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RICE UNIVERSITY

**The Dynamics of Large-Scale Winds in Nearby
Starburst Galaxies**

by

Patrick L. Shopbell

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

Doctor of Philosophy

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Abstract

The Dynamics of Large-Scale Winds in Nearby Starburst Galaxies

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We present detailed spectroscopic and multiband photometric observations of the nearby galaxy M82 in order to study the high-velocity outflows observed in such galaxies as a property of the energetic starburst phenomena associated with their nuclei. The high spatial and kinematic resolution of our observations has allowed us to perform photometric analysis of $H\alpha$, $[N\ II]$, and $[O\ III]$ spectral lines at roughly one hundred thousand positions across the extent of the galaxy.

The observed velocities of the $H\alpha$ -emitting gas in M82 suggest a bipolar outflow of material along the minor axis at a projected velocity of ~ 300 km/s, fueled by the bright nuclear starburst regions in the galaxy's disk. All three spectral lines show double components in the centers of the outflowing lobes, with the $H\alpha$ line split by ~ 300 km/s over a region almost a kiloparsec in size. We argue for a model in which the optical emission is radiated by denser ambient material on the surface of "bubbles" that have been evacuated by a hot wind ($\sim 10^8$ K) visible at x-ray wavelengths. The outflow is confined to a cylinder within 350 pc of the disk, but flares outward in a cone beyond that point. The optical line-emitting filaments consist of both gas that has been entrained from the disk by the outflow and material already present in the halo of M82. Although the detailed structure of the bubbles is complex, we confirm the major predictions of galactic wind hydrodynamical simulations.

Line ratio maps reveal high $[N\ II]/H\alpha$ in the disk, suggesting the presence of a diffuse ionized medium (DIM) similar to that seen in NGC 891 and other star forming galaxies. The halo of M82 is also observed in emission lines, but only as dust-scattered disk radiation. We conclude that M82 has an active star-forming disk, a dusty scattering halo, and a bipolar starburst-driven wind.

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Chapter 1

Introduction

Ten years ago Chevalier and Clegg (1985) published a brief letter in which they conjectured that a high supernova rate in a galactic nucleus could heat the the surrounding gas to temperatures with sound speeds exceeding the escape velocity of the galaxy. This hot, tenuous gas would expand outward from the galaxy in the form of a “wind”, enriching the surrounding intergalactic medium. This thesis will apply the contemporary incarnation of this model to observations of the nearby starburst galaxy M82, including detailed Fabry-Perot observations at optical wavelengths.

The galaxy M82 is a strong source at infrared wavelengths, implying the presence of the high star formation rates required to fuel a galactic wind. The convincing evidence for a galactic-scale outflow in this galaxy is the presence of optical, x-ray, and radio emission along the minor axis of the galaxy, above and below the plane of the disk. This emission arises from the interaction of a hot outflowing wind with the halo of the galaxy. The velocity structure of the optical minor axis emission, resolved herein for the first time across the entire outflow, provides conclusive support for the presence of a galactic wind in M82.

This thesis will emphasize strongly the optical Fabry-Perot observations of M82. The imaging Fabry-Perot is a unique instrument with the capability to obtain high-resolution spectra over a narrow wavelength range (i.e., a single spectral line), across a field limited only by the detector in size and spatial resolution. The effective throughput of a Fabry-Perot greatly exceeds that possible with normal slit spectroscopy. However, these instruments have not been widely used because the massive amounts of data have proved difficult to analyze and interpret. The photometric analysis of imaging Fabry-Perot data described herein, as well as the associated software techniques, provide a clear reduction path for obtaining independent photometric spectral diagnostics from these complex data sets.

This thesis is arranged in six chapters. Following this introduction, Chapter 2 will provide a brief overview of galaxies, with special attention paid to the class known as

starburst galaxies. The galactic wind paradigm to be used throughout the thesis will then be presented, emphasizing its relevance to the starburst galaxy M82.

Chapter 3 will describe the new observations of M82 that have been obtained and analyzed for this thesis. Emphasis will be placed on the optical imaging Fabry-Perot data and the issues involved with its reduction and analysis. Chapter 3 concludes with a presentation of the detailed flux, velocity, dispersion, and ratio maps of M82 derived from these observations.

Chapter 4 will discuss a three-component model for M82, interpreting our observations and others in terms of a starburst disk, spherical halo, and galactic wind. The synthesis of these three components in the final section of Chapter 4 represents the primary achievement of this work, and provides a summary of the current understanding of M82.

Chapter 5 will briefly examine a few additional galaxies where large-scale winds and outflows are seen, interpreting select observations in light of our conclusions concerning M82, and pointing the way to further applications.

Finally, Chapter 6 will provide a summary of the primary conclusions of this thesis.

Chapter 2

Starburst Galaxies and Galactic Winds

Galaxies have been objects of fascination for thousands of years. Far before Magellan's observations of our southern neighbor galaxies, those that now bear his name, ancient peoples looked upward with their mythical understanding of our home galaxy, the Milky Way. Over the centuries, as more technical means of observation were brought to bear on the heavens, these explanations began to take on a more scientific form with the resolution of the Milky Way into stars by Galileo in 1610 and the discovery and tabulation of the "Messier list" in 1784 by Charles Messier, a French comet hunter (Phillips 1993). Following the relatively recent discovery in 1925 that the "spiral nebulae" were located at extreme distances outside our own galaxy (Hubble 1925) interest in galaxies has flourished. Many of the most basic questions confronted by astronomy will ultimately be answered through studies of galaxies: Where did we come from? Why are we where we are in the universe? What will ultimately happen to the universe? Galaxies are the building blocks of the universe, providing the link between smaller-scale stellar observations and cosmological studies of large-scale structure. The problems of galaxy creation and evolution are vitally important to an ultimate understanding of the universe.

As was done by Hubble in the 1920s, the classification of galaxies by morphology, or visual appearance, yields immediate insight into their common features. All "normal" galaxies fall into three categories based upon their appearance: elliptical, spiral, and irregular. Figure 2.1, Hubble's "tuning fork" diagram, illustrates this classification. Elliptical galaxies are roughly spherical distributions of stars; they can be ordered by their apparent ellipticities. Spiral galaxies are flat disk distributions of stars, usually containing spiral "arms" extending outward from a nuclear "bulge". Irregular galaxies are those remaining collections of stars and gas which appear to have little or no ordered structure. All galaxies that have been observed can be placed in these three categories, the distribution being approximately 13% ellipticals, 33% spirals, and 54% irregulars (Seeds 1989).

Figure 2.1 The Hubble “tuning fork” diagram, illustrating the classification of galaxies into the primary categories of elliptical and spiral. On the left are the elliptical galaxies, ordered by their ellipticity, while spiral galaxies are further divided on the right into those with and without bars. All other normal galaxies belong to the class known as irregulars.

While this classification is illuminating, its limitations should be kept in mind. For example, the Hubble classification, as much of astronomy, is based upon two-dimensional projections of three-dimensional objects. Only with assumptions of symmetry or more complex kinematic modeling can the three-dimensional structure of galaxies be inferred. The rather complex issue of the evolution of galaxies between ellipticals and spirals is also implied by Figure 2.1, but it is still a matter of hot debate as to the existence and direction of any evolution. Studies of galaxy clusters and galactic mergers seem to point to the creation of elliptical galaxies from spirals (e.g., Schweizer 1982; Seeds 1989), but this involves difficulties such as the creation of globular clusters (Barnes & Hernquist 1992). On the other hand, more detailed instrumental observations of elliptical and spiral galaxies have also strengthened this classification. For example, it is well known that elliptical galaxies are composed almost entirely of old (Population II) stars, with little or no gas (e.g., Baade 1944; Mihalas & Binney 1981). Young (Population I) stars and the star formation process,

which requires gas, are seen only in spiral and irregular galaxies. This clearly has important implications for the evolution of galaxies.

Overlapping the realm of “normal” galaxies, i.e., those that fall neatly into the Hubble classification, there has developed over the past 40 years a galaxy class known as “active galaxies”. As opposed to their quiescent counterparts, these galaxies are more luminous, particularly in their nuclei, and show very different (“nonthermal”) spectral properties. In addition, we often observe energetic phenomena such as high-velocity jets and enormous lobes of radio emission associated with these galaxies. The objects known as “radio galaxies”, “quasars”, “QSOs”, “Seyfert” galaxies, “BL Lac’s”, and “blazars” are all members of the active galaxy class, also referred to as “Active Galactic Nuclei”, or AGN (e.g., Osterbrock 1989). From a physical standpoint, the activity in these galaxies can be explained with a “standard model” based upon a supermassive ($M \sim 10^6 - 10^9 M_\odot$) black hole at the galaxy’s nucleus. The crushing gravity of such an object draws the material in the center of the galaxy into a rapidly rotating hot accretion disk. The actual process of accretion is a difficult problem, but current models are adequate to produce the observed copious amounts of radiation, the spectral nature of the emission, and other phenomena such as jets along the axis of the accretion disk. The most compelling evidence for the central black hole hypothesis, however, is the high-velocity kinematic signature seen in AGN. Recent high-resolution HST observations (Ford *et al.* 1994; Harms *et al.* 1994), for example, track rotational velocities on the order of ± 750 km/s within 18 pc of the center of M87. Such high velocities imply a central mass of $\sim 2.4 \times 10^9 M_\odot$, several orders of magnitude more mass than could be accounted for by a collection of normal galactic components, such as stars. Such central black holes are now believed to be more common than originally thought, with candidates galaxies including our neighbor M31 (the Andromeda Galaxy) (e.g., Kormendy 1988; Melia 1992) and the Milky Way itself (Genzel & Townes 1987). Perhaps there is no such thing as a “normal” galaxy!

In the middle ground between quiescent and active galaxies there are, of course, a range of intermediate cases. One of the most interesting is that known as a “starburst” galaxy. Starburst galaxies are those in which a significant amount of active star formation is taking place, usually concentrated in the central regions of the galaxy. In typical star-forming (spiral) galaxies, star formation takes place at a more moderate rate across the entire disk, primarily associated with the H II regions of the spiral arms. Although starburst galaxies are often extremely luminous, particularly

in the infrared, they are not technically classified as AGN, because they do not observationally require the central black hole engine as a power source. Clearly the issue of star formation is crucial here. From small-scale studies of the local spiral arm to the broader issues of galaxy formation and evolution, starburst galaxies are stellar nurseries of incredible scale, providing laboratories for the study of all aspects of star formation. Because the stars are formed quickly in large collections, starburst galaxies also provide an excellent opportunity to study supernovae and the interaction of the stellar death cycle with the surrounding interstellar medium. Only in starburst galaxies can one observe the effects of massive star clusters, stellar winds, and supernovae outside of single isolated events.

As such, starburst galaxies have been intensely studied for two decades. First noted by Larson & Tinsley 1978 in order to explain the colors of galaxies with morphologies indicative of interaction, high levels of star formation have been seen in many galaxies (Balzano 1983), from spirals (e.g., Gehrz, Sramek, & Weedman 1983; González-Delgado *et al.* 1994) to dwarfs (e.g., Skillman 1994), and in many locales, from galaxy nuclei (e.g., Noguchi 1988) and spiral arms (e.g., Vogel *et al.* 1993) to streamers of intergalactic debris (e.g., Mirabel, Lutz, & Maza 1991; Mirabel, Dottori, & Lutz 1992). In most cases, the origin of the starburst can be traced to large-scale gravitational instabilities, such as those induced by galactic mergers and bars. Such instabilities produce massive complex motions in the gaseous component of the galaxy, often bringing large quantities of outlying gas into the nuclear regions. The resulting regions of density enhancement, such as the sites of molecular cloud collisions, are extremely conducive to star formation. (See Elmegreen 1994 for a more detailed review of starburst theory.)

Observationally, starburst phenomena are best investigated using multiwavelength techniques sensitive to the products of star formation: optical, ultraviolet, and infrared emission lines for gas temperature, density, abundance, and metallicity determinations; radio line and continuum observations of supernovae remnants and complexes of molecular gas; infrared continuum emission produced by young stars embedded in dust and other obscuring material; and so on. Important observational quantities for theoretical starburst models include the star formation rate (SFR_t), supernova rate (SNR_t), star formation efficiency, and the initial mass function (IMF) of the stars.

A revolution in the study of starburst galaxies has occurred recently, fueled by the discovery of a phenomenon known as “galactic winds” (e.g., Mathews & Baker

1971; Bregman 1978; McCarthy, Heckman, & van Breugel 1987; Heckman, Armus, & Miley 1990). In several nearby starburst galaxies, evidence is seen for massive ejections of gas, dust, and energy, presumably powered by the high stellar winds and large numbers of supernovae occurring in these galaxies. These outflows are generally observed as large ($\sim$ few kpc), roughly conical structures originating in the nuclear starburst region and oriented along the minor axis of the galaxy. Galactic winds are usually seen in disk galaxies, where presumably the higher ambient densities in the plane of the galaxy force ejections to move out of the plane, along the direction of the greatest negative density gradient.

Galactic winds are seen at a number of wavelengths; primarily radio continuum, optical emission lines, and X-rays. Because of the detailed structure of the outflow (see Chapter 4), the low densities of the wind material produce optical emission lines that are often very difficult to detect, except in relatively nearby galaxies. Fortunately, the x-ray emission from these winds encompasses more energy on larger scales and is thus detectable to greater distances.

Table 2.1 Useful observational values and statistics for the galaxy M82. All values are obtained from de Vaucouleurs *et al.* 1991, except where otherwise noted.

Names	M82, NGC 3034, UGC 5322, ARP 337, 3C 231
Position (2000.0)	$\alpha = 09^{\text{h}} 55^{\text{m}} 54^{\text{s}}; \delta = 69^{\circ} 40' 57''$
Galaxy type	I0, Irr II
Dimensions	$11.2' \times 4.3'$ (10.1×3.9 kpc)
Position angle of major axis	65°
Disk inclination	81.5° ^a
Heliocentric radial velocity	203 ± 4 km/s
Distance	3.25 ± 0.20 Mpc ^b
Total magnitude	$B = 9.30 \pm 0.09$
Galactic extinction	$A_B = 0.13$
Infrared magnitude	$m_{\text{FIR}} = 5.58$
Colors	$B - V = 0.89 \pm 0.01; U - B = 0.31 \pm 0.03$

^a Lynds & Sandage 1963

^b Tammann & Sandage 1968

Figure 2.2 An unsharp-masked visual-band photographic image of the galaxy M82, taken at the 3.9m AAT. The unsharp-masking process has removed the smooth image structure, revealing the dust lanes and complex morphology of the disk. (Photo courtesy of R. B. Tully; unsharp-masking provided by D. Malin.)

The prototype galactic wind galaxy is indeed the topic of this thesis, M82. Table 2.1 gives a number of basic observational parameters of the galaxy, including its morphological designation, position, and distance. Since the original discovery of “Evidence for an explosion in the center of the galaxy M82” (Lynds & Sandage 1963), this galaxy has been the target of numerous studies attempting to understand the starburst nucleus and associated minor axis emission. M82 is an unusual irregular galaxy, in that its starlight is dominated by old Population II stars, similar to an elliptical galaxy. While the elongated optical appearance of the galaxy suggests a disk morphology, the usual designation of “irregular” results from the complex warped

dust lanes and hints of off-axis emission. Figure 2.2 is an unsharp-masked visual-band photographic image of M82 which illustrates the complex appearance of the galaxy. The absence of a thin disk seems to imply that we are not observing an edge-on spiral, but neither is the form of the emission what is expected for an inclined spiral, an elliptical, or a typical irregular.

Figure 2.3 A deep (~60 minute) visual-band photographic image of M82, taken at the 3.9m AAT. The filaments of emission extending along the minor axis of the galaxy are impressive. The morphology and spectra of these filaments form the basis for the interpretation that a strong outflow of gas, or galactic wind, is evolving along the minor axis of the galaxy. This figure is remarkably similar to that of Lynds & Sandage 1963 (Figure 1), from which the presence of an outflow, or “explosion” was first proposed. (Photo courtesy of R. B. Tully.)

Examination of the extremely deep image of M82 in Figure 2.3 provides additional insight. While the form of the galaxy at this exposure level is similar to that of an edge-on spiral, the extensive filaments along the minor axis of M82 are clear

and impressive. Defying other explanations, this complex filamentary structure is the primary optical evidence for a galactic wind in M82. Following the initial observations by Lynds & Sandage 1963, the first detailed spectroscopic study of the filaments (Burbidge, Burbidge, & Rubin 1964) showed kinematics indicative of a bipolar, roughly conical, outflow of gas along the minor axis of the galaxy.

