pc also implies that the Dor cloud extends 5 pc closer to the Sun than previously detected.

Many cloud components were detected crossing clouds that were not predicted

by the kinematic model. This indicated to me that the existing kinematic model boundaries (like all models) are imperfect in describing this region. However, every detected component in this study was attributable to either a distinct predicted component or a combination of two predicted components within 20° of the sight line, demonstrating the enduring value of the model's predictive power.

I also collaborated with other researchers, applying my growing skills to two additional sight lines, exchanging theories and data, and resulting in one co-authored paper so far. Additionally, I have created a searchable database (described in Appendix A) of existing *HST* observations towards nearby stars that are well-suited to LISM spectroscopic analysis and will streamline further collaborative studies of archival data.

6.2 Future Work

These six sight lines contribute to the overall effort of better characterizing the LISM sky, and refinement of the cloud boundaries established by S. Redfield & J. L. Linsky (2008) in an area where there are many subtleties. However, there are many more areas of the observable sky where we still lack sufficient observations in order to truly capture the more granular distinctions.

Future work on the database will include migration to a more permanent home on the Wesleyan architecture, development of a mechanism to query MAST and add additional new observations in a semi-automated fashion, and making the database accessible to other users through a front-end interface. While maintaining the tables of literature references and spectral analysis will still need to be performed manually, these occur less frequently and can be managed by someone in the subfield who remains alert to new LISM publications.

The full value of this database depends on its ability to be refreshed with new observations on a semi-regular basis. Throughout the course of this research, I encountered several instances where new, highly suitable observations appeared in MAST, but which were not yet included in the database because they had been obtained after I made the initial query. Two weeks before submitting this thesis, I noted that a new *HST*/STIS observation (associated with *HST* Program 18057) had appeared on MAST, taken with the E230H grating. The proposal that generated this observation is not primarily concerned with the LISM; rather, the investigators are motivated by the elemental abundances of many nearby solar-like stars. However, this data is perfect for the kind of LISM analysis as performed in this thesis, and there are many important connections between stellar abundances and LISM abundances, as discussed in Chapter 4. I took a first look at

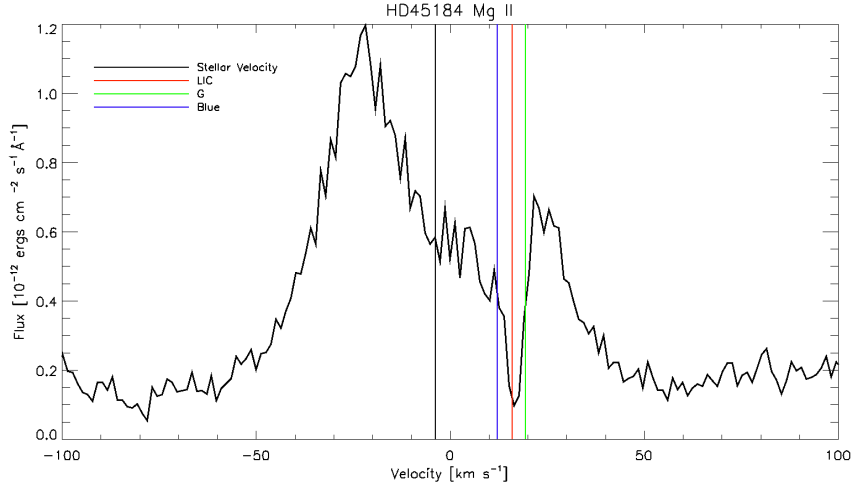


Figure 6.1 Quick-look view of HD 45184 Mg II, normalized to the rest wavelength of Mg II 2796 Å, along with three nearby LISM cloud predictions. There is absorption at the appropriate velocity to indicate that the sight line to HD 45184 could traverse one or more of these clouds.

this dataset with a comparison of the sight line's coordinates in the dynamical model (see Figure 6.1), and noted clear LISM absorption consistent with one or

more nearby LISM clouds. Additionally, I noted that this sight line happens to fall along the mixing zone studied in this thesis, near HD 52698. My research supervisor, Seth Redfield, has made contact with the PI of this observing program to discuss analyzing the LISM for this sight line. It is my hope that the database will illuminate many other datasets that are highly relevant for multiple research interests, and enable future collaborations between LISM scientists and those in other subfields.

