H I Line Profiles of Galaxies: Tilted Ring Models

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Abstract

Two-dimensional information on the kinematics and spatial distribution of gas in spiral galaxies is encoded in radio observations of their one-dimensional 21-cm neutral hydrogen (HI) line profiles. More than ten thousand HI profiles have been published and are publicly available. In order to explore the parameter space mapped out by the 21-cm neutral hydrogen line profile, we have modified and run a FORTRAN-based computer simulation code. We have identified 7 control parameters that define the morphology of the modelled galaxy: they describe the neutral hydrogen gas distribution (density and spatial location of the gas), characteristics of its rotation curve, warps, asymmetries, and finally, the viewing angle. All except the last of these parameters tell us significant physical information about the galaxy but a determination of them is not immediately apparent from the two-dimensional 21-cm line profile. Hence, the goal of this exploration is to find meaningful correlations between the observed 21-cm line profile features and the underlying physical parameters.
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Chapter 1

Introduction

1.1 Introduction

From an indicator of potential star forming regions to a tracer of galactic interaction history for use in redshift surveys, extragalactic neutral hydrogen as measured by the 21-cm emission line has a rich history of scientific use in astronomy. It has been studied extensively using single-dish radio telescopes, which yield an integrated line flux profile as a function of heliocentric velocity of an unresolved galaxy in the beam. For the wealth of published profiles, we introduce a classification scheme based HI line profile morphology and a model to translate between profile shape and physical properties of the contributing galaxy.

Until the early 20th century, the word galaxy was synonymous with the word universe (Kauffman, 2002). The extent of the known universe encompassed 1 billion stars and extended light sources then thought to be stars in early stages of formation. However, in 1923 Edwin Hubble established the ex-
istence of an external galaxy by finding the distance to M31 (Hubble, 1929), launching the study of the universe through an important structural building block galaxies. While stellar structure and evolution and cosmological structure and evolution are somewhat well understood, our understanding of the structural properties and evolution of galaxies lags behind, creating a strange gap in knowledge in the midrange of astrophysical sizes.

Galaxies are comprised of stars, dust, gas, and dark matter and are classified by their optical morphologies roughly in two types: elliptical galaxies and spiral galaxies. Elliptical galaxies are old, gas and dust-free, star-dominated, and elliptically-shaped. Spiral galaxies morphologically take the form of a disk-like structure with a centrally located bulge. The highly flattened spiral galaxy is an organized structure in which stars, gas, and dust move in circular orbit around the center of the galaxy (Kauffmann, 2002). Characteristically younger, the disks of these galaxies are rich in gas and dust and have active star formation processes (figure 1.1).

The composition of spiral galaxies varies, but we can say a few things about the relative abundances of the various components from observation. The overall baryonic mass is dominated by stars with the ratio of gas to total baryonic mass \(< M_{\text{gas}}/M_{\text{total}} >\) ranging from 0.04 to 0.25 as shown by analyses of neutral hydrogen HI, ionized hydrogen (HII), and carbon monoxide (CO) emission (which is a good tracer of molecular hydrogen \(H_2\)) (Carol & Ostilie, 1996). Gas constitutes a greater fraction of the total mass in galaxies with low bulge-to-disk ratios, while stellar mass dominates to a greater
Figure 1.1: Sample Spiral Gemini and Elliptical galaxies. (Spiral galaxy M74 - courtesy of the Gemini project, Elliptical galaxy M87 - courtesy of the Anglo-Austraian Telescope. Image credit: www.galex.caltech.edu/SCIENCE/galaxies.html)

extent in galaxies with high bulge-to-disk ratios.

Spiral galaxies have a rich variety of spiral structure in terms of the number of spiral arms and how tightly these arms are wound. Structurally they range from grand design spirals with two arms, to multi-armed spirals, to flocculent spirals with indistinguishable arms. These arms are dominated by O- and B- type main sequence stars and HII regions, with dust and HI regions more prevalent on the inner edges of the arms. Spiral structure is due to density waves in which a spiral arm has a mass density that is greater than the average mass density of the galaxy by 10-20% (Carol and Ostilie, 1996).
1.2 Neutral Hydrogen

In the following introductory remarks, I have relied heavily on the comprehensive review by Riccardo Giovanelli and Martha Haynes. Readers are referred to that article for further details and references therein. Galaxies can be observed in a vast range of different wavelengths corresponding to different galactic components with different associated energetic processes. One of these is 21-cm line emission from the hyperfine energy transition in neutral hydrogen gas (HI). This is the magnetic dipole transition between the two ground state energy levels of the hydrogen atom. The hyperfine splitting of energy levels in the ground state comes from the electronic and nuclear spin vectors being parallel or anti-parallel. If they are parallel, the atom is in a slightly higher energy triplet state; if they are anti-parallel, the atom is in a slightly lower energy singlet state. When an atom makes the very small (or rather hyperfine) energy transition between these two energy levels, it emits a low-energy photon that has a wavelength of 21-cm (see Figure 1.2).

The 21-cm line conveys a great deal of information about a galaxy as tracer of composition and evolutionary history. Neutral hydrogen clouds play an important role in stellar evolution as the starting point for collapse of matter into stars. Neutral hydrogen is the first phase of star formation before the gas congeals into denser molecular hydrogen and collapses to start stellar nuclear burning. As an indicator, abundant HI then signals potentially active star formation processes, while a lack of HI is a guarantee of a
barren galaxy with an old stellar population. (Giovanelli & Haynes, 1988) Therefore, neutral hydrogen is of primary importance in understanding stellar population evolution of a galaxy.

HI is also useful as an indicator of galactic evolutionary history in terms of interactions. HI is vulnerable to environmentally driven gas removal mechanisms and can therefore be used to probe the effect of the environment surrounding a galaxy on its development. The fragile outer layers of HI are easily disturbed by close encounters with other galaxies. This means HI can be used to probe the nature of galactic interactions, which are essential to a complete picture of galaxy formation and evolution (Giovanelli & Haynes, 1988).

While HI is an important part of the evolutionary history of a galaxy, its dynamical role is somewhat less important as a result of its small mass.
fraction in most galaxies. The optical surface brightness of the disk in a spiral galaxy falls off exponentially with distance from the center of the galaxy, resulting in half the spatially integrated luminosity being contained in a 4-5 kpc radius. Similarly, most of the interstellar gas lies in the plane of the disk and its density falls off exponentially with a similar effective radius. Within this optical radius, HI constitutes 10% of the total mass of $1.5 \times 10^{11} M_{\odot}$.

Considering galactic composition out to 100 kpc, the dynamic mass increases to $10^{12}$, making the HI mass fraction only 1% of the total. This fraction is not, however, entirely constant – HI varies in importance as a constituent with morphological type. Galaxies of late morphological type are richer in HI than galaxies of earlier morphological type (Giovanelli & Haynes, 1988).

Thus distribution and content of HI are related to optical morphology,
but optical light and HI emission do not necessarily originate from the same locations in the galaxy. In optical disk galaxies, the HI distribution is also disk shaped with a radius as described above and a thickness that is constant within the inner 10-12 kpc. Defined out to the point where the HI density is half of its density in the plane of the galaxy, the disk is 150-250 pc thick. The most noticeable feature of this disk is the central HI surface density depression (see Figure 1.4a). While HI is dominant in the periphery of the galaxy, extending the farthest of any of the visible components (see Figure 1.4c), in the inner regions of the galaxy, molecular hydrogen dominates the interstellar medium (see Figure 1.4b). The strength of the depression is related to optical morphological type. Early-type galaxies with large nuclear bulges have bigger depressions. At the extreme end with S0 galaxies, the bulge is so dominant that the HI distribution is almost ring-like surrounding it. In intermediate galaxies, just the central region dominated by the bulge is barren of HI. On the other end, late-type galaxies have a HI distribution similar to the distribution of their optical light: clumpy and disorganized (Giovanelli & Haynes, 1988).

A substantial portion of HI mapped galaxies show evidence of warps and/or asymmetries. A warp is a deviation in the outer regions of the HI distribution from the plane defined by the inner regions. They can be detected either by edge-on observation of the warp or more face-on observations due to the deviation from circular motion in velocity fields. These warps could be due to tidal interactions, but the mechanisms for their creation and
(a) Central depression in HI shown in blue
(b) The central regions of spiral galaxy IC 342 are dominated by molecular gas (green) while atomic hydrogen, H I, dominates in the outer regions (red)
(c) images of NGC 2403 in HI on left and optical on right in the same scale showing the HI disk extending far beyond the optical light.

Figure 1.4: image credit: NRAO
Asymmetries in the density distribution of HI are also common in spiral galaxies and are also likely due to interactions with neighboring galaxies.

1.3 Velocity Fields

The rotation of spiral galaxies can be described by a rotation curve - a function $V(r)$ that describes the tangential velocity ($V$) in the plane of a rotating disk in terms of the distance from the center of the galaxy ($r$). This rotation curve is a tracer of the gravitational potential energy of the galaxy and thus a probe of total mass content of the galaxy - its stars, gas, dust, dark matter, and radiation. It was thought until the 1970s that the luminous matter was a good tracer of the total mass of the galaxy. Since the tangential velocity at a given radius is proportional to the total mass enclosed ($M$) in a radius ($r$), tangential velocity should be observed to decrease with $r^{-1/2}$ at large radii. Measurement of rotation curves outside the optical disk showed that rather than decreasing as $r^{-1/2}$, tangential velocity actually remains roughly constant for large radii, meaning that the total mass of the galaxy does not fall off exponentially with radius but rather increases linearly (Giovanelli & Haynes, 1988).