Thirty years and over 500 published papers later, the initial interpretation of the M82 filaments in terms of a bipolar outflow still stands. Support for the much more detailed current model now encompasses observations at every wavelength from radio to gamma rays, as well as a wealth of theoretical models. The starburst nature of the nucleus of M82 has been verified through its strong infrared emission (e.g., Soifer, Houck, & Neugebauer 1987; Rice *et al.* 1988; Telesco *et al.* 1991) and numerous compact radio supernovae (e.g., Kronberg, Biermann, & Schwab 1985; Huang *et al.* 1994; Muxlow *et al.* 1994). Models of the starburst evolution are able to produce appropriate quantities of energy and mass on reasonable timescales to create and sustain the observed nuclear and galactic wind behavior (e.g., Rieke *et al.* 1993; Doane & Mathews 1993). The wind itself has been observed in great detail optically in both spectral (e.g., McCarthy, Heckman, & van Breugel 1987; McKeith *et al.* 1995) and imaging studies (e.g., Ichikawa *et al.* 1994), in emission lines (e.g., Armus, Heckman, & Miley 1990) and broadband radiation (e.g., O'Connell & Mangano 1978).

Perhaps the most stunning confirmation of the outflow has been at x-ray wavelengths, where a massive x-ray halo is seen oriented along the minor axis, extending up to 6-7 kpc from the disk, far beyond the visible extent of the optical filaments (e.g., Watson, Stanger, & Griffiths 1984; Schaaf *et al.* 1989; Bregman, Schulman, & Tomisaka 1995). This observation, illustrated in Figure 2.4, suggests that much of the supernova energy from the starburst is deposited in a very hot "x-ray wind", which is able to escape the disk of the galaxy at high velocities. A similar minor axis concentration is detected at radio continuum wavelengths (e.g., Seaquist & Odegard 1991).

Kinematical evidence for the existence of a galactic wind in M82 has been presented by several optical emission line studies (e.g., Heckathorn 1972; Axon & Taylor 1978; Bland & Tully 1988; Heckman, Armus, & Miley 1990; McKeith *et al.* 1995), and even in molecular observations (e.g., Nakai *et al.* 1987). The observed kinematical signatures consist of outflow along the minor axis as well as split emission lines, suggesting bipolar expanding "bubbles".

Figure 2.4 An Einstein x-ray image of M82 contoured over an $H\alpha$ image. The broad correlation of the X-rays with the minor axis optical filaments requires the galactic wind to produce both extremes of emission. Chapter 4 will describe in more detail a two-zone model for the wind which explains this observation. (Image taken from Watson, Stanger, & Griffiths 1984.)

The closeness and edge-on nature of M82 have led to a wealth of convincing observational evidence for an outflow of material along the minor axis of the galaxy. This has led to its use as the *prototypical galactic wind system*; observations of outflows in other galaxies are frequently compared to that in M82. Table 2.2 lists several galaxies in which phenomena indicative of large-scale galactic outflows are seen. Chapter 5 examines a few of these objects in more detail, comparing observations of the galaxies with the model developed in this thesis for M82.

Theoretical developments in the area of galactic winds have flourished as a result of the observational advances. Large-scale starburst-driven galactic outflows were first proposed by Mathews & Baker 1971 to account for the lack of gas in elliptical

Table 2.2 Galaxies in which evidence has been observed for galactic-scale winds and outflows. Sample references are provided for each object.

Galaxy	References
NGC 253	Ulrich 1978
	Fabbiano & Trinchieri 1984
NGC 1569	Tomita, Ohta, & Saitō 1994
NGC 1808	Phillips 1993
	Dahlem, Hartner, & Junkes 1994
NGC 2992	Colina <i>et al.</i> 1987
NGC 3034 (M82)	(this thesis)
NGC 3079	Filippenko & Sargent 1992
	Veilleux <i>et al.</i> 1994
NGC 3628	Fabbiano, Heckman, & Keel 1990
NGC 4945	Nakai 1989
NGC 5253	van den Bergh 1980
	Graham 1981

galaxies. The theory of winds in elliptical galaxies has since evolved in tandem with research on starburst-driven galactic winds (e.g., White & Chevalier 1983; Smith, Kennel, & Coroniti 1993a; Smith, Kennel, & Coroniti 1993b). The first model of a starburst-driven outflow was developed only ten years ago by Chevalier & Clegg 1985. Although basic in its assumptions, their model is able to predict not only the velocity, pressure, and density profiles of the wind, but also the observed optical filaments and extensive soft x-ray halo.

Since that original model, extensive advances have been made in both analytical studies (e.g., Koo & McKee 1992a; Koo & McKee 1992b) and hydrodynamical simulations (e.g., Suchkov *et al.* 1994) of galactic-scale outflows. Models of winds in other astrophysical situations, such as stellar winds (e.g., Shu *et al.* 1991) and winds in AGN (e.g., Smith 1993; Arav & Li 1994; Arav, Li, & Begelman 1994), have contributed to our understanding as well. Nevertheless, the basic model has remained essentially the same (Figure 2.5): A starburst is initiated by a galactic encounter, bar, or other large-scale gravitational instability, leading to a high spatial concentration of star formation, usually in the nuclear regions of the galaxy. The resulting supernovae

Figure 2.5 A schematic of a starburst galaxy with a galactic wind. Large molecular clouds in the nuclear regions of the galaxy (blue) give birth to great numbers of massive stars (*), which quickly die in violent supernovae events ($\odot$). These supernovae, as well as strong winds from the more massive stars, produce an expanding spherical bubble of hot gas. This bubble is confined from horizontal expansion by the galaxy's disk, forced instead to extend along the minor axes of the galaxy, creating a galactic wind.

from this population, assisted by the stellar winds from the more massive stars, heats the ambient gas, driving it outward in an expanding bubble. If the bubble encounters the disk of a spiral system, the higher densities in the plane of the galaxy force the bubble to expand along the minor axis, converting the spherical wind into a bipolar outflow. The wind material itself is assumed to be very hot ($\sim 10^8$ K) gas visible only at x-ray wavelengths, while optical emission appears in the boundary layer between the wind and the ambient galactic medium.

Following a detailed discussion of our observations and the associated data reductions in Chapter 3, we will use the galactic wind model just described to interpret the data in Chapter 4. The detail provided by our Fabry-Perot observations is unprecedented. It will allow us to investigate the star formation activity and its impact

on the disk and outflow, the velocity and emission characteristics of the outflowing gas, and the production mechanism for a large spherical halo detected around the galaxy. The interactions between these three components will prove to be crucial in the production of the unusual phenomena observed in M82.

Chapter 3

M82: Observations and Reductions

The major part of this thesis will be an in-depth examination of the outflow in the galaxy M82, the nearby “prototype” galactic wind and starburst galaxy. This chapter describes the multiwavelength data used for the study of this object, with emphasis upon the optical Fabry-Perot studies. Data from other instruments at additional wavelengths is used in primarily a supportive role.

The data obtained for the galaxy M82 consist of optical Fabry-Perot imagery at the wavelengths of $H\alpha$ (6563Å), $[N\ II]$ (6583Å), and $[O\ III]$ (5007Å), broadband imagery through B (0.44 μ m), R (0.65 μ m), I (0.8 μ m), and H (1.6 μ m) filters, longslit spectropolarimetry in the wavelength range 6000-6800Å, and soft x-ray imagery taken by the *ROSAT* High-Resolution Imager (HRI). We also make significant use of optical, infrared, and radio imagery of the galaxy as reported in the astronomical literature. We now describe the reduction of these data sets, concentrating primarily on the high-quality Fabry-Perot observations, as the application of this instrument to the galaxy M82 is the major scientific thrust of this thesis.

3.1 Fabry-Perot Imagery

The driving force behind this thesis – that which has enabled it to indeed be an original study – are the optical imaging Fabry-Perot observations of the galaxy. These data have provided us with high signal-to-noise, high spectral resolution, high spatial resolution spectra over a field encompassing the entire inner disk ($r \sim 2$ kpc) and almost the entire minor axis outflow ($r \sim 2$ kpc) in M82. Such detail is unprecedented in the study of this object.

In the field of astronomy, an imaging Fabry-Perot interferometer consists of a pair of extremely flat closely-placed reflective surfaces which are kept parallel to a high degree of accuracy. Light enters the “etalon”, as it is called, through one surface and interferes with itself via repeated reflections between the plates. Figure 3.1 illustrates the behavior of light in the etalon. To increase efficiency, the inner surfaces of the

(usually glass) plates are highly reflective (i.e., 95% – 99%), while the outer surfaces are anti-reflective coated. At the initial etalon surface, a large percentage of the incident light is transmitted through the glass and into the etalon, while a small portion is reflected. Usually this scattered light is absorbed in the optical system, although possible reflections back to the detector are an important consideration. Similarly, at the second glass plate, the majority of the light is reflected back into the etalon, while a small percentage is transmitted through the etalon. It is this small transmitted portion which is measured at the detector.

Figure 3.1 A Fabry-Perot etalon comprising two parallel glass plates with highly reflective interior surfaces, R_1 and R_2 , and anti-reflective exterior coatings, AR_1 and AR_2 .

The key to the understanding the operation of a Fabry-Perot is the realization that the peaks of transmission through the etalon obey the familiar interference formula

$$n\lambda = 2\mu l \cos \theta, \quad (3.1)$$

where n is the order of interference, λ is the wavelength of radiation, μ is the index of refraction of the material between the plates (usually vacuum, so $\mu = 1$), l is the separation of the etalon plates, and θ is the angle of the incoming light ray relative to the optical axis. The combination μl is often referred to as the “optical gap”.

The complete instrumental profile of a Fabry-Perot, known as an Airy function, is described in more detail elsewhere (e.g., Bland & Tully 1989).

It is clear from Equation 3.1 that, for a fixed etalon spacing l , the behavior of the Fabry-Perot is axisymmetric, with the wavelength varying in a radial direction. A normal slit spectrograph produces an image by dispersing a single illuminated line (the slit) in a perpendicular direction, creating a two-dimensional image on the detector with separate spatial and frequency axes. In contrast, an imaging Fabry-Perot spectrometer actually observes a two-dimensional spatial region, selecting at each pixel the specific wavelength dictated by Equation 3.1. In other words, the radial “dispersion” axis is not a true dispersion axis, as the light focussed on each pixel originates from a different point on the sky. The spatial and spectral domains are “multiplexed”.

For this reason, a Fabry-Perot instrument is often used in “scanning” mode, where images are taken repeatedly through a sequence of optical gap settings. Each pixel on the detector, while mapped to the same spatial image point, is thereby scanned through a sequence of wavelengths, generating a spectrum. This scanning of the optical gap can be accomplished by changing the gap spacing, l , or the refractive index inside the etalon, μ . A few Fabry-Perot systems vary the refractive index by modifying the pressure of a gas between the plates, a technique called “pressure scanning”. However, it is generally accepted that the former method, “gap scanning” is superior in accuracy and repeatability.

There are instances where the Fabry-Perot may be used without scanning, such as for narrow band imaging applications. Non-scanning Fabry-Perots have also been used recently to obtain observations of faint diffuse emission that encompasses the entire field of view (e.g., Kuttyrev & Reynolds 1989; Bland-Hawthorn *et al.* 1994; Reynolds & Tufte 1995). Utilizing the assumption of a uniform field, the observed image can be binned azimuthally to create a single “average” spectrum for the entire field, allowing the Fabry-Perot to obtain extremely deep spectra in a very efficient manner.

There are several significant characteristics of a Fabry-Perot etalon. Important figures of merit include the free spectral range (FSR), $\Delta\lambda$, which is the distance, in Å, between subsequent orders of interference, and the finesse, N_R , which is the ratio between the FSR and the width of the effective bandpass at a pixel. The free spectral range determines the wavelength span over which a spectrum may be obtained; the finesse determines the spectral resolution. Other values of theoretical interest are

Figure 3.2 The on-axis response of a Fabry-Perot etalon through three orders of interference of an $H\alpha$ emission line. The solid, dotted, and dashed lines represent decreasing plate reflectivities R , corresponding to decreasing values of the etalon finesse, N_R . The solid line reproduces most closely the response of the etalon used for the $H\alpha$ and $[N II]$ observations. The lower axis gives the order of interference at the wavelength of $H\alpha$ while the upper axis gives the wavelength at the 72nd order of interference.

the order of interference, n , and the zero-point etalon gap, l_o , in microns. A typical etalon might operate with $n \sim 100$, $\Delta\lambda \sim 50$, and $N_R \sim 30$, although this is heavily application-dependent. Figure 3.2 shows the Airy function response of a Fabry-Perot etalon, illustrating the concepts of free spectral range and finesse.

We will now describe the imaging Fabry-Perot observations made for this thesis. The subsequent data reduction steps will be outlined briefly as an introduction to the final data products, or “maps”, presented at the end of the chapter.

3.1.1 Observations

Two separate sets of imaging Fabry-Perot observations were analyzed in this work. The primary optical Fabry-Perot observations of M82 were obtained in February, 1986 in the emission lines of $H\alpha$ and $[N II] \lambda 6583$, at the 3.6-meter Canada-France-Hawaii telescope (CFHT) on Mauna Kea. The Hawaii Imaging Fabry-Perot Interferometer (HIFI) was used with the CFHT3 etalon. The theoretical and experimentally determined characteristics of the instrument are given in Table 3.1. Important features of the system include the high spatial resolution ($0.86''/\text{pix}$) and moderate spectral (velocity) resolution ($1.4\text{\AA} = 65 \text{ km/s}$, at $H\alpha$), as well as the wide field of view ($\sim 3.5' \approx 3 \text{ kpc}$).

Note that the combination of the $85\text{\AA}$ free spectral range etalon with a $50\text{\AA}$ FWHM interference filter has eliminated interorder problems. Regardless of the high finesse ($N_R \sim 60$) of this etalon, the Airy instrumental profile does not fall to zero transmission at any wavelength. This requires an interference filter of narrower width than the etalon FSR to ensure photometric integrity. Extreme care has been taken in this work to allow meaningful photometry to be performed. For example, the HIFI system has been optimized to remove the internal reflections, or “ghosts”, that plague all Fabry-Perot systems. Ghost images are extremely difficult to remove in the data analysis stage, complicating any attempt at photometric analysis. To remove reflections instrumentally, the etalon itself is tilted in the optical path by approximately 5° , shifting the position of the optical axis to the edge of the detector while reflecting all primary (cross-optical axis) ghosts out of the field of view. In addition, the plates of the Fabry-Perot can be manufactured as wedges, resulting in automatically tipped outside faces of the etalon. Figure 3.3 illustrates the optical path of the HIFI instrument, including features which specifically address the problem of internal reflections.

The second set of optical Fabry-Perot observations were made on the University of Hawaii’s 88” telescope on Mauna Kea in March 1992. The HIFI system was used with an etalon owned by Dr. Sylvain Veilleux. The theoretical and experimentally determined characteristics of the instrument are given in Table 3.2. Although the free spectral range of this etalon is smaller than that used for the $H\alpha$ and $[N II]$ observations, the finesse was essentially identical, as were the effective spatial and spectral (velocity) resolutions (after 2×2 binning of the $H\alpha + [N II]$ data). The key difference for this data set was not the instrument but the smaller aperture of the telescope, i.e.,

Table 3.1 Characteristics of the Fabry-Perot instrument used for the H α and [N II] observations in February 1986. Both the theoretical, or design, values and the observationally determined values are given.

Variable	Constant	Theoretical Value	Experimental Value
Observatory: Mauna Kea			
b	longitude	155:28.3	
l	latitude	19:49.6	
h	altitude	4215 m	
tz	timezone	GMT-10	
Telescope/Instrument: CFHT + HIFI			
D_{tel}	telescope diameter	3.6 m	
A_{tel}	telescope aperture	101788 cm ²	
f_{tel}	telescope focal length	28404 mm	
f_{coll}	collimator focal length	355 mm	
f_{cam}	camera focal length	90 mm	
Detector: IfA CCD + VISACOM			
p_{μ}	pixel size	15 μ m	
p''	plate scale	0.43''/pix	
n_p	CCD size	500 $\times$ 500 pix	
σ_{RO}	read-out noise	25.30 e ⁻	32.6 e ⁻
g	CCD gain	2.00 e ⁻ /ADU	
t	exposure time	450 sec	
Etalon: CFHT3			
$\Delta\lambda$	free spectral range (FSR)	85 Å	87.9 Å
Δz	free spectral range (FSR)	2656	2667
N_R	reflective finesse	60	45-50
n	order of interference	75	72
l_o	zero-point etalon gap	26 μ m	
Λ_v	velocity resolution	65 km/s	
R_{λ}	resolving power	4500	
Observations			
$\delta\lambda$	sampling increment (Å)	(0.96 Å)	0.99 Å
δv	sampling increment (km/s)	(44 km/s)	45 km/s

Figure 3.3 The optical trains for an imaging Fabry-Perot interferometer, including the interference filter (a), focal plane (b), field lens (c), collimator (d), tilted Fabry-Perot etalon (e), camera lens (f), and CCD detector (g).