As *HST* nears the end of its operational lifespan, we are preparing to lose the ability to perform this kind of analysis with high-resolution UV spectra. This means that the ability to avoid duplicating effort by having an accurate picture of the observed LISM sky (whether intentionally collected or not) is a valuable asset that can help guide future proposals as we aim to gather as much high-quality data on the LISM as possible. Additionally, as astronomers optimistically prepare for the future Habitable Worlds Observatory¹, *HST*'s remaining lifespan allows us a limited window to obtain the measurements we need to accurately characterize the LISM towards the Habitable Worlds target list. As shown through our collaboration with Brian Wood, this is critical to the study of astrospheres, which are themselves important indicators of planet habitability.

During the months spent writing this thesis, I was struck again and again at the irony of witnessing the real-time systematic dismantling of the American educational and scientific infrastructure that enabled me to do this work at all. There were times when working on it felt futile, when I questioned whether I had a future in this field, or whether I had a future at all. But science is a collective endeavor, and even when progress seems slow or incremental, each piece

¹A proposed flagship space telescope to identify potentially habitable exoplanets, with launch potential in the 2040s.

contributes to a more complete picture of the universe. These six sight lines help us know the LISM sky just a little bit better than we did before, and give us new questions to consider. This work built on many such pieces of knowledge established by earlier Wesleyan astronomers, including the work of Katy Wyman, Craig Malamut, Eric Edelman, Julia Zachary, Fallon Konow, Hunter Vannier, and Rewa Bush; and I hope it will be followed by many more future astronomers seeking to better understand our local interstellar environment, and our home within it.

Acknowledgments

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This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2018, 2013); matplotlib, a Python library for publication quality graphics (J. D. Hunter 2007); and NumPy (C. R. Harris et al. 2020).

This research made use of MariaDB, an open-source relational database software.

The acknowledgments were compiled using the Astronomy Acknowledgment Generator.

Appendix A

A.1 A Searchable LISM Database

The **D**atabase of **O**bservations and **L**iterature for **LISM** **S**ight lines (DOLLS)¹ is designed to facilitate the analysis of the LISM along sight lines where the LISM is not necessarily the primary focus of the proposal, as well as providing an archive of existing LISM measurements across ions and sight lines. DOLLS is built using MariaDB, a free, open-source alternative to MySQL, and responds to standard MySQL queries. Some helpful examples will be provided throughout. Database commands are case-insensitive, but are shown here in uppercase in order to distinguish them from field and table names.

A.2 Getting Started

To launch the database:

```
> mariadb  
> USE lism;
```

To show the available tables:

```
> SHOW TABLES;
```

To describe a particular table:

¹Thank you to E. Mansell for workshopping this acronym with me.

```
> DESCRIBE table;
```

Sight Lines

The table `sightlines` contains basic identification data for stars within 100 pc of the Sun, such as spectral type, other names, coordinates, and distance.

Observations

The `observations` table is primarily sourced from the MAST Archive, and provides enough information in order to locate the observation set within MAST. Names have been standardized, and observation records have been filtered to include only stellar targets within 100 pc (i.e., targets that should appear in the `sightlines` table). Fields of particular utility include the grating/filter and spectrum start/end, which are critical for establishing whether a particular ion is observed within the dataset.

Literature

The `literature` table contains reference information for papers including analysis of LISM sight lines. The field with the most utility is `ref`, which provides an easily readable identifier for the source of each measurement in the format “last name of first author last two digits of publication year,” e.g., “REDFIELD02” for S. Redfield & J. L. Linsky (2002).

Spectral Analysis

The `spec_analysis` table contains one line for every observed LISM component in every ion, and includes the fitting parameters and their errors.

Components

The `components` table contains one line for every observed LISM component (irrespective of the number of observed ions), and provides physical parameters such as temperature, turbulence, H I column density, cloud assignment, and depletion for Fe II and Mg II where available.

Unanalyzed

The table `unanalyzed` contains sight lines which have been observed by HST (as per the `observations` table) but which have not been analyzed (as per the `spec_analysis` table).

A.3 Tips and Tricks

To show only the first x results:

```
> SELECT * FROM table LIMIT x;
```

To show only unique results along a particular field:

```
> SELECT * FROM table GROUP BY field;
```

To search for a particular target by name or HD number:

```
> SELECT * FROM table WHERE LOCATE (table.field, target_name);
```

To generate a temporary table during a session:

```
> CREATE TEMPORARY TABLE temp SELECT * FROM table WHERE  
(criteria1 <= threshold) AND (criteria2 IN ('list', 'of',  
'options')) ;
```

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