A typical rotation curve is shown in Figure 1.3 with the characteristic linear rise of the velocity to a maximum ($V_{\text{max}}$) at which it remains flat. $V_{\text{max}}$ is a function of the luminosity and morphological type of a galaxy.

preservation are not yet completely understood (Giovanelli & Haynes, 1988).
Figure 1.5: Rotation curve of a typical spiral galaxy. Note the linear rise to a maximum rotational velocity then a leveling off of the velocity value out to a large distance. image credit: http://archive.ncsa.uiuc.edu/Cyberia/Cosmos

The higher the luminosity and earlier the type, the higher the maximum rotational velocity will be. The highest $V_{max}$ observed is 500 km/s in S0a galaxy UGC 12591 (Giovanelli & Haynes, 1988).

1.4 21-cm Line Observations

The 21-cm line is observed using radio telescopes. A radio telescope has two basic components – a large radio antenna and a radio receiver. The most familiar type of radio telescope is the radio reflector, which is a parabolic antenna. In this set-up, a receiving antenna is used to focus incoming radiation onto a small feed antenna. The feed transfers the incoming signal to a radio
Figure 1.6: A visual representation of HI data. a) Radial density profile with radius on the horizontal axis and density on the vertical axis. b) Distribution of the above HI density profile in the disk of the galaxy with the grey scale proportional to the HI column density. The solid lines show isovelocity contours (locations that have the same tangential velocity). c) Rotation curve that shows tangential velocity on the vertical axis with respect to radius on the horizontal axis. d) Spatially integrated HI line flux from observations of unresolved disk with single dish observations with flux in the horizontal direction and tangential velocity in the vertical axis – the 21-cm HI line profile. (figure adapted from Giovanelli & Haynes, 1988)
receiver using a waveguide (NRAO.edu).

The 21-cm line was first detected in the Milky Way galaxy by Ewen and Purcell in 1951 and again two years later by Kerr and Hindeman (1953). With the work of M. S. Roberts, 140 extragalactic objects were detected (review article 1975). Since that time, the emission of thousands of galaxies out increasingly higher redshifts have been observed (Freudling et al. 1988; Giovanelli et al. 1986; Giovanelli and Haynes 1989; Giovanelli and Haynes 1993; Haynes and Giovanelli 1986; Haynes et al. 1997; Magri et al. 1988; Scoddeggio et al. 1995; van Zee et al. 1995; Wegner et al. 1993) on single dish radio telescopes: primarily Nancay, Greenbank, Effelsberg, and Aricibo (Springob et al.). By the mid 1970s, spectral line aperture synthesis techniques evolved at Cambridge, Green Bank, and Owens Valley developing into the VLA. Aperture synthesis allows HI distributions to be spatially resolved providing HI mapping capabilities.
If a galaxy is resolved, we can imagine its 21-cm line data as a data cube with HI emission flux as a function of a two-dimensional position and radial velocity. Shown in Figure 1.6 is an example of an idealized intermediate-type galaxy having the entirety of its HI content in a flat disk as well as having axially symmetric radial velocities and HI gas distribution. This galaxy has a radial density profile (H I density as a function of radius) shown in Figure 1.6 panel a and a rotation curve (radial velocity as a function of radius) shown in Figure 1.6 panel c. Integrating the flux of this galaxy over radial velocity yields the spatial flux distribution (Figure 1.6 panel b). If the galaxy is not spatially resolved as with all extragalactic single dish observations the data cube of the galaxy is integrated over spatial position to give HI flux as a function of radial velocity (Figure 1.6 panel f). Thus we can see for single-dish observations that any position information about the HI distribution is lost (Giovanelli & Haynes, 1988).

1.5 Modeling and Classification

As a first step in understanding a collection of objects, it is helpful to classify them according to their morphological characteristics. To this end, Fisher and Tully (Fisher and Tully, 1975) were the first to classify the forms of line profiles encountered in 21-cm neutral hydrogen studies. In the course of observing 179 DDO dwarf galaxies with the NRAO 91-m radio telescope, they gave “shape profile codes” to the HI profiles. This classification scheme
divided profiles into two major Types and four different Shapes. Type 1 profiles are double peaked profiles and Type 2 are single peaked profiles. Shape 1 is steep sided with a flat or double peaked top. Shape 2 has a single peak at the top and is triangular or gaussian with nearly equal slopes on either side. They expanded the classification scheme to account for asymmetry with Shape 3 and 4. Shape 3 has well defined sides and would be the same as Shape 1 except for either a sharply sloping top or very asymmetrical peaks. Shape 4 is the same as Shape 2 except for notably different slopes in either side.

This classification scheme was subsequently expanded upon by Tifft (1978) who, for (non-mainstream) reasons of his own, included suffix descriptors to the two main Types (which he renamed Classes) to qualify the asymmetries with more explicit information about the extent of asymmetry and its velocity location in the profile. The result was nine classes ranging from symmetric through slightly asymmetric (S) and moderately asymmetric (M) to extremely asymmetric (E), applied to either the high-velocity (H) or low-velocity (L) side of the profile. Noisy profiles were classified as (X), while complex (multiple peaked) profiles received a terminal code, indicative of the total number of peaks (3, 4, or M for multiple).

Seemingly independently, Shostak (1978) described a classification scheme based on a ‘p parameter’ relating to HI distribution with respect to the rotation curve, with the goal of showing a correlation between Hubble type and HI morphology.
To explain a peculiar velocity field in the HI distribution in M83 (and subsequently in M33), Rogstad et al. (1974 & 1975) proposed warping in the plane of the galaxy. To model this warp, they analyzed the HI velocity field with a model consisting of neutral hydrogen located in concentric rings rotating around the center of the galaxy. Each ring was allowed to have an arbitrary tangential velocity, inclination to the line of sight, HI mass density, and tilt angle with respect to the its neighboring rings.

Progress was made in modeling by Roberts (1978) who created a program to generate HI line profiles in an attempt to better model velocity profile characteristics as part of a study of 21-cm line widths. His model takes into account the rotation curve, velocity dispersion, HI distribution, antenna beam size, and the velocity resolution of the observation.

Building on the work of these groups, I focused on the classification and modeling of neutral hydrogen line profiles. This model, built by my advisor
Barry Madore and inspired by the work of Roberts (1978), is a computer simulation code, which produces a theoretical HI line profile from a set of control parameters. The model uses seven control parameters to characterize the morphology of the galaxy in 21-cm; these parameters describe the spatial location and density of the neutral hydrogen gas distribution, the galaxy's rotation curve, and the viewing angle of the observer with respect to the galaxy. Besides the viewing angle, all of these parameters relate to significant physical information about the galaxy. This model in hand, I explored correlations between the observed 21-cm line profile features and the underlying physical parameters.

In the upcoming chapters I will discuss different aspects of coming to understand the relationships between profile shape and various physical parameters. Chapter 2 discusses the construction of the model – the parameters used and how it works. Chapter 3 considers two different ways of classifying profile shape (one qualitative, one quantitative), how well these two classification schemes agree, and how galaxies are distributed amongst the different profile types in nature. Chapter 4 describes the method by which parameters are investigated in running the model. Chapter 5 presents the results of running the model with the parameters described and synthesizes the model’s output with real galactic HI data.
Chapter 2

The Model

Capturing the essence of the immeasurable complexity of a galaxy containing tens of billions of stars, and billions of solar masses of gas, dust and dark matter requires distilling down to only the bare essentials of composition and motion. In order to extract useful information about the most fundamental parameters, we have modeled spiral galaxies using a tilted ring model considering the density profile, rotation curve, and viewing angle.

Consider the geometry of observing a disk galaxy as shown in Figure 2.1. We can define the three principal axes with respect to the observer. In the plane of the galaxy, the minor axis follows our line of sight out through the galaxy. The major axis, also lying in the plane of the galaxy, is perpendicular to the minor axis and to our line of sight, connecting points $A$ and $B$. The third, mutually perpendicular axis is in the direction of the vector normal to the plane of the galaxy.
Figure 2.1: A rotating disk viewed from above. An observer sees the galaxy edge-on, looking down the minor axis; the major axis is perpendicular, connecting points A and B (Image Credit: Sparke & Gallagher)
As a first approximation, we idealize a spiral galaxy as being a thin disk, with the mass and motion predominantly in the plane of the disk. In addition, most of the parameters have a primarily radial dependence, so it is effective to use the time-tested tilted ring model (Roberts, 1978). In this model, the galaxy is divided into thin concentric rings or annuli. These annuli can be filled with varying amounts of neutral hydrogen, made to rotate at different velocities, and tipped and tilted with respect to each other.

2.1 Viewing Angle

While not a physical property of the galaxy, the orientation of the galactic disk with respect to the observer has a significant impact on the observed shape of the HI line profile. Thus, we will define the orientation of the galaxy relative to the observer with a quantity called the viewing angle. The viewing angle \(i\) is the angle between the line of sight and the galaxy's normal vector (See Figure 2.2. That is to say, a galaxy with an viewing angle of \(i = 0^\circ\) is completely face-on and a galaxy with an viewing angle of \(90^\circ\) is edge-on. While unimportant physically, understanding the effect of viewing angle on profile shape is crucial to being able get a grasp on the other physical properties of the galaxy. In optically resolvable galaxies, the viewing angle can be roughly measured by finding the ratio of the major and minor axes, so being able to extract the effect of the viewing angle on the profile would be useful for recovering the physical information buried underneath it. In
Figure 2.2: The observers line of sight makes and angle $i$ (the viewing angle) with the disk’s rotation axis $z$ which is perpendicular to the plane of the disk (Image Credit: Sparke & Gallagher)
the model, the viewing angle can be set to any value between $i=0^\circ$ and $i=90^\circ$ degrees. With this angle specified, radial velocities can be calculated accordingly. Needless to say, the situation is much more complicated when the tilted ring model is fully deployed, and the concept of a unique viewing angle becomes obscure at best.