2.2 versus 3.6 meters. This placed a limit on the depth of the observations, but the small spatial extent of strong [O III] emission in M82 was still sufficient for meaningful results.

3.1.2 Reductions: CCD

A scanning Fabry-Perot data set consists of a series of images, each taken at a slightly different optical gap setting for the etalon. These sets of images are referred to as data “cubes”, as they are often stacked during the data reduction process, creating three-dimensional data structures with two spatial axes and one spectral (velocity) axis. The Fabry-Perot observational data set is the same as that used for standard two-dimensional spectroscopic work, except in the form of three-dimensional scanned cubes: the target data cubes, a whitelight cube (obtained by imaging a white source), a calibration cube (obtained by imaging a standard lamp), and standard star cubes.

Most modern Fabry-Perot instruments use a CCD (charge-coupled device) as a detector, so the initial stages of data reduction are identical to those applied to any application of CCD imaging. These steps include bias subtraction, cosmic ray removal, bad column removal, and flatfielding. The following discussion of these data reductions assumes a moderate familiarity of the reader with CCD detectors in astronomy. (For more information on this subject, see the excellent references Jacoby 1990 and Howell 1992.) Essentially all of the data reduction was performed under

Table 3.2 Characteristics of the Fabry-Perot instrument used for the [O III] observations in March 1992. Both the theoretical, or design, values and the observationally determined values are given.

Variable	Constant	Theoretical Value	Experimental Value
Observatory: Mauna Kea			
b	longitude	155:28.3	
l	latitude	19:49.6	
h	altitude	4215 m	
tz	timezone	GMT-10	
Telescope/Instrument: UH88			
D_{tel}	telescope diameter	2.24 m	
A_{tel}	telescope aperture	39408 cm ²	
f_{tel}	telescope focal length	22665 mm	
f_{coll}	collimator focal length	254 mm	
f_{cam}	camera focal length	50 mm	
Detector: CCD			
p_{μ}	pixel size	24 μ m	
p''	plate scale	0.846 ''/pix	
n_p	CCD size	432 $\times$ 432 pix	
σ_{RO}	read-out noise		21.8 $\times g$ e ⁻
g	CCD gain		
t	exposure time	480 sec	
Etalon: SV1			
$\Delta\lambda$	free spectral range (FSR)	61 $\text{\AA}$	55 $\text{\AA}$
Δz	free spectral range (FSR)	502	325
N_R	reflective finesse	60	
n	order of interference	91	91
l_o	zero-point etalon gap	19 μ m	
Λ_v	velocity resolution	60 km/s	
R_{λ}	resolving power	5462	
Observations			
$\delta\lambda$	sampling increment ($\text{\AA}$)		0.67 $\text{\AA}$
$\delta\lambda$	sampling increment (km/s)		40.5 km/s

the Zodiac image processing system (Miyashiro 1982; Shopbell 1995), encompassing standard routines as well as a large number of programs written by the author and optimized for Fabry-Perot data.

Bias subtraction: Every CCD pixel contains a small specific amount of charge, even when not exposed to light. This residual charge is known as the “bias” value of the pixel. The bias value is clearly not related to the amount of light received by the pixel and therefore should be subtracted from the image. Fortunately, the bias value for a given pixel is reasonably constant over time. A bias frame is usually taken during an observing run; it is in essence a CCD image with an exposure time of zero. This frame, or preferably the average of several frames, is then subtracted from each CCD frame, including all of the calibration images. In some cases, a single value, rather than an entire frame, is subtracted from the image, since the bias value can often be assumed to be constant across the CCD.

For the $H\alpha$ and [N II] observations, seven bias frames taken throughout the observing run were averaged and then subtracted from each of the image frames. The issue was more complex for the [O III] observations, since no bias frames were obtained on that observing run. However, the CCD frames themselves were saved including both the data region of the chip as well as the region outside of the exposed frame known as the “overscan” region. Since this region is kept entirely dark during the exposure, the pixel values there serve as reasonable estimates of the bias value. Due to the non-zero exposure time, a few counts in these pixels are also attributable to what is known as the “dark current”, the slow leak of electrons into the pixels of a CCD. Since the CCD is maintained at a very low temperature, the dark current in modern CCDs is only a tiny fraction of the bias value. It is not of concern except for extremely high-accuracy photometry. In such cases, “dark” frames are also obtained and subtracted from the data.

Initially for the [O III] observations, the median of a frame’s overscan region was used to determine a bias value for the frame, and this value was then subtracted from the image. However, a trend became evident in the bias values, in the sense that the value increased with the time of observation. In addition, a strong horizontal banding pattern appeared prominently in the later observations. We suspect that this banding is a manifestation of an increased dark current as the temperature of the CCD rose (through loss of coolant, etc.). In order to remove this artifact as well, a bias “column” was created for each frame by averaging the columns in the overscan

region. This column was then subtracted from every column of the image. This method worked reasonably well, although a slight *diagonal* pattern is still evident in the images, implying that the dark current banding was not precisely horizontal in nature.

Cosmic ray removal: Cosmic ray hits are a noise source that plagues ground-based and, especially, space-based CCD observations. When a cosmic ray deposits its energy in a pixel of a CCD chip, the pixel is flooded with electrons, producing a spurious high signal. For very energetic cosmic rays at oblique angles, the energy deposition can be across many pixels.

There is a small industry associated with trying to remove these artifacts automatically (e.g., Windhorst, Franklin, & Neuschaefer 1994; Bland-Hawthorn, Serjeant, & Shopbell 1995), using techniques such as exposing multiple identical images and removing flux on the scale of single pixels in the Fourier domain. For our ground-based data, we chose to remove the cosmic rays essentially by hand, denoting each with a cursor click. While time consuming, the completion level was deeper than that of most automatic cosmic ray removal algorithms. The *xzplot* software written by the author was used to identify and remove the cosmic rays. *xzplot* is a tool for visualizing the spectra in a Fabry-Perot cube. It provides, among other things, functions for scaling, binning, and fitting spectra, contour maps, and cosmic ray removal. (See Appendix A for a more detailed description.)

The removal of cosmic rays is facilitated in Fabry-Perot work by the fact that the observer has a number of nearly identical frames, which vary only slightly in wavelength. Although the spectral resolution is usually not sufficient to use pairs of frames for automatic cross-correlation and removal of cosmic rays, it is sufficient that an examination of each spectrum clearly show the presence of cosmic rays. This solution is made tractable by *xzplot*, which can display grids of spectra, each one scaled to its own minimum and maximum. Figure 3.4 illustrates the detection of a cosmic ray using *xzplot*. A simple mouse click then replaces the appropriate pixel in the data with the median of the surrounding pixels, a reasonable assumption for our high-spatial resolution data. Multiple-pixel cosmic rays are removed in an iterative fashion. A total of approximately 600 cosmic rays were removed from the H α and [N II] data frames; a similar number were removed from the [O III] observations. Most of the calibration data frames are of sufficiently short exposure time that cosmic rays

Figure 3.4 An xzplot display of spectra from the raw $H\alpha + [N II]$ data cube. The axes denote the spatial positions in the cube from which the spectra were extracted. Each spectrum is scaled between its own minimum and maximum, revealing a cosmic ray hit covering three pixels.

are unimportant, although a few were removed in an identical fashion to reduce noise levels for fitting procedures.

Bad column removal: “Bad columns” are an internal artifact present in all CCDs to varying degrees. This noise contribution appears as columns of the CCD with irregular flux levels, implying defective gain values, full well depths, or other anomalies in the chip. The doping walls of the CCD semiconductor are arranged vertically, thus limiting these effects (in most cases) to a single column. Clearly the bad columns are present in the same pixels in all frames taken with a given CCD. This, combined with the fact that bad columns are usually small in number, makes these defects straight-

forward to remove. (Note, however, that the bad columns cannot be removed in the course of flatfielding, as the pixels may have nonlinear flux-dependent characteristics.)

Bad columns are most easily seen in a uniformly illuminated image, such as those obtained with a white lamp source. Figure 3.5 shows the sum of all of the whitelight frames from the $H\alpha+[N II]$ data set, scaled to reveal the defective columns. The position of each bad column can easily be determined from such an image. The artifacts are then removed via interpolation across each row of the bad column.

Figure 3.5 The sum of the whitelight images from the $H\alpha+[N II]$ data set. The image has been scaled to reveal the bad columns, as well as the chip defects and dust rings to be removed by the flatfielding process.

As a brief aside, the optimal form of interpolation across bad columns is an important consideration. The usual form, linear interpolation, is adequate, especially if a sufficiently wide portion of each row is used. Higher order polynomial interpolants can be shown to work slightly better, although it can be argued that these are not worth the additional effort. Polynomial interpolants, however, do not adequately sample the inherent noise and higher order moments of the image. In the spatial domain, a linear interpolation is in essence a top-hat function, whose Fourier transform is a sinc function. Clearly such a function produces periodic and uneven sampling of the noise power in an image. The preferred choice of interpolation function is the sinc function itself, as the Fourier transform of this is the top-hat function, implying even sampling of the image noise structure over a finite range. The bad columns in the data sets described herein have been removed via sinc interpolation.

Flatfielding: The final stage of CCD-like data reduction for Fabry-Perot observations is the process of flatfielding. Flatfielding uses a uniformly illuminated image to quantify the pixel-to-pixel variances in the sensitivity of the CCD. These sensitivity variations are divided out of the data frames, so that each count in each pixel corresponds to the same number of incoming photons. The flatfielding process also helps to remove dust marks and defective spots on the CCD chip.

The flatfield image was constructed for our data by summing all of the whitelight frames. Figure 3.5 illustrates the $H\alpha + [N II]$ flatfield before bad column removal, nevertheless illustrating the chip defects and dust “rings” to be removed by flatfielding. Examination of individual whitelight images suggested that the spatial illumination was not sufficiently uniform, so a two-dimensional linear fit was made to each image and any slope in the illumination removed. (A two-dimensional parabolic fit would probably have been more desirable, as the expected illumination pattern from a single source is azimuthally symmetric.) Following this, the flatfield was smoothed, and the smoothed version was divided into the original image, removing all structure larger than the scale length of the smoothing (i.e., $\sigma \sim 3$ pixels). As mentioned, we are only interested at this stage in removing small scale structure associated with the CCD chip. Finally, the flatfield was normalized to a value of unity and divided into each data and calibration frame.

To verify the performance of the flatfielding process, the histograms of relatively flat image regions were examined before and after flatfielding. Proper flatfielding should reduce the width of the histogram, signifying the removal of noise from the

image. In most cases, the flatfielding process did not substantially alter the noise content of the frames. This is due to a number of reasons, including problems with on-chip binning, the movement of dust and transient defects between images, and temperature fluctuations of the CCD. Examination of the histogram of the flatfield, however, shows that the pixel-to-pixel sensitivity variations comprise a noise source at a level of $\sim 1.6\%$, a number sufficiently small compared to other Fabry-Perot photometry errors that uncertainties due to flatfielding may be ignored.

3.1.3 Reductions: Fabry-Perot

We now describe the data reduction steps specifically oriented to Fabry-Perot data. Up to this stage, the separate images have been treated as standard CCD frames, each being individually processed through bias subtraction, cosmic ray removal, bad column removal, and flatfielding. (In fact, we may often take advantage of the large numbers of similar frames in Fabry-Perot data sets to automate many of the basic CCD processing steps beyond that normally possible for simple CCD observations.)

The reduction steps to be described in this section do not treat the images as separate frames, but rather as portions of scanned Fabry-Perot observations. In other words, the steps about to be described make use of the third axis in our data “cubes”, the spectral relationship between the frames.

Cube building and trimming: The first Fabry-Perot reduction step involves constructing three-dimensional data structures from the sets of (~ 40) two-dimensional images. The only complication with this obvious process is the bookkeeping required to ensure that the frames are ordered three dimensionally with respect to a monotonically increasing optical gap setting. In order to randomize variations in the sky background due to changing hour angle, approaching dawn, etc., as well as instrumental fluctuations, the data frames are usually not observed with a strictly increasing or decreasing optical gap. Rather, the frames are observed in a stepped fashion, obtaining every fifth frame, for example, in the cube on the first pass. Subsequent passes then obtain every fifth frame starting with frame two, every fifth frame starting with frame three, etc., eventually filling in the sequence of observations. Care must be taken to ensure that the individual frames are then stacked in the appropriate order in the data cube. This reordering process is not necessary for calibration cubes, as they are usually observed in a single sequence of monotonically increasing optical gap settings.

It should be noted that many spectral cubes may not be evenly sampled at this stage. The separation between frames in optical gap setting, z , may vary within a cube, and from cube to cube. This will be corrected in a later reduction step. Finally, as noted above, the stacking of the two-dimensional images into cubes is often actually performed earlier in the reduction process, to allow automation of various CCD reduction steps.

Whitelight calibration: The purpose of obtaining a Fabry-Perot data cube of a whitelight source is two-fold. First, it provides a series of flat images that may be summed to form a flatfield frame. The use of this image to remove the pixel-to-pixel variations in the CCD gain was described in the previous section on CCD reductions. Second, since the frames of the whitelight cube are taken at a sequence of etalon spacings across a presumably white source (i.e., constant flux with wavelength), the whitelight cube maps the spatial and spectral shape of the interference filter.

Spatial variations in the transmission of the filter will clearly appear as irregularities in each frame of the whitelight cube. Recall that such features were not removed in the flatfielding process due to the removal of large-scale flatfield structure via smoothing. It would have been inappropriate to remove spatial variations in the filter response at that stage, with a single flatfield, since such spatial structure in the filter could vary with wavelength. More importantly, it should be remembered that the data frames are not, at this point, monochromatic. The Airy response function of the Fabry-Perot ensures that the wavelength varies radially in each image, resulting in filter transmissions that vary radially as well. Until the phase correction step of the Fabry-Perot reductions, the spectral and spatial domains are intertwined.

Spectral variations in the transmission of the filter are usually of far greater concern, especially if the sampled wavelength range approaches the filter bandwidth. (We assume the use of a blocking filter with a bandwidth smaller than the Fabry-Perot free spectral range. Use of a filter wider than the FSR permits the passage of multiple interference orders simultaneously, greatly complicating photometric work.) Figure 3.6 illustrates a portion of the "spectra" from the whitelight cube associated with the $H\alpha + [N II]$ observations. The filter bandwidth was $\sim 50\text{\AA}$; $47\text{\AA}$ were sampled in the whitelight cube. Note that the shape of the filter is clearly evident in the spectral variation of the whitelight cube. The effect is large for frames near the ends of the filter bandpass.

Figure 3.6 A portion of the whitelight cube from the $H\alpha + [N II]$ data set. Each spectrum illustrates the wavelength response of the interference filter at that pixel.

To remove the spectral and spatial signatures of the blocking filter from the data, the whitelight cube is first smoothed heavily in the spatial domain (i.e., $\sigma \sim 15$ pixels). This removes any remaining pixel-to-pixel variations and small scale spatial noise. The whitelight cube is then re-sampled along the spectral axis, if necessary, such that the final sequence of optical gap settings, z , for the whitelight frames corresponds exactly to the sequence of settings for the data frames. This ensures that an appropriate scaling is made for each pixel of each data frame, with respect to its position in the filter bandpass. Finally, the whitelight cube is normalized to a value of unity and divided into the data cube. Since this stage affects most readily the final photometric calibration, the standard star frames should also be divided by the appropriate whitelight frames. Other calibration cubes need not be corrected for the filter response.

Frame alignment: Because the Fabry-Perot obtains a number of images of the target object over several hours of time, the frames must be aligned such that each pixel of a spectrum corresponds to the same spatial point on the sky. This is done in the usual manner by aligning stars in the field. In the case of M82, there is a single very bright star in the field, AGK 3+69 428 (Bettoni & Galletta 1982), about 2.5' southwest of the nucleus, as well as two smaller stars. In fact, the bright star is saturated in our data, requiring that the frames be aligned on the remaining two stars. Accurate positions of the stars were first determined for each frame using a centroiding algorithm. Each frame was then shifted spatially such that the two stars aligned on their average positions. Fractional pixel shifts were made by reinterpolation of the images.