2.2 Density Profile

The distribution of HI in spiral galaxies lies relatively flat in the plane of the galaxy, amassed in roughly continuous arm-like structures extending from the interior to exterior of the galaxy. The gas is arranged into a clumpy distribution – a patchwork of high and low surface density regions. Peak surface density typically ranges from $5 \times 10^{20}$ atoms $cm^{-2}$ in M81 to $5 \times 10^{21}$ atoms $cm^{-2}$ in M31. The HI distribution generally extends significantly further than the extent of optical light, generally well beyond one Holmberg Radius ($R_H$ - a size estimate of a galaxy defined as the radius at which the surface brightness of a galaxy is 26.5 magnitudes arcsec$^{-2}$ in blue light) (Binney, 1981).

To characterize the spatial distribution of HI mass in the galaxy, it is useful to define the density of gas as a function of position, as it tells us the relative quantity of mass at a given position, giving a density function that could vary radially, axially, or with height above or below the plane. To simplify this model, we can make a few assumptions. First, we will compress
the galaxy into its two-dimensional plane making it flat. This eliminates dependence of the density as a function of height above or below the plane. This is a relatively good assumption given that a spiral galaxy such as the Milky Way is fifty times larger in diameter (100,000 ly) than it is thick (2000 ly) (Bok & Bok, 1981). Second, the gas distribution can be modeled as azimuthally symmetric. While this is not generally true, it is useful for our purposes, especially for dynamical considerations for which the mass enclosed within a given radius is the only important quantity for gravitational force.

With these two assumptions, we have a height and azimuthally symmetric model for HI distribution giving a density function that varies only radially. The density profile gives the density as a function of radius, \( r \), and is a useful rough representation for most spiral galaxies.

The observed radial distribution of neutral hydrogen is found to vary significantly from galaxy to galaxy, often in correlation with optical morphology. While radial density profiles vary, 21-cm emission is not nearly as centrally concentrated as its optical counterpart and often the HI gas has a deep central depression. We can see the range of density profiles in Figure 2.3.

A simple first approximation that captures the general behavior of observed HI radial density profiles involves a parameterization using the difference of two Gaussians. The height and width of a primary and secondary Gaussian can be specified. For highly centrally concentrated distributions, the narrower secondary Gaussian can have a positive amplitude and add ad-
Figure 2.3: Azimuthally-averaged, HI surface densities in eight Spiral galaxies (Image Credit: Mihalas & Binney, 1981)

Figure 2.4: Sample density profiles that are possible using the sum of two gaussians in the model
ditional gas to the central region of the galaxy. For galaxies with a central depression, this narrower Gaussian can be subtracted. See Figure 2.4 for a sampling of the profiles that are possible using this model. In our program, the density profile is thus described with four parameters: the width and height of the primary Gaussian ($height1$ and $width1$), and the width and height of the secondary Gaussian ($height2$ and $width2$).

### 2.3 Rotation Curve

Rotation is generally the dominant form of motion in disk galaxies with the typical rotation rates of 200 km/s or more. While there is frequently some radial motion and motion perpendicular to the plane, these random speeds are typically only 8-10 km $s^{-1}$. Thus, the velocity field of a modeled galaxy can be described to a pretty good approximation by considering just rotational velocity and disregarding radial motion or motion perpendicular to the plane. This simplified velocity field can be described by a rotation curve – tangential velocity as a function of radius $V(r)$. We will also consider our galaxy to have circular motion. (Mihalas & Binney, 1981)

Typically, we can consider the rotational properties of a galaxy in two parts. Near the center, rotational velocity increases linearly with increasing radius. Then at some radius, velocity levels off and is essentially constant. This behavior is due to the mass distribution of the galaxy. At the time of its discovery, the flat portion of the rotation curve was very surprising to
astronomers and has now become convincing evidence for the existence of dark matter.

The form of a rotation curve can vary relatively significantly from galaxy to galaxy (see Figure 2.5) tending to correlate fairly well with optical morphological type. For early-type systems, the radius of maximum rotational velocity is small in comparison to the Holmberg optical radius. The rotation curve has a clearly defined maximum within the optical radius. Later-type galaxies on the other hand have a poorly defined radius of maximum rotational velocity and reach this maximum rotational velocity at a radius outside of the disk. Additionally, the maximum rotational velocity that is reached by a galaxy decreases as a function of advancing morphological type, although the range of maximum velocities is relatively small. (Mihalas & Binney, 1981)

Consider the velocity as an observer sees it, that is, only motion toward or away from the observer can be detected. Connecting lines of points of constant velocity with respect to the observer, iso-velocity contours can be
(a) On the left is the rotation curve $V(r)$ for a sample galaxy potential. On the right is the spider diagram consisting of isovelocity contours of a disk viewed $30^\circ$ from face-on. Negative velocities are shown as dotted. (image credit: Sparke and Gallagher)

(b) Spider diagram for galaxy NGC 864 (image credit: Espada et al.)

Figure 2.6:
Figure 2.7: Sample density profiles that are possible using the sum of two gaussians in the model

plotted. (See Figure 2.6) In the region of solid body rotation, the isovelocity contours are straight and parallel to the minor axis. The minor axis is a locus of points with the same velocity as the nucleus of the system, its systemic velocity.

In our model we have described this rotation curve using a linear rise with increasing radius to the maximum rotational velocity, at which point the velocity remains constant. While most of the real rotation curves are not two connected straight line segments, this mathematical simplification makes modeling significantly easier and should not tremendously impact the resulting profile. This rotation curve can be fully specified by two parameters: the maximum velocity and the number of annuli it takes to reach this maximum rotational velocity. This gives a dynamic range that covers the azimuthally
averaged rotational velocity parameter space relatively well (See Figure 2.7)
Chapter 3

Classification

3.1 Introduction

Classification is often the first tentative step towards understanding. By taking a continuum of elements and making it discrete, and taking a multi-dimensional volume of attributes and selecting its principal components, we can define linear sequences distinguished and partitioned by a finite number of manageable mnemonic tags. Classification places objects into boxes; inevitably, exceptions occur and contradictions arise resulting in discoveries both within the system and from its failings. While the original ordering (e.g., ABCD) may not withstand the test of time as our understanding of astrophysical phenomena improves, elements of a theory-less classification scheme might persist re-ordered and re-interpreted (e.g., OBAGFKM). While most objects in astronomy have already been classified, one exception is the 21-cm
HI line profile shape. Thus in an attempt to quantify the distribution of shapes of observed and modeled HI line profiles, we have developed following classification scheme.

3.2 Visual Classification: HPST

Through close examination of the many thousands of published profiles, we see a variety of galaxies within and beyond the scope of these bimodal and largely parenthetical classification schemes that merit interpretation and inclusion in a new classification scheme. Namely, as Tifft, noticed, asymmetries in the height and shape between the high- and low-velocity peaks in the horned profiles exist and should be noted as part of a classification scheme. In addition, the region between the two peaks can have varying shapes and depths – a feature that is not taken note of in previous classification schemes. Other features appear and become significant in high signal to noise ratio profiles – central features, structure in the wings, and shape of the peaks – but will not be dealt with in this paper. The following classification scheme is an attempt to produce and apply a classification scheme that comprehensively encompasses the vast majority of all observed line profile types – a task thus far largely unattempted.

The goal of this classification scheme is to use the variety of HI line profile properties found in nature as a basis for a classification scheme that is rich enough to capture the observed variety of shapes and simple enough to be
easily used for visualization and description. We have a-priori knowledge of the HI gas morphology and kinematics that allow us to anticipate the primary features of a profile. The HI line profile is a collapsed, one-dimensional version of the three-dimensional velocity field weighted by the three-dimensional gas density distribution, projected along our line of sight.

The HPST classification scheme acronym is highly contrived. And it is a double entendre. In the first instance, HPST stands for “HI Profile Shape Type”. At a deeper level it is a mnemonic for the four high-level classifiers of the HI line profiles: H – horn, P – Plateau, S – Shoulder, and T – Triangular.

The printed symbol H has the same appearance, to a first order approximation, as the profile itself: two horns steeply rising and falling at the velocity extremes, with a central valley or plateau between the two.

Decreasing one or both of the horns in the H-Type profile to be level with the central plateau and the object morphologically transitions into the P-Type profile. These profiles show either a rise and fall, connected by a relatively structureless Plateau or one horn coming down into a plateau at one of the extremes where one might otherwise have expected to find a second horn. Hence the name Plateau.

The S-Type profile does indeed have a shoulder in its intensity distribution, also at one of the extremes where one might otherwise have expected to find a second horn. In the symmetric case, it lies between the plateau shape and the triangle shape in its width vs. height dimensions.
Figure 3.1: The range of profile types is shown here, from ‘the bottom two H-Type profile shapes, up to the next two P-Type profiles, to the S, T at the top.
At the shoulder region diminishes in extent, but while the profile is still resolved by the instrument, we have the T-Type (triangular) profiles. These can resemble both Gaussians (with smoothly curving surfaces up to and over the single maximum) and more distinctly triangle-like profiles (with linear sides convering on a rather angular single central peak)

To quantify the distribution of observed galaxies amongst the different classes, and eventually tie this understanding of the distribution to physical characteristics of HI rotation properties and distribution, we have classified 2098 published HI line profiles. The following table lists the authors who produced these profiles, the year they were published, and the number of profiles used from a given paper. A full citation can be found in the bibliography.
Visual classification of these 2098 HI line profiles resulted in the distribution shown below (figure 3.2). The most common profile shape is the H type, 56% of the profiles; then T type, 18%; S type, 17%; and P type, 9%. Given that the H type shape is the characteristic shape produced by any annulus that isn’t completely face-on, it is reasonable to expect that this would be the most common profile shape. The other shapes are produced by more specific (and therefore relatively less common) HI density distributions
Figure 3.2: Histogram of frequency of each HPST type from visual classification of 2,098 galaxies from a variety of authors (listed in previous table). 

and viewing angles.

### 3.3 Quantitative Classification: Kurtosis

Another means of classification relies on the statistical moments. While visual classification is useful to acquaint the scientist with their dataset and oftentimes captures the important features of a profile more reliably, it is useful to be able to classify a galaxy in a faster, more repeatable way. To this end, statistical moments can be used to characterize a distribution and are easily yielded by a computer in a fast and repeatable way. We will be using the fourth statistical moment, kurtosis, as a measure of the weighted distribution of flux relative to the systemic velocity.
With some 9,000 HI line profiles already published and many more to be published in the future, to implement a classification scheme, it is essential that it be automatable if it is to be able to be used as a means of probing large datasets or in databases. Thus, a method of classification that could be automated and mapped back to a concrete scheme – like the visual classification scheme – would be ideal. With a scheme like this, from a class given by the automated classification scheme one could still construct a mental picture of the shape of the profile.

Statistical moments, the first four of which are mean, variance, skew, and kurtosis, characterize the shape of a distribution. The kurtosis is a measure of the flatness or 'peakedness' of a distribution - how centrally concentrated the distribution is. The more centrally concentrated a distribution is, the higher its kurtosis value will be. This quantity is given by

\[ \gamma_2 = \frac{\mu_4}{\mu_2^2} \]

where \( \mu_4 \) is the fourth central moment and \( \mu_2 \) is the second central moment - the variance.

Consider Figure 3.3 showing sample distributions corresponding to different kurtosis values. In the middle, a Gaussian distribution (shown in black), has a kurtosis of zero. As the distribution becomes more centrally concentrated, its kurtosis becomes increasingly positive. An example of an extremely large kurtosis is the laplacian shown in red which has a kurtosis of 39.
Figure 3.3: Sample kurtosis values for some common distribution functions ranging from a square distribution (magenta) with kurtosis of -1.2 to a Normal (Gaussian) distribution (black) with a kurtosis of 0, to the Laplace distribution (red) with a kurtosis of 3. Image credit: http://en.wikipedia.org/wiki/Kurtosis)
three. As distribution becomes less centrally concentrated, its kurtosis gets increasingly negative. A common model the HI line profile is the cosecant function which has a kurtosis of -1.3.

In this range of kurtosis values, we can see the range of different profile shapes represented. From high-kurtosis, sharply-peaked $T$ types to low-kurtosis, double-peaked $H$ types and $S$ and $P$ in between (see Figure 3.4). Hence, kurtosis values could potentially correlate well with classification types and therefore be a good way to automate classification. However, even if they do not correlate exactly with our visual classification scheme, they still could provide interesting insights into the flux distribution in our HI profiles.

### 3.4 Classifying with Kurtosis

To test automated classification using kurtosis, we extracted these values from a single dataset. This dataset is a compilation of neutral hydrogen line spectral parameters and profiles for 9,000 optically targeted galaxies in the local universe that have been observed over the past twenty plus years and amassed by Springob et. al. (2005) Observations were conducted on a number of single dish radio telescopes: Aricibo, Greenbank NRAO, Nancay and Effelsberg. (See table 3.5 for telescope specifications and references) Exposure times ranged from 5 minutes on Aricibo to 2 hours on Nancay and the Greenbank 42-m telescopes.
Figure 3.4: T-type profile with high kurtosis value, H-type profile with low kurtosis value, and P-type profile with medium kurtosis value. The variety of profile shapes is reflected in visual classification type as well as kurtosis value.
Figure 3.5: Characteristics of single-dish telescopes and their data sets.

Figure 3.6: (a) 21-cm line profile before zero-cross cut-off. The noise on the
edges of the profile would significantly affect the calculated moments. (b) Line
profile with zero-crossings and mean velocity marked
We calculated the statistical moments of each observed galaxy profile using FORTRAN code originally written by BFM. Each galaxy has a datafile, which contains heliocentric velocity, flux density, and polynomial baseline fit for each of the 512 radio frequency channels. Before calculating the moments, the data needed to be cleaned up to take out the influence of the baseline and as much noise as possible. To remove the baseline, the program subtracted the baseline fit from the flux density for each channel. In most cases the bandwidth was relatively large in comparison to the velocity dispersion of the galaxy, resulting noise in channels that are not covered by the galaxy contributing significantly to the statistics calculated for the galaxy, if they span the rest of the bandwidth (see Figure 3.6). In order to take into account as much signal and as little noise as possible, we want to look at only the region of velocity space in which the galaxy is actually contained. To this end, the program considers only this region of velocity space. This interval can be defined by the last zero crossing, or the last time the value of flux density goes from negative to positive crosses zero before the peak flux(es). The interval in which the moments are calculated is the region between the high and low velocity zero-crossings. If the baseline fits given by Springob et al. are correct, the baseline should average to zero, meaning the zero-crossing should occur relatively close to the edge of the galaxy’s signal. The mean, or the systemic velocity, is defined as the average of the two zero-crossings hopefully the galactic center. The moments are then calculated using this mean over the interval defined by the zero-crossings. As a check, the line
profile corresponding to each galaxy is plotted with the zero-crossings, corresponding mean velocity, as well as the mean given by Springob et al. marked. This last feature makes problems with the code somewhat more transparent by showing its steps (see Figure 3.6).

To appraise the accuracy of the data output, I systematically visually inspected the profiles of galaxies that had outlying moment values, covering the 30 galaxies with each the highest and lowest skew and kurtosis values, then sampling the next 600 in each of those categories by looking at three galaxies at each hundred galaxy interval. This assessment of the data produced revealed two major problems with the program and source data.

First, the zero-crossing-defined boundaries of the galaxy were not always correctly marked, which resulted in incorrect statistical moments being generated. If the baseline had been properly subtracted from the profiles, the zero-crossing should fall roughly where the physical distribution of HI gas ends. However, the baseline does not seem to be well subtracted in all cases, resulting in a background that does not average to zero over some intervals. If this interval has a close proximity to the profile, the program selects an incorrect cut-off for statistical analysis. The Figure below shows an example of one such galaxy, the edges of the galaxy (the zero-crossings) and the mean derived with these values are marked with thick lines. The right zero-crossing is much further right than it should be, throwing off the mean. To fix this problem, the subtracted baseline was increased by 2%, While arbitrary, this fix seemed to eliminate the zero-crossing problem and yield accurate moment
Figure 3.7: The zero-crossing of this galaxy was marked incorrectly, shown by the dark line on the right side of the plot. Consequently, the mean is also marked incorrectly. The mean is marked by the thick central line going through a peak not through the middle of the galaxy.

values. Since we are not using the integrated flux for any part of this analysis, subtracting an extra 2% should have negligible negative impacts on our data.

The signal to noise ratio given by Springob et al. (2005) ranges from 0 to 649 with a mean value of 15.2 and a standard deviation of 14.1. Little significance should be given to the data from profiles with a signal to noise ratio so low that morphological structure is obscured by noise, so these profiles should be cut from the primary sample. To find what an appropriate cut was, I took the data file containing the signal-to-noise ratio and edited it using emacs, so that it contained only the galaxy numbers and their respective signal to noise ratios. These values could be merged with the other statistics
in Microsoft Excel using galaxy numbers. One point to note is that four of the galaxies were different between the two data files, so these four galaxies were deleted. To find an appropriate SNR cut, I visually inspected a subset of 41 profiles stepping through the low and high ends of the SNR quickly and focusing on profiles with SNRs from 4-6.5 the region in which profiles transition from noise dominated to signal dominated. Since signal to noise is a continuum, an exact break is somewhat difficult to infer. I considered six samples in each SNR step of 0.1 from 5.7 to 6.1. For each of these SNR values, I recorded the fraction of the profiles I inspected that had visually obvious signal dominance. All SNR values under 6.1 had less than 65% (one standard deviation above the mean) of their sample being signal dominated (that is, more than 35% of profiles were noise dominated), leading me to choose 6.1 as a signal to noise cut-off, which threw out 1173 galaxies (see histogram for distribution of SNRs).

### 3.5 Results of Kurtosis Classification

In the interest of exploring how a large number of galaxies fit into this quantitative classification scheme, we want to look at their large scale distribution in parameter space. Despite being a somewhat unusual course of action, it is actually instructive to analyze the distribution of our quantitative galaxy characterizations (their statistical moments) in terms of statistical moments, as they are such a good measure of trends in data.
Figure 3.8: Signal to noise ratios of observed profiles ranging from SNR = 2 to SNR = 643.
3.5.1 Kurtosis

The derived kurtosis values range from -2.1 to 4.1 (see histogram below). Giving a range in shapes from virtually two separated delta functions to a very sharp single peaked profile. The mean of this distribution of -1.3 corresponds to a shape somewhere between a square and a cosecant, or most likely a slightly horned profile. The distribution of kurtosis values is skewed toward the horned end of the shape scale (negative kurtosis) and is relatively concentrated there.

3.5.2 SNR Effects

To see the effects of the SNR cut, I looked at the kurtosis histograms of the original data set, of the low SNR galaxies that were cut, and the resulting
dataset. For the Kurtosis histogram, the mean kurtosis value was affected by the SNR cut. The original data had a mean kurtosis of -1.16, the SNR cut galaxies had -1.24, and the final data set had -1.15. This makes some sense in that the mean kurtosis of noise should be more negative than that of a real galaxy since it is less centrally concentrated. I would, however, expected this effect to be larger if the galaxies that I cut were too dominated by noise to give significant information.