While the spatial registration was deemed accurate to a fraction of a pixel ($\lesssim 0.5''$), a couple of comments are in order. First, our alignment process did not account for expansions or rotations of the images. While the former is usually not an issue with stable optics, an adjustment for rotations would have been desirable. Second, although the HIFI system is relatively free of ghost reflections, the location of the bright star in the southwest corner of the frame was such that a pair of concentric ghost images of the star appear in the southeast corner of the frame. Because they are reflections, the ghost images fluctuate spatially from frame to frame in an opposite sense to the position of the star itself. Therefore, alignment of the frames on actual stars produces a wide spread in the positions of the ghost images. The result is that a region much larger than a single ghost image has been ignored in the southeast corner of the frame. This is unfortunate, in that the minor axis emission of M82 runs directly through this region.

Rotating and binning: At some point in the reduction process, it is beneficial to rotate the data cube to the normal astronomical orientation, in which north is up and east is to the left. Keep in mind that any calibration cubes remaining to be used will need to be rotated as well. For this reason, this step is often left until the very end, although we mention it here as this was the point in the reductions at which the $H\alpha + [N II]$ data cube was rotated.

A reduction step less often applied is that of spatially binning the data. Usually great care is taken to employ a pixel scale which samples the seeing disk at the Nyquist frequency, e.g. an observation with 1'' seeing attempts to sample the data with 0.5'' pixels. Often this is done at the time of observation by using CCD features such as

on-chip binning. In cases of extremely poor seeing or less flexible instrumentation, however, it may often be desirable to bin the data itself spatially to match the seeing disk. As with the rotation of the data cube, binning of the data cube can be performed at any point in the reduction process, provided that all calibration cubes yet to be used are also binned. In the case of our $H\alpha + [N II]$ data set, this step was somewhat complicated by the fact that although the data had been binned on-chip, many of the calibration frames had not. Although theoretically on-chip binning and software binning should yield identical results (to the level of the readout noise), a few complications arose in the alignment of the frames that were binned differently. The exact locations of the bad columns served as guide points for alignment of the frames, and the results were reasonable.

Ring fitting: The two most common problems associated with Fabry-Perot systems concern the issues of internal reflections and etalon drifts. We have discussed the difficult problem of ghost reflections briefly in this chapter. Etalon drifts involve both spatial and spectral variations in the expected response of the Fabry-Perot, resulting from a number of instrumental effects, such as flexure of the optical system. One of the most notorious drifts is that induced by variations in the optical gap between the etalon plates, usually in the form of temperature and humidity variations in the index of refraction, μ . In this reduction step, we attempt to parameterize the possible extent of systematic drifts, through the fitting of Fabry-Perot “rings”.

Recall now from Equation 3.1 that the dispersion axis in a Fabry-Perot image is radial in form, although multiplexed with the spatial domain. Observation of a single spectral line, such as that produced by a standard lamp, therefore is mapped by the Fabry-Perot to a ring on the detector. Assuming a fixed optical gap setting for the etalon, any variations in the radius, ellipticity, and position of such a ring over the course of an observing run represent drifts in the optical system. For this reason, calibration (e.g., Neon) lamp images are taken periodically throughout the run, using a fixed etalon gap setting. Figure 3.7 shows one of the rings obtained during the $[O III]$ observations. Often a calibration ring image is observed between every five or six data frames, depending on the stability of the system.

The author has developed extensive software techniques for fitting Fabry-Perot rings. The radial peak of each ring is fitted with an ellipse, from which the ring center, radius, and ellipticity are derived. Fits to the radial profile of the ring are also helpful. This fitting process is non-trivial due to complications such as non-uniform

Figure 3.7 A monochromatic Fabry-Perot ring image obtained with the [O III] observations by observing a Neon calibration lamp. Such rings are obtained several times throughout the course of the observing run, to verify the spatial and spectral stability of the system.

rings and partial rings. For the data sets described herein, no noticeable variation was found in the radius of the ring throughout the observations, indicating that the spectral stability of the etalon was extremely good. The ring ellipticity also remained extremely close to unity. There was, however, a clear trend in the position of the ring center over time, corresponding to a shifting of the optical axis by approximately two pixels ($\sim 1.5''$). Such a shift is probably due to flexure of the optical system as the

telescope tracked the target, and is relatively harmless. Correction for this fluctuation is performed by the alignment process described previously.

Data cube resampling and smoothing: While obtaining the data, one usually attempts to observe the frames of a Fabry-Perot data cube in evenly separated increments of optical gap setting, z . If this was not possible, due to observing time constraints, for example, the frames should be interpolated to an evenly spaced series at this point. The difficulty of this reduction step is determined by how well the observations sample the velocity resolution of the etalon. As in the spatial domain, it is desirable to sample the spectral axis at the Nyquist frequency of the etalon's inherent resolution. If the sampling is substantially less frequent than this, it may be difficult to accurately interpolate intermediate frames, depending on the frequency of the underlying spectral fluctuations. Our $H\alpha + [N II]$ data required interpolation of several frames across the $[N II]$ portion of the spectra. Although a linear interpolation was performed without difficulty, a slightly larger error should be assumed for the final $[N II]$ fluxes and velocities. The $[O III]$ data set required interpolation of only a single frame at either end of the spectrum.

At this stage in the reduction we also apply a slight spectral smoothing to the data. The inherent Fabry-Perot process of obtaining the points in each spectrum from separate exposures does not guarantee standard (Poisson) noise characteristics in the spectral domain. Fluctuations in the seeing disk and other instrumental effects induce spurious noise along each spectrum. We remove such noise by applying a Hanning filter to the data. The Hanning filter replaces each pixel in a spectrum by the sum of itself, weighted by 50%, and its two neighbors, each weighted by 25%. Although this smoothing induces little change in the final spectral fits, we find it necessary to allow efficient automated fitting of the large numbers of spectra in a Fabry-Perot data cube.

Phase calibration: As mentioned previously, the instrumental profile of a Fabry-Perot etalon is a complex function of spatial position, wavelength, and optical gap setting, known as an Airy function. Figure 3.8 displays the three-dimensional monochromatic surface produced by an etalon. The surface is well approximated by a paraboloid, where the curvature is a function of the order of interference (n), the pixel size (p_μ), the camera focal length, (f_{cam}), and the on-axis free spectral range (Δz_0). The Z axis in the figure represents the etalon gap setting. Observations at a single gap setting,

such as those used above for the system stability checks, clearly contain monochromatic rings, like that seen in Figure 3.7.

Figure 3.8 The monochromatic surface generated by the instrumental profile of a Fabry-Perot. Although technically referred to as an Airy function, the surface is well approximated by a paraboloid. Fits to the surface, as observed in the emission lines of the calibration lamp cube, provide estimates of the free spectral range (FSR) and order of interference of the etalon. Spatial (X-Y) slices of this surface contain Fabry-Perot rings, such as that seen in Figure 3.7.

The primary point of this exercise, as illustrated in Figure 3.8, is to emphasize that spatial frames of the observed data cube are not monochromatic. In other words, the z axis must not be misinterpreted as a wavelength (λ) axis at this point in the reduction process. Conversion to a single wavelength axis for all spatial points is accomplished through a process known as “phase calibration”. The concept is simple: One uses the observed monochromatic lamp calibration cube to parameterize the Airy function for the instrument. These parameters are then used to shift the spectra at each pixel in the data such that the resulting frames are monochromatic.

In reality, this process is equally simple. Fabry-Perot phase surfaces, as observed in the monochromatic lines of a calibration lamp, are extremely well parameterized by the Airy function. Figure 3.9 shows a Y-Z cut through the calibration cube from the $H\alpha + [N II]$ data set. A cut through the theoretical surface has been overplotted to demonstrate the accuracy possible. In most cases, the observed surface is fitted with a fixed pixel size and camera focal length, while the order of interference and the FSR are allowed to vary. Both of these values are then determined to high accuracy by the fit. Complications do arise, such as ghost reflections from the bright calibration lines and the variation in the FSR with wavelength.

Figure 3.9 A spatial-spectral (Y-Z) cut of the observed Airy surface from the $H\alpha + [N II]$ data set. A theoretical fit with $n = 72$ and $\Delta z_0 = 2667$ has been superimposed to illustrate the excellent correspondence between the predicted and observed surfaces. The single glitch near row 27 is a trio of bad columns, a defect in the CCD.

Once the observed Airy surface has been parameterized by the fit, it is then used to shift each spectrum in the data cube by the appropriate value to generate monochromatic frames. In other words, the phase correction process “flattens” the curvature of the Airy surface shown in Figure 3.8.

In the case of our $H\alpha + [N II]$ data set, the phase correction process worked extremely well. To verify this, one monitors monochromatic features in the data, such as night sky lines. The convergence of two OH night sky lines in this data set into a single frame each confirmed that the data was properly phase corrected. The phase correction of the $[O III]$ data was less straightforward, however, because the FSR of the etalon was, in essence, unknown. It is usually desirable to scan the lamp calibration cube through slightly more than one order of interference, thus determining the effective FSR extremely well. This was not done in the $[O III]$ data set. In addition, the calibration cube was extremely poorly sampled, complicating fitting of the Airy surface. Following several failed attempts at a reasonable phase correction, the decision was made to bypass this step in processing the $[O III]$ data set. The major implication of this omission is that the absolute velocities determined from the line fits will not accurately represent the velocity field of the object. This was deemed acceptable only because the small scale of the $[O III]$ emission suggested it would be of little assistance in kinematic studies.

Sky subtraction: As mentioned above, night sky lines can be used to confirm that the phase correction step has produced spatial frames that are monochromatic. Following that process, it is appropriate to remove those night sky lines, as well as any night sky continuum, from the data. The usual way of accomplishing this is to compute a mean sky spectrum by binning spectra from spatial regions of the data cube that are representative of the sky background. This average spectrum can then be subtracted from each spectrum in the data cube, leaving only the flux of the desired target.

If night sky lines are present, these may serve another purpose as well: wavelength calibration. In the case of the $H\alpha + [N II]$ data set, for example, two strong night sky lines were present. Due to the presence of $H\alpha$ flux from M82 across the entire field of view, our composite “sky” spectrum contained not only the two sky lines and continuum, but also $H\alpha$ and $[N II]$ flux that clearly originated with the galaxy. Based on the location of the night sky lines relative to the $H\alpha$ and $[N II]$ lines, we were able to identify the lines as OH emission at 6553.61Å and 6577.28Å (Osterbrock &

Martel 1992). These two points allowed us to map the Z axis to wavelength, assuming a linear relationship between the two. Following this, we subtracted two Gaussians at the spectral positions of the night sky lines from each spectrum in the data set. Although spatial variations in the night sky flux and other factors produced poor sky subtraction in many areas of the field, this process improved the spectral fits across the frame. Note, however, that galaxy and sky continuum are both still present in our data (as would be evidenced by a continuum map). Sky subtraction of the [O III] data was not performed, due to the low level of sky flux and the difficulties of sky-subtracting data that has not been phase calibrated. Any resulting errors in the final spectral fits should be negligible.

Flux calibration: The most crucial reduction stage of any photometric work is the flux calibration, i.e., the translation of the pixel values from CCD counts (or ADU) to photons. In normal CCD or slit spectroscopy observations, this is accomplished by observing a “standard” star, a star whose inherent photon flux is known to high accuracy. The same basic method is also applied to Fabry-Perot observations, although the complexity of the Airy instrumental response adds a few additional considerations. Most of the previous Fabry-Perot studies in the literature are only velocity studies and do not attempt this stage of the reduction, or at the very least merely scale to a slit spectrum that has been flux calibrated in the usual way.

The steps in the flux calibration of Fabry-Perot data are:

1. Apply corrections to the standard star cubes.

Data cubes consisting of a few frames of one or more standard stars are obtained with the observations. The cubes do not need to be scanned in optical gap, as standard star fluxes are tabulated only in relatively wide ($\sim 40\text{\AA}$) spectral bins. The cubes should have all of the previous reduction steps applied to them to some extent. Cosmic rays and bad columns should be removed where they interfere with the stellar images. The whitelight correction for the filter response should be done carefully, with attention paid to the optical gap settings at which the standard star frames were obtained. Phase calibration is usually not necessary.

2. Measure the counts from the standard star images.

The CCD counts from the star image in each frame are summed using normal

aperture photometry: sum the counts in a circular aperture centered on the star, then subtract the sky contribution measured from a sky region of the frame.

3. Scale the counts by the aperture and exposure time.

A simple division by the telescope aperture and the exposure time yields a value for each standard star image in units of $\text{counts cm}^{-2} \text{ sec}^{-1}$.

4. Correct for the “effective bin size”.

The Airy instrumental profile passes a specific region of the spectrum through at each pixel, the width of which is determined by the finesse (N_R) of the etalon (see Figure 3.2). Also, as mentioned before, the Airy function does not drop to zero outside of this bandpass, except in the limit of infinite finesse. Thus, the effective width of this spectral bandpass must be divided into the measured counts from the star. The effective bin size is usually determined by summing the flux under an entire order of the theoretical Airy function (created from the parameters determined during the phase correction step) and dividing by the peak value of the Airy function. The result is a value for each standard star image in units of $\text{counts cm}^{-2} \text{ sec}^{-1} \text{ \AA}^{-1}$.

5. Determine the flux of the standard star at the telescope.

standard star calibrations are available in the literature, tabulated in magnitudes in $40\text{\AA}$ bins (e.g., Hayes 1970; Hayes & Latham 1975). The appropriate values are first corrected for atmospheric extinction (e.g., Walker 1987), and then converted to flux values in units of $\text{ergs cm}^{-2} \text{ sec}^{-1} \text{ \AA}^{-1}$.

6. Compute the scaling factor.

The ratio of the values calculated in the previous two steps is the desired scaling of ergs per ADU. Using the known energy of the photons at that wavelength, a system efficiency (ADU per photon) may also be determined. The final scaling factor for the data frames is obtained by dividing this ratio by the exposure time, telescope aperture, and effective bin size, and multiplying by the spectral separation of the data frames. Each pixel in the final spectra will then have units of $\text{ergs cm}^{-2} \text{ sec}^{-1} \text{ frame}^{-1}$, yielding total fluxes from the line fits in units of $\text{ergs cm}^{-2} \text{ sec}^{-1}$.

The star ϵ Orionis was used to calibrate our $\text{H}\alpha + [\text{N II}]$ observations, while both α Lyrae and η Hydrae were used for the $[\text{O III}]$ observations. The flux calibration

procedure was applied successfully, with a final estimated systematic error of $\sim 7.5\%$. Our emission line fits described below yield a total $\text{H}\alpha + [\text{N II}]$ flux from M82 of 1.4×10^{-10} ergs cm^{-2} sec^{-1} , reasonably close to the value of 6.5×10^{-11} ergs cm^{-2} sec^{-1} reported by Armus, Heckman, & Miley 1990. Assuming a distance to M82 of 3.25 Mpc, our $\text{H}\alpha$ flux of 9.9×10^{-11} ergs cm^{-2} sec^{-1} gives a total $\text{H}\alpha$ luminosity of M82 of 1.2×10^{41} ergs sec^{-1} , only slightly below the value of 2×10^{41} ergs sec^{-1} given by Heckman, Armus, & Miley 1990. Issues such as the saturation of the central regions and internal extinction complicate these comparisons, but they illustrate that the flux calibration procedure yields reasonable results.

Line fitting: Finally, the emission lines were fit with Gaussian profiles across the field. This fitting was performed with the *xzplot* software introduced above. Spectral fitting features include interactive and automated fitting of multiple-component spectra, linear continuum fitting, and masking of poorly fit spectra. The features of *xzplot* are described in more detail in Appendix A.

Single-component fits were made to the $\text{H}\alpha$ and $[\text{N II}]$ lines across the majority of the field, well into the halo of the galaxy. There were regions north of the galaxy's disk where double components were fit to the $\text{H}\alpha$ line profile, as well as regions south of the galaxy where double components were fit to both the $\text{H}\alpha$ and $[\text{N II}]$ lines. In the course of the fitting procedure it became clear that the $[\text{N II}]$ line profile is truncated north of the disk. The observations were not obtained to a sufficient optical gap setting to fully account for the curvature of the phase surface in the $[\text{N II}]$ line. An assumption of increased errors in the $[\text{N II}]$ fit parameters must therefore be taken into account when examining the maps presented in the next section.

The $[\text{O III}]$ line was fit as a single component throughout the nuclear regions of M82, although signs of split components were evident in specific locations. The spatial extent of the $[\text{O III}]$ line emission is substantially smaller than that of the $\text{H}\alpha$ and $[\text{N II}]$ emission, as evidenced in the maps to follow.