Analyzing the statistical moments of these 9,000 HI line profiles has yielded quantitative knowledge about the shapes of these profiles and corresponding insight into the HI distribution and velocity fields of these galaxies. The mode of the kurtosis values was -1.3, which corresponds to a shape

Figure 3.10: Histogram of HI line profile derived kurtosis values
somewhere between a square and a cosecant shape. These shapes generally correspond to galaxies that have HI gas concentrations at higher velocities (larger radii), consistent with our current understanding of HI gas distribution in spiral galaxies.

Ideally, the HPST visual classifications given to galaxies would be correlated with their computed kurtosis values. To test this, we can compare the distribution of kurtosis values with the distribution of HPST classifications.

This relationship (or lack thereof) can be seen by plotting kurtosis vs. HPST class. If these relations are mapping as we would hope they do we should see a clustering of points around a line. For this plot, I used a relatively small sample size as a consequence of differences in the galaxies cataloged in the two datasets. Springob et. al. started a new catalog AGC (Arecibo General Catalog) to organize their compiled HI line profiles that agrees with the UGC up to UGC 12921 then before AGC numbers diverge. Strangely, even up to this point, the two samples do not overlap significantly, leaving a
Figure 3.12: Plot of Kurtosis value vs. HPST classification. While there is some scatter in the kurtosis values of each HPST type, a reasonably good correlation ($R^2 = .634$) exists between them.

The correlation between HPST type and kurtosis value is not perfect, and it was not expected to be. First, HPST type is a discreet variable - it assigns one value to a whole range of profile shapes. Kurtosis, on the other hand is
a continuous variable assigning a different number to each different profile shape (in the case that it is not degenerate). For a naturally continuous system, a correlation between a discrete variable and a continuous variable will not be perfect under almost any circumstances. However, both these methods of classification have benefits: kurtosis more accurately reflects the continuous nature of profile shape while HPST can be used easily for quick visual classification and evokes a clear image when used for description.

Second, the two classifications are not measuring exactly the same thing. HPST type reflects a profile’s shape while a kurtosis reflects the distribution of its flux density with respect to the center of the profile. Generally these characteristics are similar. For example, a T-type profile will typically have a high central density and high kurtosis while a H-type profile will have a low central density and therefore a low kurtosis (see Figure 3.5.2). This, however is not always the case, as in the image shown in Figure 3.5.2. So in this sense also, the two classification schemes should not be expected to be perfectly correlated.

In both the above ways, it is apparent that while both of these types of classification Kurtosis values and the HPST visual classification scheme are related, they do not represent the same thing. They are distinct ways of classifying galaxies that highlight different aspects of these galaxies. The both do, however, provide ways of quantifying how common different profile shapes are. Hence both could be useful as a means for characterizing profiles produced by our model. We can use our knowledge of the distribution of
Figure 3.13: **T**-type profile with high kurtosis value and **H**-type profile with low kurtosis value.

(a) **T**-type profile with expected kurtosis value: -0.312

(b) **H**-type profile with expected kurtosis value: -1.373

Figure 3.14: In these two profiles, the kurtosis values are slightly off from the profile shape we see.

(a) **S**-type profile with a slightly low kurtosis value: -0.97

(b) **H**-type profile with a slightly high kurtosis value: -1.01
observed galaxies with respect to these parameters to quantify the frequency
of different regions in physical parameter space.
Chapter 4

Data

With the modeling code and two methods for classification in hand, the program was iteratively run for a range of input parameters with the goal of finding connections between line profile shapes and input physical parameters. I used two approaches to running simulations and manipulating the parameter space to get two complementary sets of data. First, simulations were run for each parameter individually (i.e., viewing angle, rotation curve parameters, and density profile parameters) to get a general sense of the effect of each physical parameter has on the HI line profile shape. That is, each parameter was changed individually while holding the other parameters constant. Second, to more accurately reflect the state of nature, multiple parameters were changed in the same simulation. Visualizing the parameter space of all seven changing at once would be difficult if not impossible, and largely unfruitful. So some dependent parameters were strategically com-
bined. Combining parameters cuts down the dimensionality of the parameter space allowing insight into the interplay of the three remaining parameters. The program was modified to cycle through a series of values for a given parameter or set of parameters which could be adjusted before each run, to be enable to efficient exploration of parameter space.

4.1 Modeling Individual Parameters

I approached simulating the individual parameters by moving from the simplest possible model to the most complex - moving from single rotating ring evenly filled with neutral hydrogen to models with increasingly complex and realistic density profiles and rotation curves. As I am modeling spiral galaxies as concentric annuli, a good first step is to look at the effect of an individual annulus with various characteristics on the line profile. For a summary of the changing and control parameters for each run, see Figure 4.1.

Consider first an annulus in which only its inclination is varied while holding all other parameters constant. We can vary the viewing angle ($vangle$) from face-on (0°) to edge-on (90°). I sampled every 10 degrees in order to get an accurate picture of how the profile was changing. For this run, none of the other parameters matter except for a scaling factor. While viewing angle in not a physical parameter that describes a galaxy in a fundamental sense, it has an unfortunately significant effect on the shape of the profile. Consequently, it is an important parameter to understand the effect of, so
Figure 4.1: This table shows the values of the parameters used in each simulation - each row corresponds to one simulation. The first column is the parameter that was manipulated for that run, the second is the name of that parameter, the third is the range over which it was run and the intervals at which I sampled, the fourth lists the parameters held constant and their values if relevant.

<table>
<thead>
<tr>
<th>Changing Parameter</th>
<th>Name</th>
<th>Range (min:max:interval)</th>
<th>Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viewing Angle</td>
<td>vangle</td>
<td>0°: 90° : 10°</td>
<td>nannuli=1; nrise, vcirc, height1, width1, height2, width2 = arbitrary</td>
</tr>
<tr>
<td>Maximum Rotational</td>
<td>vcirc</td>
<td>50 : 400 : 50</td>
<td>nannuli=1; vangle=90°; nrise, height1, width1, height2, width2 = arbitrary</td>
</tr>
<tr>
<td>HI Density</td>
<td>height1</td>
<td>.2 : 2 : .2</td>
<td>nannuli=1; vangle=90°; nrise, vcirc, width1=1x10^7, height2=0, width2 = arbitrary</td>
</tr>
<tr>
<td>Velocity turnover</td>
<td>nrise</td>
<td>10 : 50 : 10</td>
<td>nannuli=50; vangle=90°; vcirc=250 width1, height2, width2 = arbitrary</td>
</tr>
<tr>
<td>Width of density</td>
<td>width1</td>
<td>10 : 100 : 10</td>
<td>nannuli=50; vangle=90°; nrise=50; vcirc=250; height1=1; height2=0; width2 = arbitrary</td>
</tr>
<tr>
<td>profile primary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gaussian</td>
<td>height2</td>
<td>-1 : 1 : .2</td>
<td>nannuli=50; vangle=90°; nrise=50; vcirc=250; height1=1; width1=1x10^7; width2 = 25</td>
</tr>
<tr>
<td>Height of density</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>profile secondary</td>
<td>width2</td>
<td>10 : 50 : 10</td>
<td>nannuli=50; vangle=90°; nrise=50; vcirc=250; height1=1; width1=1x10^7; height2 = -.9</td>
</tr>
<tr>
<td>Gaussian</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary run</td>
<td>width1,</td>
<td>10 : 100 : 10</td>
<td>nannuli=50; vangle=90°; nrise=50; vcirc=250; height1=1</td>
</tr>
<tr>
<td>width2,</td>
<td>height2</td>
<td>10 : 50 : 10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-1 : 1 : .1</td>
<td></td>
</tr>
</tbody>
</table>
its influence can be removed to the extent possible from data regarding the other parameters.

Next, the rotational velocity of the annulus ($v_{circ}$) was varied. A viewing angle of $90^\circ$ was used to make the trend especially apparent and all other parameters are arbitrary. Not surprisingly, we can expect that changing the circular velocity will change the width of the HI line profile. The horizontal axis of a HI line profile is recessional velocity. As rotational velocity increases, recessional velocity of the blueshifted side will decrease and the redshifted side will increase, enlarging the space spanned along the velocity axis, widening the profile.

The other parameter with unsurprising effects for a single ring is HI density. As density increases, intensity (height of the profile) should increase as well because 21-cm luminosity is directly proportional to HI gas density. Scaled surface densities from 0 to 2 in the model were simulated. Again, for clarity, an edge-on viewing angle was assumed and all other parameters were held constant.

Adding a level of complexity, next consider a solid-body rotating disk. That is a flat, circular plate of constant density rotating as if its components were connected by a rigid lattice structure. To model this, the density profile was held constant and the velocity was increased linearly with radius. Now instead of a one annulus ring-like structure, 50 annuli were used to create a disk. The density profile was set to have a maximum of 1 and a large (essentially infinite) FWHM to make the density essentially constant at all radii.
The galaxy was still edge-on and the maximum circular velocity was 250 where it reached at the edge of the galaxy, the 50th annulus.

The next level of complexity comes from modeling the fact that a galaxy is best approximated as a differential rotator, not a solid body rotator. The velocity of a solid body increases linearly out to the edge of the body. Differential rotation of a galaxy can be approximated by a velocity that increases linearly with radius (or annulus number) out to a certain radius at which the linear rise becomes flat (the annulus number for this point is denoted \( n_{\text{rise}} \)). For this model, everything is the same as above except that we vary \( n_{\text{rise}} \).

At the same level of complexity, we can model a galaxy as having solid body rotation but a having varying density. We can model the density profile (density with respect to radius) as a Gaussian in which we can specify the height and the width. As we already know the effect of changing the height of the density profile, I looked at the effect of changing its width. Typically in spiral galaxies 70% of the HI mass is contained within 1.2 Holmberg radii \( R_h \). So I will test density profiles that range from 0.2 \( R_h \) to 2.2 \( R_h \) (10 to 100) in the model. I returned to a linearly increasing rotation curve \( n_{\text{rise}}=\text{annuli}=50 \).

Making the density profile more accurate, it was next modeled with two Gaussians instead of one. Using a second Gaussian gives more dynamical range to make the density more or less centrally concentrated that a single Gaussian allows a range that is certainly seen in reality. These two Gaussians can have different widths and heights and be either added or subtracted.
from each other. To make it clearer, how changing various density profile parameters is changing the profiles, a solid body rotation curve was still used. Additionally, for ease of reference, one Gaussian will typically be broader and taller and the other narrower and shorter. Hence, the former will be called the primary Gaussian and have $height_1$ and $width_1$. The latter will be called the secondary Gaussian and have $height_2$ and $width_2$.

To see the effect of the secondary Gaussian, its width and height were varied. For both of these, the height of the primary gaussian was set to 1 and its width to 1000000 (essentially infinite) so that the profile is basically flat. Setting the primary Gaussian flat makes the visualization of the role of the changing secondary gaussian much transparent. To look at the effect of the height of the secondary Gaussian on profile shape, its height was independently varied from almost the height of the primary Gaussian subtracted to added. The secondary Gaussian was varied in height ($height_2$) from -1 to 1. Finally, the last parameter considered individually was the width of the Secondary Gaussian ($width_2$). It was varied from 10 out to the edge of the galaxy at 50, holding the height constant at -0.9 - a realistic size depression.

### 4.2 The Parameter Cube

For the final portion of data collection, the goal was to draw relationships in the reverse direction. Namely, investigate ways to narrow down a range of physical parameters from the shape of the HI line profile. To do this we need
to generate profiles to fill the full range of parameter space rotation properties (\(n_{rise}, v_{circ}\)), density distribution (height and width of primary and secondary Gaussians – \(height1, width1, height2, width2\) respectively). Filling a seven-dimensional parameter space with profiles would provide very little insight into potential relationships between physical parameters and profile shape characteristics because the difficulty of representing and viewing a seven-dimensional space would be overwhelming. Fortunately for this reason, the profile shape does not depend on each of these parameters independently. When it comes to profile shape, what matters predominantly (especially in terms of horn height) is how much material lies outside the point where the velocity levels off (\(n_{rise}\)). The flux from any material outside of \(n_{rise}\) will be added to this same maximum velocity bin, making the horns higher. Meaning, what matters is where the HI distribution lies relative to the location where maximum rotational velocity occurs. To this end, we can fix \(n_{rise}\) and adjust the density profile width with respect to it. Additionally, as we will show in the following chapter, the absolute height of the density profile and the maximum rotational velocity simply scale the height and width of the HI line profile; they don’t change its shape. Thus we can fix both of these parameters as well. Finally, while profile shape does change with viewing angle, the angle of a galaxy with respect to us is not a parameter that is instructive about the physics of a galaxy. Therefore, for the purposes of this simulation, I will fix it to edge-on. However, since it does have a very real effect on profile shape, we will have some degeneracy in our model.
With these four parameters fixed, we can fill a three-dimensional parameter space of width of the primary Gaussian vs. width of the secondary Gaussian vs. height of the secondary Gaussian. Within this parameter space, we can see a range of profile shapes which we can hopefully map back to a region of this physical parameter space. $width_1$, $height_2$, and $width_2$ were varied through the ranges and with the intervals discussed before, and with the remaining parameters held at their previously mentioned constant values.
Chapter 5

Analysis

The result of running the aforementioned models while varying the input parameter models is presented in this chapter. A series of graphical outputs are presented accompanied by kurtosis values and visual classifications for relevant profiles. By mapping the changes in physical parameters to the corresponding distinct and predictable changes in profile shape, the possibility opens up to be able to map back the other way - from profile shape to physical parameters. The goals of this chapter are four-fold: First, to investigate the effect of changing each parameter on profile shape. Conclusions to this investigation will fall simply out of marching through individual parameters in the first approach. Second, to get a sense for the range of physical parameters that correspond to the range of kurtosis values and profile types. This can be done using the first and second approach by classifying each galaxy by profile type visually and by kurtosis as output by the program for each
model galaxy. Third, to explore what region of the parameter space was most common in terms of density distribution vs. rotation curve properties. This was done by comparing the output of the second approach to observed data. Namely, by mapping the most common kurtosis values and shape types onto physical parameter space. Finally, to examine the degeneracies involved with this mapping.

Starting, as described in the previous chapter, with a single ring’s contribution to the HI line profile, consider the effect of three parameters: the viewing angle, the maximum circular velocity, and the radial density profile of the HI gas.

## 5.1 Viewing Angle

First, we consider the viewing angle. Varying the angle at which we view the galaxy from $0^\circ$ to $90^\circ$ produces the following profiles (figure 5.1):

As the viewing angle decreases, the characteristic shape remains basically the same, of the profile collapses in its overall velocity width. When the galaxy is edge-on ($90^\circ$), the geometry dictates that the peaks be at the maximum rotational velocity. As the viewing angle decreases, the projected rotational velocity decreases, causing the peaks to move inward. The peaks continue to move closer together until the galaxy gets to be edge-on at which point they are entirely overlapping creating a Gaussian-shaped profile. So as the viewing angle changes, the width of the profile shrinks. Viewing angle
Figure 5.1: The affect of viewing angle on profile shape. Viewing angle is shown in the first and third rows by an image of the model galaxy’s appearance to the observer (in the plane perpendicular to the observer’s line of sight). The galaxy starts as edge-on in panel a and rotates towards the observer until it is face-on as in Panel l. Below each panel showing the viewing angle is the HI line profile corresponding to that viewing angle and its kurtosis value. The axes of these profiles, as with all subsequent HI line profiles output from the code, are Intensity (in arbitrary units) on the vertical axis and velocity (in arbitrary units) on the horizontal axis. As the galaxy rotates closer to face-on, the separation of the horns grows smaller until collapsing at a viewing angle of $0^\circ$. 

66
is not a particularly important physical parameter, so, appropriately, the classification scheme does not really reflect this change in profile shape due to changing the viewing angle. All the profiles shown are of type H except the last, in which the galaxy, being totally face-on, removes any circular velocity resolution yielding a T-type profile. Kurtosis values are also unaffected by the viewing angle until the collapse to Gaussian at angles approaching completely face-on. From a viewing angle of 90° to 30°, the kurtosis value lies between -1.51 and -1.57. At viewing angles of 20° down to 0°, the profile gets so narrow that kurtosis blows up from -4 to -29, and finally to -380. Thus while in some ways, the viewing angle makes profiles look qualitatively different, this difference is not reflected before approaching very small angles in either of the classification schemes, as we would hope.

5.2 Maximum Rotational Velocity

Next, changing the maximum circular velocity of the galaxy (v\text{circ}) results in the graphs shown in Figure 5.2. Varying the maximum circular velocity does not change the shape of the HI line profile, but it does change the width. So this parameter also does not change the visual classification for a given galaxy or its kurtosis. The kurtosis values (shown with the HI line profiles below) vary only between -1.49 and -1.54. Note also that this low value (-1.54) is the most significantly different from the other six, and is probably as a consequence of calculation errors due to the small number of bins. The maximum
Figure 5.2: The effect of the maximum rotational velocity (vcirc) reached by the galaxy on profile shape. In the top row, the rotational (circular) velocity is plotted against the radius, or number of annuli from the center. The bottom row shows the HI line profile that corresponds to each value of maximum circular velocity. As the maximum rotational velocity increases, the profile gets wider and the kurtosis value stays relatively constant.
circular velocity (or velocity width) is tied to the intrinsic luminosity and thus mass of a galaxy through the Tully-Fisher relation. Thus the width of the profile scales up and down with the dynamical mass of the galaxy so this width tells us something of the size of a given galaxy but little directly about its morphology. In addition, the juxtaposition of consideration of viewing angle and the maximum circular velocity highlights the degeneracy between these two parameters. A change in either of them have the same effect of making the resulting profile wider or narrower. Fortunately, we have also discovered that neither really affects the shape of the profile - our primary interest here - so do not really impact our current analysis.

5.3 HI Density

The effect of final parameter, the scaling of density of the HI gas (height1), is best visualized in (Figure 5.3) using the single-ring model. As the density scaling increases, the height of the resulting profile increases linearly with it. This does not dramatically affect the classification assigned or the kurtosis value derived. The viewing angle, the maximum circular velocity, and the density scaling factor are the only three factors that can affect an individual annulus. However, they do not affect the visual classification or the kurtosis of the profile. Thus, the properties that do affect the shape of the profile must derive from the remaining parameters and/or their relation to these three. To test the effect of these remaining parameter and the effect of their
Figure 5.3: The effect of the height of the HI density profile on the line profile. The first and third rows show the density values for the annulus. The vertical axis of these plots is an arbitrary density scale and the horizontal axis is meaningless, the purpose is simply to be able to visualize how the relative density of the annulus is increasing. In the second and fourth rows are the corresponding HI line profiles (flux vs. recessional velocity) showing that as density increases, the line profile increases in height throughout.)
relation on profile shape, we can fix all three of the parameters just discussed and vary others in relation to them.

## 5.4 Adding up the Annuli

Before we start varying all these parameters, however, let’s look at how all the individual annuli add up to form the full galaxy profile. We begin with 50 concentric annuli, each with the same gas surface density. In this case the annuli are set rotating as a solid body, meaning their individual velocities are increasing linearly with radius. Each annulus will add to the overall profile the characteristic shape just shown above with the outer edge of each ring’s horned profile corresponding its maximum circular velocity. Figure 5.4 shows the contribution of each individual annulus to the overall profile.