3.1.4 Final Maps

In this section we present the final data products from our imaging Fabry-Perot observations. The two-dimensional images herein will be referred to as "maps" with respect to particular parameters (e.g., flux maps, ratio maps, dispersion maps). Each map will be presented with a short caption that emphasizes particular details visible in the image. Physical interpretation of the images is left to the following chapter,

when we develop a three-component model for the galaxy M82. Chapter 4 will rely heavily on the maps presented in this section.

All of the maps are presented at approximately the same scale, with tick marks separated by one arcminute, or about 900 pc. For scale, a line representing 500 pc is provided on most maps. The maps from the $H\alpha + [N II]$ data set contain regions in which the spectral lines are split. In these cases the map shows both the flux-weighted total for the entire galaxy as well as the values for the individual components separately. Due to their appearance in the velocity maps, the components are referred to as the high-velocity component (HVC) and the low-velocity component (LVC). The maps and components are labeled accordingly. North is up and east is to the left in all images. The position angle of the major axis of the galaxy lies at approximately 65° east of vertical. The inclination angle of 81.5° is such that the nearer edge of the galaxy is projected above the nucleus. We are seeing the nuclear regions through the southern side of the disk.

The irregular shape of the data in the maps represents the region over which the Fabry-Perot line profiles could be fit. The regions beyond this radius had flux levels too close to the background noise to be reliably fit. The region of valid fits is identical for the $H\alpha$ and $[N II]$ maps, although, as mentioned above, the $[N II]$ fits in the northern-most regions of the maps have significantly higher errors, due to clipping of the $6583\text{\AA}$ profile. The region of valid fits is much smaller for the $[O III]$ maps. It should be noted also that the $H\alpha$ and $[N II]$ maps have regions at the center of the galaxy which are saturated.

Figure 3.10 Flux map of M82 in the spectral emission line of $H\alpha$ 6563Å. The upper map represents the total flux in that line at each pixel, in units of $\text{ergs cm}^{-2} \text{sec}^{-1}$. The values have been log scaled between $10^{-15.5}$ and $10^{-13.0}$. The lower panels represent the flux in the high- (HVC) and low- (LVC) velocity components of the line, in the regions where the line is split (designated by an outline in the upper panel). Note the lack of emission line flux along the major axis. The minor axis morphology is chaotic to the north with a more collimated structure in the southern direction. There appears to be an abrupt reduction in the southern emission along a line parallel to and approximately 500 pc from the disk. Beyond 500 pc, the flux in the HVC drops rapidly, while the flux in the LVC is brighter and more uniform throughout. Note finally the presence of diffuse emission at a low level throughout the halo of the galaxy.

Figure 3.11 Flux map of M82 in the spectral emission line of [N II] 6583Å. The upper map represents the total flux in that line at each pixel, in units of $\text{ergs cm}^{-2} \text{sec}^{-1}$. The values have been log scaled between $10^{-15.5}$ and $10^{-13.0}$. The lower panels represent the flux in the high- (HVC) and low- (LVC) velocity components of the line, in the regions where the line is split. (Split [N II] emission lines are detected only in the south.) The morphology of the [N II] flux is very similar to that seen at $\text{H}\alpha$ wavelengths (Figure 3.10).

Figure 3.12 Flux map of M82 in the spectral line of [O III] 5007Å. The flux is scaled to a fainter range ($10^{-16.0}$ to $10^{-14.2}$ ergs cm $^{-2}$ sec $^{-1}$) and is present above the noise level in a much smaller region than in the lines of H α and [N II]. There is essentially no emission from the disk at this wavelength, with the majority coming from the nucleus and southern outflow regions. The central regions are not saturated in [O III].

Figure 3.13 Velocity map of the H α emission in M82, in km/s. The upper map represents the total velocity of that emission line at each pixel. In regions of multiple components, the component velocities have been combined with flux weighting to yield an “average” velocity. An ellipse centered on the 2.2 μ m nucleus has been superimposed on the image. The lower panels represent the velocities in the high- (HVC) and low- (LVC) velocity components of the line, in the regions where the line is split (designated by an outline in the upper panel). Note that the velocity range is much larger for these panels than for the total velocity map. The most prominent feature is that of rotation of the disk. Along the minor axis, strong blue-shifting of the emission is seen south of the galaxy; strong red-shifting to the north. The rotation signature merges into this minor axis motion in a gradual fashion. The component velocity maps reveal the origin of the HVC and LVC designations: the former consists of heavily red-shifted and blue-shifted emission, while the latter component is essentially at the systemic velocity.

Figure 3.14 Velocity map of the [N II] emission in M82, in km/s. The upper map represents the total velocity of that emission line at each pixel. In regions of multiple components, the component velocities have been combined with flux weighting to yield an “average” velocity. An ellipse centered on the $2.2\mu\text{m}$ nucleus has been superimposed on the image. The lower panels represent the velocities in the high- (HVC) and low- (LVC) velocity components of the line, in the regions where the line is split (designated by an outline in the upper panel). Note that the velocity range is much larger for these panels than for the total velocity map. As for the $\text{H}\alpha$ velocity map (Figure 3.13), the most prominent feature is that of rotation of the disk. Although the signal-to-noise level is lower due to the reduced [N II] flux level, the trends in this map correlate well with those in the $\text{H}\alpha$ velocity map.

Figure 3.15 Map of the velocity separation between the components of the split $H\alpha$ and $[N II]$ lines. The degree of splitting is comparable in the two lines, being slightly greater and more uniform in the case of $H\alpha$. As in the flux and velocity maps (e.g., Figures 3.10 and 3.13), both emission lines show a drastic change in the line splitting along a line parallel to and 500 pc south of the disk. Interior to this point, the splitting is extremely small. Lower line separations are also seen toward the edges of the regions of split lines.

Figure 3.16 Velocity dispersion, or line width, map of the $H\alpha$ emission in M82. The upper map represents the total full width at half maximum (FWHM) of that emission line at each pixel. In regions of multiple components, the component line widths have been combined with flux weighting to yield an “average” width. The lower panels represent the dispersions in the high- (HVC) and low- (LVC) velocity components of the line, in the regions where the line is split (designated by an outline in the upper panel). The line widths are seen to be low in the disk, but increasing to high values (~ 300 – 400 km/s) in the halo. The outflow regions are not well-defined in this map, except where split lines are seen. The sharp edges of these regions are the result of moving from one moderately wide line to two narrow line components.

Figure 3.17 Velocity dispersion, or line width, map of the [N II] emission in M82. The upper map represents the total full width at half maximum (FWHM) of that emission line at each pixel. In regions of multiple components, the component line widths have been combined with flux weighting to yield an “average” width. The lower panels represent the dispersions in the high- (HVC) and low- (LVC) velocity components of the line, in the regions where the line is split (designated by an outline in the upper panel). The same trends seen in the H α dispersion map (Figure 3.16) are evident here but at a lower signal-to-noise level: low line widths in the disk, higher line widths in the halo. The dark region at the top is an artifact of the data caused by clipping of the [N II] line.

Figure 3.18 Map of the ratio of the [N II] 6583Å flux to the H α flux across the galaxy M82. The upper map represents the ratio of the total fluxes at each pixel. The lower panels represent the ratio in the high- (HVC) and low- (LVC) velocity components of the line, in the regions where both lines are split (designated by an outline in the upper panel). High values (1.0 - 2.0) are seen in the disk of the galaxy, particularly at large radii. Low values (0.0 - 1.0) are seen in the region of the outflow, along the galaxy's minor axis. Finally, intermediate ratios are seen throughout the halo. There are signs of an inverse relationship between the ratios in the two components: higher ratios in one component seem to correspond to lower ratios in the other.

Figure 3.19 Map of the logarithm of the ratio of the [N II] 6583Å flux to the H α flux across the galaxy M82. The upper map represents the logarithmic ratio of the total fluxes at each pixel. The lower panels represent the logarithmic ratio in the high- (HVC) and low- (LVC) velocity components of the line, in the regions where both lines are split (designated by an outline in the upper panel). The trends are clearly identical to those seen in the linear ratio map (Figure 3.18): high values in the disk, low values along the minor axis, and intermediate values throughout the halo. The southern outflow appears in the logarithmic map as a well-collimated region extending over 1.5 kpc southeast from the galaxy's center. Note that the extremely low ratios seen at the top of the map are the result of an underestimated [N II] flux.

Figure 3.20 Map of the ratio of the [O III] 5007Å flux to the H α flux across the galaxy M82. As seen in the [O III] flux map (Figure 3.12), the [O III] emission level is sufficient for flux measurements only close to the nucleus of the galaxy. Regardless, it is clear that the ratio of the [O III] flux to the H α flux increases with radius, being especially low around the saturated regions in the nucleus.

Figure 3.21 Map of the logarithm of the ratio of the [O III] 5007Å flux to the H α flux across the galaxy M82. The trends are clearly identical to those seen in the linear ratio map (Figure 3.20): the ratio increases with distance from the saturated nuclear regions.

3.2 Other Data

3.2.1 X-ray imagery

An extremely important manifestation of galactic winds are the x-ray halos seen to great distances along the minor axes. Believed to be thermal emission from the hot ($\sim 10^7\text{--}8\text{K}$) gas within the outflow, it is crucial to compare this soft x-ray emission with that seen at optical wavelengths. For this purpose, Dr. Joel Bregman has very kindly shared with us a copy of his recently published (Bregman, Schulman, & Tomisaka 1995) image of M82 taken with the *Röntgensatellit* (*ROSAT*, Trümper 1984) High-Resolution Imager (HRI) (Pfeffermann *et al.* 1987). The pair of 13' square images with total exposure time 33.8 kiloseconds were taken in early 1991 and late 1992. The resolution was about 5".

As the image had already been reduced, the only processing involved aligning the x-ray image with the optical Fabry-Perot imagery. Since the stars normally used for such work are not seen at x-ray wavelengths (unless they happen to be x-ray binary stars, of which none are seen in the M82 field [Bregman, Schulman, & Tomisaka 1995]), the alignment was performed using the astrometrical header information provided by *ROSAT* and the estimated location of optical knots in the $\text{H}\alpha$ flux map. The latter were determined by a manual comparison of the image with Bettoni & Galletta 1982. The final alignment is estimated to be accurate within 2"-3", although it should be noted that the ultimate position of the $\text{H}\alpha$ image was shifted by approximately 2" to the southwest to improve the alignment of certain emission regions.

Figure 3.22 shows the x-ray image contoured over the $\text{H}\alpha$ flux map. Note that the detailed spatial distributions of the $\text{H}\alpha$ and x-ray emission are extremely similar. This implies that the same physical process is probably responsible for the emission in both wavebands, although we leave a detailed interpretation to the next chapter.

Figure 3.22 The $H\alpha$ flux map from the optical Fabry-Perot data set overlaid with a contour map of the *ROSAT* HRI x-ray image. The $H\alpha$ image is displayed logarithmically between $10^{-15.5}$ and $10^{-13.0}$ ergs $\text{cm}^{-2} \text{sec}^{-1}$, while the x-ray contours represent 0 to 10 events per pixel, in 15 equally-spaced increments. The x-ray map has been smoothed with a Gaussian of FWHM $\sim 2''$. Note the extremely high spatial correlation between the $H\alpha$ flux and the x-ray emission. This implies a common physical origin for the radiation.

Chapter 4

M82: A Three-Component Model

The observations described in the previous chapter will now be used to develop a three-component model for the starburst galaxy M82. A morphological division will be used: the disk, the halo, and the outflow. Physically, these divisions will be examined in terms of the central starburst and wind injection zone (the disk), the dust-laden spherical “reflection nebula” (the halo), and the energetic galactic wind (the outflow). In the first three sections, this chapter will combine previous work in the literature with the observations just described to develop kinematic, energy, excitation, and other constraints to model each component separately. These constraints will then be combined in the final section to form a single coherent picture of the galaxy, encompassing a large portion of the knowledge currently available on this well-studied object.

4.1 M82: The Disk

The disk of M82 is perhaps the most intensely studied component of the galaxy. Indeed, it is the one component visible simply with a pair of binoculars, and as such, has been observed in the constellation Ursa Major since the time of Messier. Figure 4.1 shows the visual appearance of the galaxy. Encompassing an ellipse 11' long, with an axial ratio of 2.6 (de Vaucouleurs *et al.* 1991), the basic shape of M82 implies a spiral galaxy viewed almost edge-on. The actual diameter of the disk is then ~ 10 kpc, a factor of three smaller than the Milky Way. However, the disk does not appear narrow and smooth, but rather clumpy in appearance – bright and dark regions are intermingled with no visible organization. If the dark “clouds” are similar in nature to the coherent dust bands seen in other galaxies (such as M104, the Sombrero Galaxy; see Plate 67 of Ferris 1982), the chaotic appearance and poor symmetry would seem to question the assumption of M82 as a spiral galaxy. As a result, M82 is classified as an “Irregular” galaxy, with a morphological type of I0 (de

Vaucouleurs *et al.* 1991). Adjectives such as “flattened” (Bingham *et al.* 1976) are often prepended to the “irregular” designation.

Figure 4.1 Image of the galaxy M82 at optical wavelengths. Although it appears to be an almost edge-on spiral, note the dust lanes and complex patterns of obscuration across the disk. There are also signs of emission along the minor axis above and, especially, below the plane of the galaxy. (Photo taken from Ferris 1982, courtesy of the Hale Observatories.)

The primary advantage of M82 for astronomical study is its proximity. At about 3 Mpc away (Tammann & Sandage 1968), each arcsecond on the sky represents only about 15 pc in the galaxy. For the complex phenomena observed in this object, this small scale enables observations adequate for comparison with extremely detailed models. In the case of the disk, these models are primarily related to the starburst phenomena: its origin and evolutionary form, the current rate of star formation, and the assumed powering of the minor-axis outflow (Section 4.3). We look now at some of the disk observations and the resulting starburst models for M82.

The seminal paper by O'Connell & Mangano 1978 is perhaps the best morphological study of the disk of M82. Using a blue photographic plate, the authors isolate, identify, and label the primary stellar clusters present in the central 3' of the galaxy. Their identifying image is reproduced in Figure 4.2. Several large clusters that are the core of the "starburst" are labeled. The brightest clusters, *A* and *C*, are estimated to be less than 5×10^7 years old, much younger than the estimated time since the gravitational encounter with M81 ($\sim 10^8$ years) which is purported to have induced the starburst. (Such delay times are expected by current galaxy interaction models to allow accretion and condensation of central star-forming regions.) The other central clusters have similar ages, and contribute to a total star formation rate of $\sim 10 M_{\odot}$ per year. Outside these nuclear clusters, the disk beyond the central kiloparsec contains little ionized gas, implying a lack of massive stars there and a low level of recent star formation. We will use the cluster identifications from O'Connell & Mangano 1978 throughout this work.

Figure 4.2 Image from O'Connell & Mangano 1978 identifying the starburst clusters in the disk of M82.

Kinematical studies of the disk are numerous, including radio observations in CO, OI, and H I lines and continuum, as well as infrared and optical observations in both

emission and absorption lines. The molecular observations in various isotopes of CO (Nakai *et al.* 1987; Loiseau *et al.* 1988; Loiseau *et al.* 1990) are particularly enlightening. Observations of ^{12}CO clearly show a double-peaked structure in the nuclear region of M82 (see Figure 4.3 from Loiseau *et al.* 1990). This structure is taken to be a 170 pc wide molecular torus, or ring, surrounding the “nucleus” of M82 at a radius of approximately 250 pc. The velocity information from the ^{12}CO line clearly shows this ring to be rotating with the disk with $v_{\text{rot}} \sim 80$ km/s. The presence of the ring is understood in terms of the third M82 component to be discussed below, the outflow. Specifically, this molecular ring represents the regions of current star formation in the galaxy. The galactic wind and its energizing supernovae have evacuated the nuclear regions interior to this ring of the gas needed for star formation, while at the same time forcing shock waves into the molecular ring material, instigating additional star formation. Also visible in the ^{12}CO velocity field are motions along the minor axis, implying that portions of the molecular clouds are being dredged out of the disk by the galactic wind. This funneling effect of the molecular ring and other details will be discussed further in Section 4.4.

Figure 4.3 Superposition of a ^{12}CO map over a greyscale near-IR image of the central regions of M82. The two principal CO peaks are the cross-section of the molecular ring. Note that the ring lies outside of the starburst clusters that form the primary peaks in the near-IR emission. (Image taken from Loiseau *et al.* 1990.)

^{13}CO observations (Loiseau *et al.* 1988), in contrast to the ring revealed in ^{12}CO emission, show emission in a centrally concentrated region. However, it seems that this is due merely to optical depth effects. The ^{13}CO isotope is capable of seeing deeper into the galaxy, revealing that the molecular ring is not, perhaps, entirely evacuated, but may be partially filled. The ^{13}CO observations also confirm that the central molecular emission is rotating with the disk.