From the Figure 5.4 we can see how each annulus contributes to the final HI line profile. Each annulus contributes this characteristic cosecant shape due to its geometry. The density distribution gives each annulus’ contribution a relative height. Differences in density distributions among galaxies gives rise to the diversity of profile shapes we see in nature.

## 5.5 Velocity Turnover Radius

Appreciating how each annulus contributes to the whole, characteristics of the different annuli can be changed with respect to each other to see their
Figure 5.4: Each Panel corresponds to the contribution of one annulus to the overall HI line profile. Adding these contributions at different velocity widths yields the HI line profile we see. Panels proceed from inner to outer annuli.
Figure 5.5: The effect of the velocity turnover radius on profile shape. The top row shows rotation curves (rotational velocity vs. annulus number) in which the radius at which the velocity reaches its maximum value (turnover radius, or nrise - the number of annuli it takes for the velocity to rise to its maximum value) increases. The bottom row of HI line profiles show that as nrise increases, the shape of the profile changes dramatically. It goes from an H-type to a S-type as material becomes located increasingly inside nrise. This trend is also reflected in the increasing of the kurtosis value.
effect on the shape of the profile. Still considering a constant density disk, we can see how the shape of the rotation curve impacts the shape of the HI line profile. Accordingly, we hold everything constant except \( n_{\text{rise}} \) - the annulus at which the rotation curve transitions from a linear rise to flat (the velocity/rotation curve turnover radius). Displayed below is a range of 10 to 50 (remember there are 50 annuli). This set thus ranges from a very steep rise to maximum velocity (Panel f), to a relatively slow linear rise (Panel j) (see Figure 5.5). In the case of the steep rise, most of the flux goes into the two maximum velocity bins (the furthest out points on the profile) so the resulting profile has high peaks and little material in its central region. Progressing right in Figure 5.5, increasingly less flux is put in the maximum velocity bin and instead goes into all the inner velocity bins, adding more flux into the inner regions of the profile.

In terms of profile shape, this trend means that horns will become shorter and less pronounced as \( n_{\text{rise}} \) increases. In other words, as \( n_{\text{rise}} \) increases, the profile shape progresses from \( H \) through to \( S \) (this density profile is such that it is not possible to produce a Type \( T \), at high inclination). Kurtosis reflects this trend as well; increasing with increasing \( n_{\text{rise}} \), as shown in the plots in Figure 5.5 from -1.5 at \( n_{\text{rise}} = 10 \) to -1.0 at \( n_{\text{rise}} = 50 \). Physically, this means that one possibility for a profile having more pronounced horns is that it has a rotation curve that rises rapidly and flattens out closer to the center.
Figure 5.6: Mapping how changes in the width of the density profile affect the shape of the HI line profile. The top row shows density profiles (plots of density on an arbitrary scale vs. radius in annulus number). The bottom shows the resulting HI line profile (arbitrary intensity vs. recessional velocity). As the FWHM value increases, the width of the density profile increases causing the width of the HI line profile to increase and its kurtosis value to decrease.
5.6 Density Profile Width

In addition to the rotation curve, the density profile of the HI gas affects the shape of the HI line profile. To see this effect consider again a solid body rotator (a rotation curve that rises linearly and does not level off) while changing the width of the density profile. Varying the width from a small fraction of the number of annuli to more than the total number of annuli, changed the shape of the line profiles in just the way one might expect. A narrow density profile such as Figure 5.6 (Panel f) yields a narrower, more sharply peaked HI line profile corresponding to a T-type classification and a kurtosis of -0.1. A wide density profile such as Figure 5.6 Panel j yields a S-type classification and a kurtosis of -0.956. So an increasing density profile width results in increasing kurtosis and a profile type changing from the T end down to the P end. Physically, the more centrally concentrated the neutral hydrogen is, the more centrally concentrated the HI line profile will be.

Profile shape depends directly on the relationship between density profile width and rotation curve turnover radius. All material outside the turnover radius will add height to the horns of the profile, making it more distinctly H-like and making the kurtosis progressively more negative. Any material inside this radius will simply add height to a region farther in. Depending on where this material is, it will add to different parts of the profile - creating the range of profiles we see from highly centrally concentrated (T) to more
concentrated outer regions (P). Thus, what fundamentally determines the shape of a profile is where the HI density profile peaks with respect to the place at which the rotation curve flattens off.

5.7 A Central Gas Depression

Understanding in more detail how the height and width of the density profile affect the shape of the overall profile, we can add a second gaussian to see the effect of this added complexity, which in turn is motivated by prior knowledge of the known HI gas distribution in nearby galaxies.

5.7.1 Secondary Density Gaussian Height

First, consider the effect of varying the height of the second gaussian from -1 (a Gaussian with height 1 subtracted from the main Gaussian) to +1 (a Gaussian with height 1 added to the main Gaussian). The resulting density profiles and overall profiles are shown below.

In these plots, we can see the density profile goes from a strong central depression (as desired) through to a relatively flat profile, ending in a composite profile with a strong central spike. The corresponding effect in the overall profile is somewhat intuitive. When the density profile has its deepest central depression, so does the overall profile. It does not, however, go all the way to zero because each annulus still has a two portions (the front and back of the galaxy along the minor axis with respect to our line of sight) that have
Figure 5.7:
Figure 5.8: The effect of changing the width of the secondary gaussian (Width2) of the density profile on HI profile shape. The top row shows the HI density as a function of radius (in terms of annulus number) with the secondary, in this case subtracted, gaussian getting wider. The second row shows the resulting HI line profiles. As the width gets larger, the width of the central depression in the profile gets wider, getting more horned. The kurtosis value gets more negative, following suit.

small or zero projected circular velocity, adding flux to the portion of the profile that corresponds to small velocities (i.e., the central region of the profile). While subtle because I made the primary gaussian flat, the progression through visual classifications can be seen in the profiles. As we go from low central density concentration Figure 5.7 Panel (a) to high (Panel(l)), shape profile type goes from H or P-like to S or T-like. Kurtosis also smoothly and monotonically increases though this progression from -1.1 for a Gaussian of height 1 subtracted, to -0.9 for a Gaussian of height 1 added (all kurtosis values can be found listed under their respective HI line profiles.)
5.7.2 Secondary Density Gaussian Width

Next, consider the effect of varying the width of the second density profile on the overall profile shape. Figure 5.8 shows the density profiles with different second Gaussian widths. The height is -0.9 (0.9 subtracted). In the density profiles, the central depression widens and the slope gets less steep. The effect of this on the overall profile is a minor central depression getting wider as the depression in the density profile gets wider. While this effect sounds somewhat like the effect discussed at the beginning of this chapter as a consequence of viewing angle or maximum circular velocity, it is not. While both of those parameters change where the edges of the profile are, this changes where the peaks are without affecting the location of the edges. While changing the width of the second gaussian does subtly change the shape of the overall profile, it is debatable how much it really changes how that profile would be classified visually. The effect, however, on kurtosis is clear; as more HI gas mass is carved out from the inner regions of the galaxy with increasing width, the overall profile gets less centrally concentrated and its Kurtosis gets more negative. Kurtosis values, shown in Figure 5.8 with the HI line profiles, range from -1.1 for the narrowest second Gaussian width (10) to -1.3 for the widest second Gaussian width (50).
Figure 5.9: Plot of density profiles (HI surface density in arbitrary units vs. radius in terms of annulus number) for the two varying secondary density Gaussian parameters. Positive values on the Height2 (second Gaussian) axis indicate that the second Gaussian is being added to the primary Gaussian; negative values indicate that it is being subtracted. On the horizontal axis is the Full Width at Half Maximum of the secondary Gaussian (Width2). These plots all have a primary density Gaussian width (Width1) of 10.
Figure 5.10: HI line profiles (HI flux density vs. velocity both in arbitrary units resulting from the preceding density profiles. The plot has the same axes and parameters as explained in the previous caption.
Figure 5.11: Plot of the density profiles for varying secondary density Gaussian heights (Height2) and widths (Width2) for a primary gaussian width of 20.
Figure 5.12: Plot of the HI line profiles for varying secondary density Gaussian heights (Height2) and widths (Width2) for a primary gaussian width of 20.
Figure 5.13: Plot of the density profiles for varying secondary density Gaussian heights (Height2) and widths (Width2) for a primary gaussian width of 30.
Figure 5.14: Plot of the HI line profiles for varying secondary density Gaussian heights (Height2) and widths (Width2) for a primary gaussian width of 30.
Figure 5.15: Plot of the density profiles for varying secondary density Gaussian heights (Height2) and widths (Width2) for a primary gaussian width of 40.
Figure 5.16: Plot of the HI line profiles for varying secondary density Gaussian heights (Height2) and widths (Width2) for a primary gaussian width of 40.
Figure 5.17: Plot of the density profiles for varying secondary density Gaussian heights (Height2) and widths (Width2) for a primary gaussian width of 50
Figure 5.18: Plot of the HI line profiles for varying secondary density Gaussian heights (Height2) and widths (Width2) for a primary gaussian width of 50.
5.8 The Changing Parameter Cube

In the final run of the simulation, a cube of parameter space was investigated, not simply a one-dimensional parameter vector. The three axes, chosen to eliminate dependent parameters, were all parameters of the density profile which was created from the sum of two gaussians. The three parameters were the width of the primary gaussian ($width_1$), the height of the secondary gaussian ($height_2$), and the width of the secondary gaussian ($width_2$). Consider first, moving in the positive direction along the $width_1$ axis. The density distribution gets wider, extending out into larger radii. The HI line profiles consequently become less centrally concentrated, moving generally from T-type to H-type profiles, and have decreasing kurtosis values. These patterns can be readily seen by looking at the general trends moving sequentially through Figures 5.10 to 5.18: the density profiles start very narrow at $Width_1 = 10$ (less than half the velocity turnover radius, $nrise = 25$) and grows to twice the turnover radius. The profiles in the first Figure are predominantly T- and S-type and evolve into exclusively H-type by $Width_1 = 50$. Then, consider moving up the $height_2$ axis from a gaussian that subtracted 0.8 (referred to as -0.8), to one that added 0.7 to the primary gaussian for the density profile. As this quantity increases from negative to positive, the density profile transitions from having a central depression, to being a normal gaussian, to having a central elevation. The consequences of this type of change in the density profile depend on the other two parameters.
Earlier in this chapter, when this parameter was modeled individually, its effect was clear; making the density profile more or less centrally concentrated resulted in the same effect in the HI line profile. Now, though, other interactions come into play, and the relationship is not so simple. When the width of both the primary and secondary Gaussian is small, the correlation is as expected. However, we now have a rotation curve that becomes flat midway out into the disk and a changing secondary gaussian width. So, as the width of the secondary gaussian gets larger, material is put in higher velocity bins. Especially if it gets put into the maximum circular velocity bin, it makes the profile less centrally concentrated rather than more. Additionally, as the width of the primary gaussian gets larger, the height of the second gaussian seems to become less significant in determining profile shape. The reason for this effect will be explained shortly.

Finally, consider moving along the $width^2$ axis in the positive direction. This axis is also interesting in that there is a sort of inflection point when $height^2$ is zero. First consider the case in which the secondary gaussian is subtracted (when $height^2 < 0$). In this case, as the secondary gaussian width increases, the HI line profile gets less centrally concentrated (lower kurtosis, moving toward H-type). In the other case, the secondary gaussian is added ( $height^2 > 0$). Now, as the secondary gaussian width increases, the HI line profile becomes more centrally concentrated (higher kurtosis, moving toward T-type). However, as the width of the primary density profile increases, the dependence of HI line profile shape on both $width^2$ and $height^2$ diminishes.
There is an additional aspect of the $width_2$ axis that is important to note. A number of profiles are missing from the Figures in the high $width_2$, low $width_1$ and negative $height_2$ region of parameter space. These combinations lead to an unphysical result - negative values in the HI density distribution. When the width of the secondary Gaussian is greater than the width of the primary Gaussian, and it is subtracted, there are points in the distribution where subtraction was being done from regions where the density was already zero, making it negative.

Investigating the effects of the multiple parameters changing simultaneously is a useful way to gauge the relative importance of the various parameters. The height and width of the secondary gaussian of the density profile have a substantial impact on profile shape when the primary gaussian width is small in comparison to the velocity turnover radius. However, when the width of the primary gaussian becomes greater than the velocity turnover radius ($width_1 = 30$), the properties of the secondary Gaussian become less important in dictating the shape of the HI line profile. As the width of the primary grows beyond that, these parameters become less and less important. The interesting thing here though is to look at the shapes of the HI gas density profiles for $width_2 = 45$ and $50$ in Figures 5.15 and 5.17. The density profiles change substantially, but there is little change in the shape of the HI line profiles (Figure 5.16 and 5.18, meaning that the exact shape of the density profile is not relevant in determining HI line profile shape. Thus, the driving force behind HI line profile shape is the position of the density
profile with respect to the velocity turnover radius. In terms of the goal of determining physical properties of the HI gas distribution from the shape of the HI line profile, this degeneracy is unfortunate. A distinct density profile cannot be inferred from an HI line profile. The most we can say spatially in this case is where the peak of the density profile lies with respect to the turnover of the rotation curve.

However, while knowledge of the location of the density profile with respect to the rotation curve does not yield specific information about the density profile, it does give insight into the nature of the galaxy and is useful in understanding it. That being said, recall from the classification chapter that \( H \) is by far the most common profile type. \( H \)-type profiles occur when a substantial portion of the galaxy’s HI lies outside the velocity turnover radius. Therefore, the most common HI density distribution is one that lies at least partially outside the turnover radius of the rotation curve.

A histogram of kurtosis values generated by the running of the this model through parameter space is shown in Figure 5.19. This distribution is relatively similar to the distribution of kurtosis values for the 9,000 observed HI line profiles published by Springob et. al. shown in Figure 5.20. The mean of the model output’s distribution is -1.26 compared to -1.15 for observed galaxies and both had modes of -1.3. A difference in mean values would be expected given that no face-on galaxies were included in this simulation, biasing our kurtosis to be more negative than for a sample that did include these galaxies. In addition, the model produced a number of profiles with
kurtosis values of approximately -0.1, a feature that is not present in the observed galaxy kurtosis distribution. This kurtosis value corresponds to the narrow, sharply peaked, HI gas density distributions, indicating that these distributions are not common in nature.
Figure 5.19: Histogram of the Kurtosis values generated by running the model in the parameter space just described
Figure 5.20: Histogram of the kurtosis values from the 9,000 galaxy data set published by Springob et. al.
Chapter 6

Conclusion

6.1 Findings

We presented here the results of an exploration into the physical properties of an HI gas distribution in relation to their appearance in the 21-cm HI line profile. This exploration was conducted by modeling HI line profiles with a simulation code and deriving and utilizing quantitative and qualitative classification schemes. From this, something can be said about the effect of individual physical parameters on the shape of the HI profile, the compatibility of our qualitative and quantitative classification schemes with each other, and the relative abundance of combinations of different parameter values.

There are a few especially noteworthy findings derived from considering parameters individually. First, with the exception of the degeneracies that occur at extreme parameter values, neither viewing angle, maximum circular
velocity, nor density affects either the shape classification given to a profile or its kurtosis value. The angle at which an observer views a galaxy certainly affects the appearance of that galaxy. However, it is not a property inherent to the galaxy, it speaks only to the orientation of the galaxy in space with respect to the observer. The fact then that viewing angle does not affect a profile’s classification (until reaching entirely face-on) in either scheme is extraordinarily fortunate given the goal of mapping between HI profile shape and physical parameters as it reduces the number of parameters under consideration by one. The maximum circular velocity has the same effect as viewing angle of scaling the width of the profile in or out. While maximum circular velocity is an important physical parameter of a galaxy, essentially it scales with the size of the galaxy. Finally, the overall HI density simply scales up the height of the entire profile. By fixing these three parameters, the effects of the other parameters with respect to each other and with respect to these three parameters can become clearer.

Second, the primary determinant of profile shape is the radius of the peak of the HI density profile with respect to the radius at which the rotation curve first plateaus. As material becomes less centrally-concentrated, flux is measured in the outer regions of the galaxy in both position and velocity space, resulting in a more H-like profile and a more negative kurtosis value. Conversely, the shape of a profile is highly indicative of where HI gas is distributed with respect to the rotation curve, a feature that should be telling of the galaxy’s dynamics.
Finally, the effect of changing the secondary Gaussian, although somewhat obvious, is worth pointing out because a central depression in HI distribution is so common. As the central depression (created by subtracting the secondary density Gaussian from the primary) gets deeper or wider, the profile becomes more H-like and its kurtosis becomes more negative.

Analysis of these trends was greatly aided by the employment of both a qualitative and quantitative classification scheme. A classification scheme helps characterize profiles by organizing them in a way which is useful in finding trends in data. The quantitative classification scheme categorized profiles based on kurtosis - the fourth statistical moment - which reflected how centrally-concentrated the profile was. The qualitative classification scheme cataloged profiles into four types based on shape, which was judged visually. Both of these classification systems are useful for characterizing profiles, and are relatively consistent with each other, giving a correlation coefficient $R^2$ of 0.634.

The most common kurtosis value, based on statistics on kurtosis values for 9,000 galaxies, was -1.3. The most common profile type based on visual classification was H. These correspond to galaxies in which a substantial portion of the HI gas is outside of the velocity turnover. While the height and width of the secondary density gaussian do affect the profile shape, the true driving force behind kurtosis value and profile shape is the width of the primary gaussian in the density profile. It is this number that determines how much HI gas will lie inside the velocity turnover radius and contribute to
the inner regions of the profile and how much HI gas is outside, contributing flux.

6.2 Future Work

This study is simply the beginning of investigation into the nature of HI movement and distribution in galaxies which I will continue in the fall. There are a number of productive avenues that could be considered to further our understanding of galactic neutral hydrogen and how it fits into the broader galactic context.

As the model became more complex and realistic through this paper, modifying the model could make it yet more realistic and our results more relevant. Resolved HI maps of nearby galaxies show that HI gas distribution is not always symmetric or uniformly distributed. Galaxies contain warps, asymmetries, bars, and spiral arms. All of these features could be incorporated into the model to consider the effects of their presence and orientation in the galaxy on the line profile.

In addition, work remains to be done to improve the classification scheme. Visual classification using the HPST scheme and quantitative classification using kurtosis values seem to be relatively consistent with each other. If the HPST classification scheme could be redefined slightly to emphasize degree of central-concentration of the profile as a factor in the visual classification, these systems could potentially become consistent enough to incorpor-
rate them into the same system in which a shape type could be synonymous with a range of kurtosis values. This is just one example of a way that the classification scheme could be adapted and ultimately automated; there are of course many others. Additionally, more modeling would be helpful to understanding the system better in order to base the classification system more firmly on physical properties of the HI.

Finally, it could be instructive to investigate the relationship between a galaxy’s HI and optical classification. A galaxy emits energy in many different wavelengths, corresponding to different processes, all of which interact to dictate the fate of the galaxy. Understanding the distribution and dynamics of HI is worthwhile in and of itself, but it takes on a whole new meaning and can give important insights when combined with data in other wave bands.