Other molecular lines have been observed, such as H I and OH (Weliachew, Fomalont, & Greisen 1984). The absorption at these wavelengths confirms the existence of a ring of radius 250 pc, thickness of 120 pc, and rotational velocity 137 km/s. (See Figure 4.4.) Also derived from these observations is an H I mass in the ring of $1.2 \times 10^7 M_{\odot}$, a value appropriate for the amount of extinction observed at optical wavelengths.

O'Connell & Mangano 1978 performed basic optical emission line analysis on the central star clusters in M82, particularly those denoted *A* and *C* (see Figure 4.2). They concluded that cluster *A* is rotating about an axis with position angle 133° , that is, an axis not aligned with either the major (65°) or minor (155°) axes of the galaxy! Meanwhile cluster *C* was interpreted as participating in normal disk rotation. We will argue that this result, based on the two slit spectra sketched in Figure 4.2, is not correct. Their extraneous rotation axis, obtained before the kinematical signature of the outflow was established, is merely the superposition of normal disk rotation and the outflow velocity profile.

More recent optical observations of the disk by Götz *et al.* 1990 in the emission lines of H, He, O, N, and S provide rough confirmation of the central ring structure observed in the molecular lines. These authors detect emission lines split by ~ 270 km/s along a line parallel to and $10''$ north of the major axis of M82, out to a radius of 380 pc. It should be emphasized that their slit is approximately 150 pc north of the central M82 clusters, and they accordingly attribute the two emission line components to H II regions in the near side of the disk and the base of the far side of the northern outflow. Nevertheless, the authors argue for an "split emission line zone" surrounding the molecular ring. The components can be associated physically with entrained material being drawn out of the disk in a cylinder around the hot wind. Note that split lines are not seen directly on the major axis of the disk. Finally, Götz *et al.* 1990 also observed the $\text{H}\alpha$ and Na D stellar absorption lines, deriving a normal stellar rotation curve with a mass for M82 of $2.9 \times 10^9 M_{\odot}$ interior to $r = 1.65$ kpc.

Figure 4.4 Contour map of the H I optical depth in the central regions of M82. The positions of a number of correlated observations are also noted: *R* and *O*, the radio and optical kinematic centers; *IR*, the $2.2\mu\text{m}$ peak; *RR*, the radio recombination peak; *P*, the continuum point source; m_1 and m_2 , masers; *A*, *C*, and *E*, starburst clusters identified by O'Connell & Mangano 1978. The H I observations confirm the existence of the molecular ring surrounding the center of the galaxy. (Image taken from Weliachew, Fomalont, & Greisen 1984.)

In light of the starburst activity in M82, it should not be surprising that the observation of supernovae (SN) and supernova remnants (SNRs) is another area of intense work. Begun with the observations by Kronberg, Biermann, & Schwab 1985, temporal changes in the radio SN population have been monitored. Kronberg, Biermann, & Schwab 1985 originally detected approximately 40 compact radio sources within 300 pc of the nucleus of M82. The more recent work by Huang *et al.* 1994 found approximately 50 compact sources, although none are classified by the authors as "new". Most sources are seen to be declining in flux, as expected, but a few seem to have increased. It is believed that the high pressure in the central regions of M82 causes young SN to compress the gas (much of which was released in the form of

stellar winds from the SN progenitors) into dense shells. When SN shocks reach this denser material, higher emissivities are seen. The existence of these dense shells is also supported by longer wavelength (3.3 mm) radio observations (Carlstrom & Kronberg 1991).

Muxlow *et al.* 1994 have recently performed an extremely high resolution (20 milliarcsecond) 5 GHz radio study of the radio supernovae in M82. They find a distribution exactly like that of Kronberg, Biermann, & Schwab 1985, but are also able to spatially resolve the radio SNe. They find that the SNe in M82 are typically an order of magnitude smaller than those in the LMC and the Milky Way, i.e., about 0.5 pc in diameter. This is expected from their younger ages and explains well the relatively increased brightness of the M82 SNe. Also confirmed from their high-resolution observations is the presence of complete or partial shells around the vast majority of SNe. Finally, Muxlow *et al.* 1994 compute a supernova rate of ~ 0.05 per year, a low value for an active starburst galaxy, implying that the starburst in M82 may be waning. (This calculation is dependent upon the reasonable assumption that the young radio supernovae are still expanding freely.)

Our observations of the disk of M82 confirm the general picture developed by previous studies. Note first the total flux maps, Figures 3.10, 3.11, and 3.12. Little ionized gas is observed in the extended disk of M82; it is primarily seen in the nuclear starburst region, where massive ionizing stars and molecular gas capable of being ionized currently coexist. This confirms the results of O'Connell & Mangano 1978, whose slit spectra show little emission line flux from the extended disk. There are a few exceptions to this in our data, most noticeably the small spots of emission $0.5'$ east of the nucleus. These are assumed to be "normal" H II regions, albeit extremely large ones. These clusters appear on the identification chart of O'Connell & Mangano 1978 near knot *H* (see Figure 4.2). This interpretation is confirmed by the $[\text{N II}]/\text{H}\alpha$ ratio map Figure 3.18, in which these two regions appear with moderate ratio values, averaging 0.56. This value is appropriate for the hotter range of photoionized H II regions (Veilleux & Osterbrock 1987; Baldwin, Phillips, & Terlevich 1981). It should be noted early in this discussion, however, that obscuration and extinction effects certainly play a major role in the apparent distribution of optical emission in the disk.

The emission line flux is the strongest in two regions at the nucleus of M82, both saturated in the $\text{H}\alpha$ and $[\text{N II}]$ maps. These "eyes", as they are called, correspond to knots *A* and *C* of O'Connell & Mangano 1978 and are known to be extremely

high surface brightness clusters of stars. These knots are, in essence, the starburst itself. Also identifiable are knots *D* and *E* (also saturated), as well as *F*, *G*, and *H*. (Compare Figure 4.2 in this chapter with our H α map in Figure 3.10.) It is clear from the flux maps (Figures 3.10, 3.11, and 3.12), and especially from the logarithmic [N II]/H α map (Figure 3.19), that the origin of the outflow coincides with these two clusters.

As seen in the total velocity maps (Figures 3.13 and 3.14), the observed kinematics of the disk are those of a simple rotating disk. Figure 4.5 is a plot of the H α radial velocities along a line through the major axis of the galaxy. The published systemic velocity of M82, 203 km/s (de Vaucouleurs *et al.* 1991), corrected to a heliocentric value of 208.7 km/s, has been subtracted from the data. The rotation curve rises to approximately 100 km/s within $\sim 9''$ or ~ 130 pc, of the nucleus and remains relatively flat to the edges of the observations. No substantial fall-off in the rotation curve is seen, as expected, since the Fabry-Perot data extends across only a small ($\sim 3'$) portion of the $11'$ optically-visible disk. The observed rotation curve matches very well those found in H α by Heckathorn 1972 (Figure 12) and McKeith *et al.* 1993 (Figure 3), including the turn-over and asymptotic velocities and the nuclear velocity gradient (11 km/s/"). The curve also agrees qualitatively with that of O'Connell & Mangano 1978, although their data only encompasses the radial extent of clusters *A* and *C*.

The only anomalous feature in the rotation curve is the rise in the west side at a radius of approximately $60''$. This feature is seen in the velocity map (Figure 3.13) as a circular region of emission at essentially the systemic velocity. The existence of a large (100 pc), stationary region within M82 at a galactic radius of a kiloparsec seems very unlikely, given the rotation curve. We find no record in the literature of a velocity structure such as this, and are therefore led to the assumption that this is a foreground object.

It should be noted that the turnover radius and velocity of the rotation curve corresponds almost exactly to those of the molecular ring found by Loiseau *et al.* 1990 and others. The rotation curve therefore strongly supports the presence of a molecular/emission-line ring. (Recall that Götz *et al.* 1990 detected an emission-line ring surrounding the molecular ring, but their observations were obtained 150 pc north of the major axis of the galaxy. Under the argument that the emission line flux is created by ionization of the molecular cloud gas by the starburst, the molecular and emission-line rings may very well coincide closely in center of the disk, as suggested

Figure 4.5 A plot of the radial velocity of the $H\alpha$ line along the major axis of the galaxy. The curve gives the velocities interpolated over a band $7'' \approx 100$ pc wide through the $2.2 \mu\text{m}$ nucleus. A systemic velocity of 208 km/s has been subtracted from the data.

by the molecular observations of Nakai *et al.* 1987.) It should be noted that galactic dynamics also predicts that any bar in M82 would terminate at such a ring.

Another set of maps of interest in understanding the disk of M82 are the $[\text{N II}]/H\alpha$ line ratio maps, Figures 3.18 and 3.19. These maps clearly show a high $[\text{N II}]/H\alpha$ ratio in the disk, especially at large radii, where the value approaches 1.5. Keep in mind that the disk is viewed through the halo, however, and the halo exhibits lower $[\text{N II}]/H\alpha$ ratios. The actual disk ratios are probably therefore slightly higher, as well as slightly more uniform, since the increased density and larger line-of-sight dimension of the halo in the central regions of the disk would be expected to have an increased diluting effect there, lowering the ratio over that seen in the outer disk.

Such high $[\text{N II}]/\text{H}\alpha$ line ratios in the disk are not expected, but neither are they unprecedented. Studies of NGC 3079 (Veilleux *et al.* 1994) and especially NGC 1068 (Bland-Hawthorn, Sokolowski, & Cecil 1991) have found high $[\text{N II}]/\text{H}\alpha$ ratios of 0.6–1.3 across much of the galaxy’s inner disk. In the latter case, the disk H II regions are found to reside in regions of lower $[\text{N II}]/\text{H}\alpha$ (~ 0.3 – 0.8), while the disk as a whole is permeated with gas exhibiting the higher ratios. In the case of NGC 1068, the excitation of this “diffuse ionized medium” or DIM, has been modeled primarily in terms of the scattered emission from the Seyfert nucleus.

The emission mechanism in the disk of M82 which produces the high $[\text{N II}]/\text{H}\alpha$ ratios is assumedly connected to the starburst phenomenon. In order to boost this forbidden line to recombination line ratio, the gas must be kept hot, yet the ionization state of the gas should be kept low. In other words, the “heating per ionization” must be high. There are a number of ways in which to accomplish this, although the primary requirement is a hard radiation bath (Sokolowski 1992). The strong energy dependence of the photoionization cross section (e.g., Osterbrock 1989) then serves to limit the level of hydrogen ionization from such radiation.

In the case of M82, a strong candidate to enhance the $[\text{N II}]/\text{H}\alpha$ ratio is a process known as “mixing layers”. Recent work (e.g., Slavin & Cox 1993; Voit, Donahue, & Slavin 1994) suggests that the turbulence resulting from the interaction of supernovae with the ambient ISM forces relatively cool gas to mix with hot gas, giving rise to an intermediate temperature phase. The radiation field from the gas in this mixing layer has been modeled and appears somewhat harder than thermal bremsstrahlung, resulting in $[\text{N II}]/\text{H}\alpha$ ratios up to roughly 1.0 (Slavin, Shull, & Begelman 1993). Considering the current optical appearance of the disk of M82, as well as its interaction with the galaxy M81 approximately 10^8 years ago, a turbulent disk would indeed be expected. Combined with the supernovae from the starburst phenomena also present in the galaxy, the observed line ratios could be expected from a mixing layer model.

However, as argued by O’Connell & Mangan 1978, there appears to be little active star formation in the extended disk of M82. Indeed, all of the radio SNRs discovered by Kronberg, Biermann, & Schwab 1985 are within 300 pc ($20''$) of the galaxy’s nucleus. Other, less likely possibilities should therefore be considered as well, such as chemical enrichment (i.e., the quantity of nitrogen has been enriched relative to hydrogen, perhaps by star formation), Alfvén heating by magnetic fields, and cosmic ray heating. The first possibility seems unlikely given current measures of radial abundance gradients in galaxies (see Fesen, Blair, & Kirshner 1985). The latter

two concepts are still in the early stages of theoretical development (e.g., Ferland & Mushotzky 1984), but could yield useful results in the near future. A combination of shock and photoionization may also provide a solution (e.g., Hunter & Gallagher 1990), although detailed models are not yet available.

4.2 M82: The Halo

The halo of M82 has only been recognized as such in recent years, although there is a rich history of controversy surrounding what is now known to be emission associated with the outflow. Early observations detected a strong linear polarization in the field of M82, with the electric vectors oriented perpendicular to a radial vector from the nucleus (Elvius 1969). This polarization was immediately interpreted as evidence for a scattering component in the galaxy (e.g., Solinger 1969), probably consisting of electrons illuminated by the nucleus. With the claim by Visvanathan & Sandage 1972 that the minor axis filaments and the halo were equally polarized at optical wavelengths, the origin of the filaments in a central explosion or outflow was brought into question. The red- and blue-shifted portions of the velocity field were then argued by Elvius 1972 to consist of nuclear emission scattered from a dust cloud through which the galaxy was moving. This interpretation of the emission line filaments as simply halo density enhancements illuminated by the nucleus culminated with the work of Solinger, Morrison, & Markert 1977, "M82 Sans Explosion: A Galaxy Drifts through Dust".

Since the discovery of two-component (i.e., split) lines in M82 (Axon & Taylor 1978) and the resulting elimination of this theory as an emission mechanism for the filaments, the presence of the halo has been largely ignored. Still, the polarization measurements must be interpreted. Several current models of the outflow component of M82 rely on the interaction of the wind and the halo to produce much of the observed emission (e.g., Suchkov *et al.* 1994). From an observational standpoint, wide-field radio images of the M81/M82 group (Yun, Ho, & Lo 1994) show massive clouds of H I encompassing the entire region, confirming the existence of a halo of some nature.

Our Fabry-Perot observations in H α and [N II] clearly confirm the existence of the exponential halo noted by Bland & Tully 1988. Figure 4.6 shows the flux along a narrow ($\sim 7''$) band parallel to and approximately $35''$ south of the major axis of the galaxy. The flux due to the outflow filaments are clearly seen superimposed upon an

exponentially decreasing halo. The halo appears across our entire region of fit lines, approaching a flux level of 10^{-15} ergs cm^{-2} sec^{-1} at a radius of 1 kpc.

Figure 4.6 A profile of the $\text{H}\alpha$ emission along a band parallel to and approximately 525 pc south of the major axis of M82. Identified in the figure are both the intense emission line filaments associated with the southern outflow and the underlying exponentially decreasing halo. The filament emission is intrinsic, while the halo emission consists of disk and outflow flux scattered by a spherical distribution of dust.

It could be argued from the flux maps (Figures 3.10 and 3.11) that the halo emission is not spherical, but rather more intensive near the minor axis of the galaxy. We are constrained by the size of our field of view. Regardless of the exact emission morphology, it is clear that this is a component separate from the outflow, as the faint halo emission is seen in regions located at position angles far from the minor axis.

The exact morphology of the halo material itself requires that we understand the ionization and emission mechanism. As mentioned in the previous section, recent extragalactic work has discovered a “diffuse ionized medium” (DIM) in a few galaxies, most notably the edge-on spiral NGC 891 (Rand *et al.* 1990). This medium is detected as a pervasive H α emission zone throughout the lower halo of the galaxy. The DIM appears spatially correlated with the underlying star-forming disk (Dettmar 1992), implying that the emission mechanism is almost certainly due to excitation and ionization by the disk stellar population (Sokolowski 1992; Dahlem, Dettmar, & Hummel 1994). Is it possible that the exponential halo we are observing is a diffuse ionized medium around M82?

We argue against this interpretation for four reasons: First, recent searches for this extraplanar emission gas in other systems (Pildis, Bregman, & Schombert 1994) have detected filaments and other small-scale structures, but no cases of extensive diffuse emission. This does not rule out the presence of a DIM in M82, but merely suggests that perhaps this phenomenon is not common. Second, the DIM in NGC 891 is found up to 2 kpc off of the disk, and is brightest at radii between 2 and 8 kpc from the nucleus (Sokolowski 1992). Such a flat disk-like distribution is markedly different from the halo of M82, which seems to be concentrated more toward the minor axis, or at least roughly spherical, in shape. Third, the observed low [N II]/H α ratio (0.5–1.0) is relatively constant over the halo, and is most certainly not increasing with radius, as is found for the DIM of NGC 891 (Dettmar & Schulz 1992). Finally, and most importantly, the halo of M82 is seen to be highly polarized along vectors perpendicular to the nucleus, as discussed above. Such polarization would not be expected from intrinsic emission, but suggests rather a scattering mechanism.

Another argument against an emission mechanism inherent to the halo rests with the observed line widths of the H α and [N II] emission (Figures 3.16 and 3.17). In the case of an ionized halo, this line width arises from internal motions of the halo gas. Assuming a fully ionized gas, the velocity dispersion is given by

$$\Delta v_e = \left[\frac{2kT_e}{m_e} + v_{turb}^2 \right]^{1/2}, \quad (4.1)$$

where v_{turb} is the characteristic velocity of turbulence in the halo. If we first assume that $v_{turb} = 0$, we derive

$$\Delta v_e = 5.5\sqrt{T_e} \text{ km/s.} \quad (4.2)$$

From Figure 3.16 we can estimate a maximum line width in the halo of ~ 500 km/s, but note that this represents the motions of the $H\alpha$ -emitting atoms. Assuming energy equipartition,

$$\frac{1}{2}m_e v_e^2 = \frac{1}{2}m_H v_H^2 \quad (4.3)$$

$$v_e = \sqrt{\left(\frac{m_H}{m_e}\right)} v_H \quad (4.4)$$

$$v_e = 43 v_H \quad (4.5)$$

$$v_e = 2.1 \times 10^4 \text{ km/s}, \quad (4.6)$$

a much higher mean electron velocity. Using Equation 4.2 above, this yields an electron temperature in the halo of $T_e \lesssim 1.5 \times 10^7$ K. Our upper estimate of the line width and the assumption of zero turbulence make this calculation an upper limit, but clearly this temperature exceeds what one would expect from photoionized $H\alpha$ -emitting gas. (Recall that typical line widths for H II regions average ~ 10 – 25 km/s [e.g., O'Dell & Townsley 1988].)

Thus, the halo model we will develop is that of a large spherical distribution of dust, which serves to scatter the disk and outflow emission into our line of sight. This model does not suffer from any of the objections raised against the idea of a DIM. For example, the possible concentration of the scattered halo emission near the minor axis is merely then a result of the proximity of the intense intrinsic nuclear and outflow emission. The large line widths in the halo can also be better explained in terms of the combined motions of both the emitting and scattering particles.

Seaquist & Odegard 1991 argue for the presence of a large (~ 8 kpc) synchrotron-emitting halo of energetic electrons to explain their large-scale radio continuum observations. If this is the case, is perhaps electron, rather than dust, scattering a viable possibility for the optical halo emission of M82? This could explain not only the radio continuum observations, but also the concentration of the emission near the minor axis, as Seaquist & Odegard 1991 assume that the outflow is the source of the energetic electrons. It is also possible that the low-mass electrons could be sufficiently hot that the equilibrium Maxwellian velocity can create the observed line widths in the halo. However, a calculation of the ratio between the scattered flux levels for dust and electron scattering will show that electron scattering is far too inefficient a mechanism to generate the observed flux.

The flux scattered by dust per unit solid angle per unit distance along the line of sight is given by the expression

$$df_d = \sigma_d n_d f d\Omega, \quad (4.7)$$

where σ_d is the scattering cross section of dust, n_d is the number density of dust particles, and f is the input flux (i.e., the intrinsic emission from the disk and outflow). The total flux scattered by electrons obeys the corresponding relationship,

$$df_e = \sigma_e n_e f d\Omega. \quad (4.8)$$

The ratio between the flux scattered by dust and that scattered by electrons is then simply the ratio of the optical depths,

$$R_{de} = \frac{\sigma_d n_d}{\sigma_e n_e}. \quad (4.9)$$

The cross section for dust scattering, σ_d , is the geometric cross section for Rayleigh scattering,

$$\sigma_d = \pi r^2 \quad (4.10)$$

$$= 3.14 \times 10^{-10} \text{ cm}^2, \quad (4.11)$$

where the diameter of the dust particles, r , is taken to be $0.1 \mu\text{m}$. The cross section for electron scattering is the Thompson cross section given by

$$\sigma_e = \left(\frac{8\pi}{3}\right) \left(\frac{e^2}{m_e c^2}\right)^2 \quad (4.12)$$

$$= 6.652 \times 10^{-25} \text{ cm}^2. \quad (4.13)$$

If we assume the optimal case for electron scattering – that the halo gas is totally ionized – we can then write

$$R_{de} = 4.72 \times 10^{14} \frac{n_d}{n_H}, \quad (4.14)$$

where n_d/n_H is the dust-to-gas ratio in the halo. Assuming a standard ISM ratio of $n_d/n_H = 10^{-12}$ (Ostriker & Silk 1973) yields

$$R_{de} \sim 5 \times 10^2. \quad (4.15)$$

Clearly dust scattering is much more likely than electron scattering. Decreased levels of ionization in the halo only serve to increase the value of R_{de} , as well.

As a caveat, we should examine our estimate of the grain radius, $r \sim 0.1 \mu\text{m}$. Although this is a typical value frequently used in the literature (e.g., Sanders & Balamore 1971), consider the work of Mathis, Rumpl, & Nordsieck 1977, which is able to model the observed interstellar extinction over the range $0.11 \mu\text{m} < \lambda < 1 \mu\text{m}$ using a power-law size distribution of dust grains. An estimate for the average grain size from their work can be obtained by integrating their size distribution over the derived size range of $0.005 \mu\text{m}$ to $1 \mu\text{m}$:

$$\langle a \rangle = \left[\int_{a_{\min}}^{a_{\max}} a a^{-3.5} da \right] / \left[\int_{a_{\min}}^{a_{\max}} a^{-3.5} da \right] \quad (4.16)$$

$$\approx 0.01 \mu\text{m}. \quad (4.17)$$

This mean value is a factor of 10 lower than our estimate, which reduces the efficiency of dust scattering, and therefore also R_{de} by a factor of 100. Such a grain distribution clearly makes electron scattering a much more viable possibility. Note that the grain distribution of Mathis, Rumpl, & Nordsieck 1977 has the advantage of explaining a number of observational effects (e.g., the $2160\text{\AA}$ feature in the interstellar extinction law, stellar polarization measurements), but only with respect to observations in the ISM of the Milky Way. Optical and infrared observations of M82 suggest that dust in that galaxy may be more abundant and significantly more important in astrophysical processes.

In light of this calculation however, we compute the electron density required to scatter the observed halo flux. The intensity of scattered flux is given by

$$I_{\text{scat}} = \frac{\sigma_e}{4\pi} n_e \frac{L_0}{4\pi R^2} d \Delta\Omega \quad \text{ergs cm}^{-2} \text{ sec}^{-1} \text{ arcsec}^{-2} \quad (4.18)$$

where L_0 is the intrinsic disk and outflow flux to be scattered; d is the line-of-sight dimension of the scattering region; R is the distance of the region from the intrinsic radiation source; and $\Delta\Omega$ is the steradians per square arcsecond (Sanders & Balamore 1971). From the $\text{H}\alpha$ flux map (Figure 3.10), we can measure a scattered intensity of

$$I_{\text{scat}} \sim 10^{-15} \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ pix}^{-1} \quad (4.19)$$

$$\sim 1.35 \times 10^{-15} \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ arcsec}^{-2}, \quad (4.20)$$

at a distance of $R \sim 1 \text{ kpc}$ from the disk. (This calculation should technically be an integral along the line of sight.) To derive a lower limit to the required halo electron density, we will take the intrinsic luminosity to be the total $\text{H}\alpha$ flux observed in our

data (including the halo itself):

$$L_0 = 9.9 \times 10^{-11} 4 \pi D^2 \quad (4.21)$$

$$= 1.2 \times 10^{41} \text{ ergs/sec.} \quad (4.22)$$

Note that this estimate is very close to the extinction corrected value put forth by Heckman, Armus, & Miley 1990, $L_0 = 2 \times 10^{41}$ ergs/sec. Finally, we can take the approximate line of sight dimension of the halo to be the same as the apparent linear dimension, say $d = 1.5$ kpc. Substitution into Equation 4.18 then yields

$$1.35 \times 10^{-15} < \frac{6.652 \times 10^{-25}}{4\pi} n_e \frac{1.2 \times 10^{41}}{4\pi(3.026 \times 10^{21})^2} 4.53 \times 10^{21} \cdot 2.4 \times 10^{-11} \quad (4.23)$$

or

$$n_e > 225 \text{ cm}^{-3}. \quad (4.24)$$

While this is indeed a moderate density, it is certainly a lower limit, due to our overestimate of the intrinsic radiation in the disk and outflow filaments. Previous estimates of the *nuclear* density in M82 vary from $\sim 30 \text{ cm}^{-3}$ (Willner *et al.* 1977; Sequist, Bell, & Bignell 1985) to $\sim 1000 \text{ cm}^{-3}$ (Heckman, Armus, & Miley 1990), although clearly the halo density should be much lower (see also Rodriguez & Chaisson 1980 and Houck *et al.* 1984). Even at the high density extreme, Heckman, Armus, & Miley 1990 show that the density falls to the derived lower limit for electron scattering at a radius of only 500 pc from the disk, and even this is along the minor axis, where the outflow filaments presumably increase the effective density over the halo value. Indeed, our own spectral measurements in the halo of M82 find the ratio of the [S II] $\lambda\lambda 6719, 6731$ doublet components to be 1.4. This value is known as the “low density limit” and merely implies that the density in the halo is less than $\sim 100 \text{ cm}^{-3}$ (Osterbrock 1989, p.134). These arguments, combined with the optical and infrared observational evidence in favor of large amounts of dust in M82, lend support to our model of dust scattering in the halo.

To return to the dusty halo model, an important issue concerns the lifetime of the dust grains. In an active environment such as M82, we must verify that the timescale for destruction of the dust by sputtering is long compared to the estimated age of the starburst wind, $\tau_{wind} \sim 3 \times 10^6$ years (e.g., Lynds & Sandage 1963; Bland & Tully 1988), especially if the wind may be a primary source of the halo dust (Burbidge, Burbidge, & Rubin 1964). Ostriker & Silk 1973 derive an equation for

grain sputtering:

$$\tau_{sput} \sim 3 \times 10^5 n_e \left(\frac{10^6}{T_e} \right)^{1/2} \left(\frac{0.01}{Y} \right) \left(\frac{r}{0.1} \right) \text{ years}, \quad (4.25)$$

where Y is the sputtering “yield”, the number of atoms released per impact. Y varies from $\sim 5 \times 10^{-4}$ at the threshold sputtering temperature of 3×10^5 K to ~ 0.01 for temperatures of 10^7 – 10^8 . From Equation 4.25 we can derive representative values for the dust lifetime:

T_e	τ_{sput}/n_e
3×10^5	10^7
1×10^6	3×10^6
1×10^7	10^5

We can derive two conclusions from these calculations. First and foremost, at the low temperatures expected in a galactic halo, the lifetime of dust due to sputtering is substantially longer than the lifetime of the outflow. Second, any dust located in the hot ($\sim 10^8$ K) wind seen in x-ray emission has probably been destroyed, unless the electron density is uncharacteristically high. Therefore, if the dust has been delivered into the halo by the wind, it must be done in the form of entrained material around the hot x-ray wind. The halo dust and optical emission line filaments may therefore have the same origin, although it is then unclear why the dust should be spread so widely throughout the halo, rather than being spatially concentrated with the filaments.

A more likely scenario for the origin of the halo dust involves the encounter between M81 and M82 that is believed to have initiated the starburst in the latter. The infall of gas resulting from tidal encounters between galaxies is well known. Recent observations have shown massive clouds of H I surrounding both of these galaxies, with large arcs and bridges joining them (Yun, Ho, & Lo 1994). It appears likely that the dust in the halo of M82 is part of the material exchanged with M81 in the course of their interaction. Indeed, Ichikawa *et al.* 1994 observe large peculiar dust lanes that seem to be related to the complex H I distribution in and around M82. Further evidence is seen in our velocity maps (Figures 3.13 and 3.14), which evidence little halo rotation, implying that it is not expanding from the outflow and conserving the disk rotation. The slight halo rotation seen near the disk can be interpreted as the interaction of a rotating disk with a stationary halo. In addition, if the scattering dust was being expelled from the disk as part of the outflow, we would expect to see

a substantial amount of red-shifted emission on both sides of the galaxy, due to the motion of the scattering particles away from the flux sources in the disk and outflow. This is not seen.

4.3 M82: The Outflow

Although the outflow component of M82 represents the characteristic for which the galaxy is best known, few recent observations have been made specifically of the wind itself. The primary reason for this is probably the low levels of emission from the outflowing gas. For example, there exists little, if any, infrared emission from the wind in M82. The primary observations in the literature fall into two categories: optical spectra and imagery of the emission line filaments associated with the outflow, and wide-field x-ray imagery of the hot gas thought to comprise the wind itself.

The optical studies have their origins in the analysis of Lynds & Sandage 1963, who determined that the kinetic energy of the filaments is in the range of $\sim 10^{55}$ ergs, only a few percent of the current estimates of the input supernovae energy. More recent studies have been primarily concerned with the kinematics of the filaments (e.g., Bland & Tully 1988; McKeith *et al.* 1995) and the issue of their polarization (e.g., Foley, Scarrott, & Axon 1991). Since the original discovery of the strong polarization in the halo of M82 (Elvius 1969), observations have fluctuated on the issue of whether the filaments themselves contain intrinsic or scattered radiation. In light of the previous section, we are clearly interpreting the observed “filament” polarization as an artifact, caused by the observation of the filaments along a line of sight through the scattering halo.

The other important area of outflow observations have been large-scale (i.e., several kpc) studies of the wind, primarily through its x-ray emission. As shown in Figure 2.4, an enormous x-ray halo is observed, extending to radii of at least several kiloparsecs (Watson, Stanger, & Griffiths 1984; Schaaf *et al.* 1989; Tsuru *et al.* 1990; Bregman, Schulman, & Tomisaka 1995). Its concentration along the minor axis implies a definite connection the wind phenomenon.

Our Fabry-Perot observations of the outflow in M82 are some of the most detailed observations ever obtained of a galactic wind. (See Figure 4.7.) The maps of the $H\alpha$, $[N\ II]$, and $[O\ III]$ emission line characteristics across the field will now be used to examine both observational parameters and theoretical models. We begin with an analysis of the velocity structure and kinematics of the wind, arriving at a geomet-

Figure 4.7 A mosaic of 16 frames from the final phase corrected data cube, sampled across the $H\alpha$ line. The frames are separated by ~ 45 km/s, where the frame at the right end of the second row corresponds roughly to the systemic velocity of the galaxy. The outflow is clearly evident as blue-shifted emission to the south and red-shifted emission to the north of the galaxy's disk.

rical model for the outflow which is supported by both our observations and recent hydrodynamic simulations. We then discuss the possible excitation mechanisms for the emission line filaments, particularly with respect to the observed line ratios.

In terms of a kinematic model, it is useful to first consider the simple hydrodynamical models from a related field, the winds from stars. Although stellar winds are thought to be an important contribution to galactic scale winds (e.g., Suchkov *et al.* 1994), supernovae comprise the primary power source and the observed kinematics

are a complex combination of the effects from a large number of sources. We therefore do not expect necessarily that the detailed observed behavior will be reproduced, but merely that a few trends may be elucidated. (More detailed summaries of this may be found throughout the literature; see Holzer & Axford 1970 and Böhm-Vitense 1989 for useful introductions.)

Begin first with a momentum (force) equation for a radially moving parcel of gas:

$$\rho \frac{\partial v}{\partial t} + \rho v \frac{\partial v}{\partial r} = -\frac{\partial P}{\partial r} + \rho F, \quad (4.26)$$

where the left side represents the net change in momentum of the moving parcel, and the right side represents the total force on the parcel of gas. We will consider here only a steady-state wind, so $\frac{\partial v}{\partial t} = 0$. The total external force per unit mass on the gas parcel, F , could include any number of physical phenomena (e.g., viscosity, magnetic fields), but will here consist only of a gravitational force directed oppositely to the direction of motion:

$$\rho v \frac{\partial v}{\partial r} = -\frac{\partial P}{\partial r} - \rho \frac{GM}{r^2}. \quad (4.27)$$

Next, we assume a conservation of mass relation:

$$\frac{\partial}{\partial r}(4\pi r^2 \rho v) = 0. \quad (4.28)$$

Solution for the final equation of motion is straightforward. Using the definition of the sound speed, $c_s = \sqrt{P/\rho}$, we may substitute its radial derivative of P and the radial derivative of ρ (from the mass equation 4.28) into the momentum equation (4.27) to derive:

$$\frac{\partial v}{\partial r} = \frac{2c_s \left(\frac{c_s}{r} - \frac{\partial c_s}{\partial r} \right) - \frac{GM}{r^2}}{v - \frac{c_s^2}{v}}. \quad (4.29)$$

At this stage, we must choose an energy relation. We will assume a simple adiabatic model,

$$P = \kappa \rho^\gamma, \quad (4.30)$$

where the isothermal case can be obtained by setting $\gamma = 1$.

Substitution of this into Equation 4.29 leads to the final equation of motion,

$$\frac{\partial v}{\partial r} = \frac{v(2\gamma c_s^2 - \frac{GM}{r})}{r(v^2 - \gamma c_s^2)} \quad (4.31)$$

which is more commonly written as

$$\frac{dv}{v} (v^2 - \gamma c_s^2) = \frac{dr}{r} \left(2\gamma c_s^2 - \frac{GM}{r} \right). \quad (4.32)$$

The above-mentioned references treat the interpretation of this equation in some detail; we will simply summarize here. The left side of Equation 4.32 clearly has a value of zero at the point where the velocity is a factor of $\sqrt{\gamma}$ larger than the sound speed. Similarly, the right side of the equation has a singularity where the gravitational potential energy per unit mass exceeds the kinetic energy per unit mass at the sound speed by a factor of 4γ . In order to satisfy the equation, these singularities must occur at the same radial point, referred to as the “critical” or “sonic” point. The latter designation refers to the isothermal case ($\gamma = 1$), where this radius represents that at which the flow accelerates beyond the local sound speed of the gas.

Figure 4.8 Radial profiles of the velocity and density as integrated from a simple hydrodynamic stellar wind model. v_c and ρ_c are the velocity and density at the critical radius, r_c . An energy relation of $P = \kappa\rho^{1.1}$ has been assumed.

Radial plots of the velocity, density, and pressure profiles help greatly in understanding Equation 4.32. Figure 4.8 illustrates two of these profiles, velocity and density, integrated for a polytropic stellar wind with $\gamma = 1.1$. The possible radial density profiles of these winds are essentially the same: a sharply decreasing density inside the sonic point, followed by a much more gradual (geometric) decline beyond that point. The velocity profiles, however, suggest a number of possibilities. If the flow is supersonic but declining inside the critical point, passage through this radius may induce a transition of the flow to subsonic velocities, or it may simply reverse the decline, accelerating the flow to increasingly supersonic speeds. A similar selection occurs for subsonic but increasing velocities interior to the critical point: the flow may either accelerate to supersonic velocities, or reverse its trend and decay to zero

velocity. Clearly in the case of stellar winds, boundary conditions require that the flow be subsonic interior to the sonic point, accelerating to a constant (supersonic) velocity beyond that point. The distance of the critical point for stellar winds is computed to be in the range of 3–60 stellar radii, in the sense that cooler, more luminous stars have more distant sonic points (Böhm-Vitense 1989).

Figure 4.9 The logarithmic dimensionless velocity (u_0), density (ρ_0), and pressure (P_0) profiles for the simple hydrodynamical wind model of Chevalier & Clegg 1985. The behavior is similar to the stellar wind model profiles presented in Figure 4.8. Differences arise from slightly different assumptions for galactic-scale winds, such as the neglecting of gravitational forces and an adiabatic energy relation with $\gamma = 5/3$. (Plot taken from Chevalier & Clegg 1985.)

The point of this exercise has been to determine if such models can be usefully applied to galactic-scale winds. Clearly the above equations are scale-independent, and as such, should be applicable. The first attempt to do so was made in a brief paper by Chevalier & Clegg 1985. Their velocity, density, and pressure profiles (reproduced in Figure 4.9), as well as their input equations, are similar to those presented above. Notable differences in the galactic-scale model include neglecting gravitational forces

and assuming an adiabatic energy relation with $\gamma = 5/3$. The critical point in their model is taken to be the radius exterior to all mass and energy inputs; i.e., the radius of the starburst region, $r \sim 200$ pc.

Figure 4.10 A plot of the radial velocity of the $H\alpha$ line along the axis of the outflow ($\sim 15^\circ$ off the minor axis of the disk). The curve gives the velocities interpolated over a band $7'' \approx 100$ pc wide through the $2.2 \mu\text{m}$ nucleus. A systemic velocity of 208 km/s has been subtracted from the data.

Figure 4.10 shows the observed radial velocity profile of our data, along the outflow axis ($\sim 15^\circ$ clockwise from the minor axis of the galaxy). A comparison with the model of Chevalier & Clegg 1985 shows broad correlation with our observations: the velocity increases continuously with radius, flattening at large distances. More specifically, Table 1 of Chevalier & Clegg 1985 suggests that the asymptotic velocity should be approximately double the velocity at the critical radius of 200 pc ($\sim 13''$); our observed values of $v_{r=\infty} \sim 100$ km/s and $v_{r=200} \sim 50$ km/s roughly confirm this.

The great detail of our observations allow a much more careful comparison, however, which shows the simple model of Chevalier & Clegg 1985 to be inadequate to explain the wind in M82. First, several assumptions of Chevalier & Clegg 1985 are probably not appropriate, primarily that of spherical symmetry. While a few authors have argued for a more spherical wind in M82 (e.g., Seaquist & Odegard 1991), almost all theoretical models and observations (including our own), have involved a bipolar outflow, often consisting of cones with opening angles much less than 90° . Perhaps more importantly, studies of the supernovae distribution (e.g., Kronberg, Biermann, & Schwab 1985) and other disk observations (see Section 4.1 above) indicate that the central injection zone is not spherical, but in the form of a flattened disk with dimensions $\sim 600 \times 200$ pc. Chevalier & Clegg 1985 themselves note that this probably introduces an error of “2 or 3” in their model predictions. As other models (e.g., Suchkov *et al.* 1994) and observations (e.g., McKeith *et al.* 1995; this thesis) have shown, the collimation of the outflow by the disk may complicate its geometry such that even conical assumptions are inaccurate. Other assumptions by Chevalier & Clegg 1985, such as the negligence of gravity, may be questionable, particularly in light of optically-observed deprojected wind velocities of ~ 600 km/s, only a factor of two greater than the estimated escape velocity of the galaxy ($v_{esc} \sim 300$ km/s for $M \sim 10^{10} M_\odot$ and $R \sim 1$ kpc). The work of Doane 1993 has considered the model of Chevalier & Clegg 1985 in more detail, including additional physical processes and the aspherical nature of the starburst region.

Another possible inadequacy of the model of Chevalier & Clegg 1985 with respect to M82 concerns the specific velocities predicted. A reasonable assumption of 0.3 SN per year (Rieke *et al.* 1980) yields an outflow velocity of 2000–3000 km/s at the edge of the starburst injection zone. This value is an order of magnitude larger than the velocities seen at optical wavelengths. However, radio continuum observations (Sequist, Bell, & Bignell 1985; Seaquist & Odegard 1991) show an extensive halo that can be explained as synchrotron radiation from a population of relativistic electrons experiencing inverse Compton scattering of nuclear IR photons as they are transported outward in a wind with a velocity of 2000–3000 km/s. This wind could correspond to the observed x-ray wind (e.g., Bregman, Schulman, & Tomisaka 1995), especially in light of the model we have outlined in which the optical filaments are on the surface of this wind cavity, not participating directly in the flow itself, but merely being dragged along with it. This would account for the lower outflow velocity seen in optical emission lines. Two additional points should be kept in mind,

however: First, Chevalier & Clegg 1985 admit that the density falls too rapidly in their model to account for the x-ray emission as thermal. They suggest instead that the x-ray emission arises from wind-cloud interactions, explaining also the apparent broad spatial correlation of the optical and x-ray emission seen by Watson, Stanger, & Griffiths 1984. Second, the radio synchrotron halo observed is much more spherical in shape than the optical or x-ray winds, arguing against identifying it with the x-ray emission, which is clearly concentrated along the minor axis. In that the energetics of the observed radio halo represent a small fraction ($\sim 2\%$ [Seaquist & Odegard 1991]) of the total wind energy, perhaps there exists a small spherical wind component of electrons.

Clearly an accurate model of the geometry of the outflow is key to the development of a physical model such as that of Chevalier & Clegg 1985. We have therefore performed a set of detailed three-dimensional Monte-Carlo simulations of the outflow kinematics, attempting to reproduce the observed optical emission line velocity structure. Although entirely geometric in nature, these models allow us to estimate the three-dimensional morphology of the outflow, thereby helping to constrain physical models of the outflow emission mechanisms and other observational phenomena.

We have chosen to use the function

$$\rho = A \cos m\theta \quad -\frac{\pi}{2m} < \theta < +\frac{\pi}{2m} \quad (4.33)$$

(ρ in spherical coordinates) as a basic geometry for an expanding wind bubble. A two-dimensional plot of this function for several values of m is shown in Figure 4.11. Observations of expanding ionized structures (e.g., Wilson *et al.* 1993; Tomita, Ohta, & Saitō 1994) suggest that spherical bubbles and cones are common morphologies. Both can be obtained from the above functional form by varying the choice of m and possibly truncating the result, as shown in Figure 4.11. The choice of an expanding bubble, rather than a conical or cylindrical wind, was motivated by our observations, which strongly support emission on the surface of expanding structures.

To model the kinematics, we have superimposed two different velocity laws upon this spatial geometry: First, we gave each particle in the bubble a velocity vector in the $\hat{\rho}$ direction. A velocity along the radial direction might be physically reasonable if we interpret each particle in the bubble as being accelerated by the flow originating in the nuclear regions of the galaxy. This picture would be expected if the outflow were truly spherical, but only released from the disk along the minor axis, where the concentration of intervening material is the least. An analogy would be the

Figure 4.11 A plot of the geometric form used for several Monte-Carlo simulations of the southern outflow bubble in M82. The formula used is $\rho = A \cos m\theta$. Plots are shown for several values of m , which allows various degrees of circular and conical forms to appear in the structure.

propagation of a circular wave through a slit; Huygen's principle predicts the circular expansion of the wave after passing through the slit.

The second velocity law is one in which each point on the bubble is given a velocity vector perpendicular to the surface of the bubble. This form of velocity structure is more appropriate for an expansion due to increasing pressure inside the bubble. Physically, this would correspond to an injection of mass and energy into the bubble, probably along its axis, which heats and expands the bubble. In this case, the walls of the bubble are accelerated not by the flow itself, but by the expansion of the material within the bubble. An analogy would be filling a balloon with air.

For each model to be discussed, an image is presented of both the spatial appearance of the bubble and a cut along the major axis of the bubble, illustrating the

observed two-component velocity profile. The parameters varied include the bubble opening angle, the inclination angle of the bubble to the observer, the direction of the velocity vectors (described above), and the velocity magnitude versus radius relation. Each Monte-Carlo simulation uses 5000 points, divided into 50 bins along the length of the bubble.

For our initial model we take an opening angle of 70° and an inclination angle of 8° toward the observer, placing the major axis of the outflow perpendicular to the disk of the galaxy (see Table 2.1). Although the choice of opening angle is somewhat larger than that often found in the literature (e.g., $\sim 35^\circ$ [Bland & Tully 1988]; $\sim 57^\circ$ [Bregman, Schulman, & Tomisaka 1995]), the curvature of the surface leads to a smaller effective opening angle if one truncates the bubble near its base, to more accurately represent the extended outflow injection zone. Figure 4.12 illustrates the physical appearance of this model (A), as well as the apparent velocity structure along the major axis of the bubble.

Figure 4.12 Monte-Carlo simulation A for the southern outflow region in M82. The opening angle of the bubble is 70° ; it is inclined by 8° toward the observer. The velocity vector is normal to the surface at every point; the magnitude of the velocity vector is a constant. The left panel shows the appearance of the simulated bubble to the observer. The right panel shows the normalized apparent radial velocities of the back and front of the bubble, along its major axis.

The primary criteria for comparing these models with our observations are the component velocity profiles along the major axis of the outflow and the physical appearance and shape of the bubble. Following a truncation at $Z \sim 20$, the spatial extent of the outflow region in model A resembles that seen in our flux images (e.g., Figure 3.10). This is even more the case if one compares the model with the results of Bland & Tully 1988, whose analysis finds that the $H\alpha$ emission along the sides of the southern outflow in M82 rejoins at a radius of approximately 1300 pc, closing the bubble. The observed filaments appear more dense along the eastern side of the southern lobe, but both the distribution of the x-ray outflow (e.g., Bregman, Schulman, & Tomisaka 1995) and the region of split lines (Figure 3.15) are fairly symmetric about the primary axis of the outflow.

Figure 4.13 A plot of the radial velocity of the two components of the $H\alpha$ line along the axis of the outflow ($\sim 15^\circ$ off the minor axis of the disk). The velocities are only shown in regions in which the $H\alpha$ line is split, interpolated over a band $7'' \approx 100$ pc wide through the $2.2 \mu\text{m}$ nucleus. A systemic velocity of 208 km/s has been subtracted from the data. Within approximately 200 pc south of the nucleus, the two components are close in velocity, but they then separate rapidly out to a radius of about 500 pc. Note the relatively constant separation of both components beyond this radius.

For the comparison of the component velocity structure, Figure 4.13 illustrates the velocities observed in the split $H\alpha$ line along the major axis of the outflow. Note that within approximately 200 pc south of the starburst nucleus, the components are separated by a small velocity (~ 50 km/s). Between 200 and 500 pc, the components rapidly separate, remaining at a constant separation of ~ 300 km/s throughout the rest of the bubble. This behavior is present over the entire region of split lines, as seen in Figure 3.15. It is exactly this kinematical signature that we want to model with our Monte-Carlo simulations. To emphasize this element, Figure 4.14 shows that the split $[N II]$ line in the southern outflow region exhibits precisely the same behavior.

Figure 4.14 A plot of the radial velocity of the two components of the $[N II]$ line along the axis of the outflow ($\sim 15^\circ$ off the minor axis of the disk). The velocities are only shown in regions in which the $[N II]$ line is split, interpolated over a band $7'' \approx 100$ pc wide through the $2.2 \mu m$ nucleus. A systemic velocity of 208 km/s has been subtracted from the data. The remarkable trends in the velocity separation of the components parallels that seen in the $H\alpha$ line (Figure 4.13).

We see immediately that although model A accurately creates a bubble with a relatively constant front-to-back velocity separation, it is unable to reproduce the

rapid separation portion of the observed velocity component profiles. The only portion of the model that approaches this behavior is that near the origin (Figure 4.12), which we have already suggested must be truncated to simulate the extended wind injection zone. In the case of model A, the only way to reproduce the rapid velocity separation between the front and back sides of the outflow, in an entirely geometrical fashion, is to use the rapid curvature of the bubble at its origin.

Therefore we ran several series of simulations, in which we attempted to reproduce this rapid velocity component separation, via a geometry-induced curvature of the velocity vectors. The first series of models (B and C) are illustrated in Figure 4.15 and represent the result of increasing the inclination angle relative to the observer. The bubble in model B is tipped by 18° toward the viewer; model C is inclined by 28° . The physical appearance of the bubbles is still within acceptable limits, and the component velocity structure along the major outflow axis has an increased rate of change in separation at a distance well-removed from the origin. However, an inclination angle of 28° is still entirely insufficient to produce the rapid observed change in velocity component separation. The increased velocity gradient that has arisen from larger inclination angles has also substantially reduced the region of uniformly-separated components, violating our observed line splitting (Figure 3.15). The poor ability of these models to reproduce the data suggests strongly that we maintain the simple assumption of a bubble aligned roughly perpendicular to the galaxy's disk. (Note, however, that the position angle of the outflow does differ from the position angle of the galaxy's minor axis by approximately 15° .)

We then proceeded to compute a second set of models (D and E), in which we maintained a constant inclination angle (8°) for the bubble, but varied its opening angle. These models are shown in Figure 4.16. Model D has a reduced opening angle of only 50° , while model E has a larger opening angle of 90° . (Compare with model A, which has the default opening angle of 70° .) The range of physical appearance of these models is perhaps greater than for models B and C but not entirely unrealistic. The induced change in the velocity structure along the axis of the bubble is only slight, and more importantly, affects both the front and the back of the bubble similarly. Recall that the observed separation of velocity components results from the a rapid increase in the velocity of only one component. Clearly the decreased opening angle of model D (similar to those hypothesized in the literature) worsens the situation by eliminating almost all of the velocity gradient beyond the origin. The increased opening angle of model E, however, still does not induce a velocity gradient of the

Figure 4.15 Monte-Carlo simulations B (upper panels) and C (lower panels) for the southern outflow region in M82. The opening angle of the bubble is 70° for both simulations. The bubble is inclined by 18° toward the observer in model B and by 28° in model C. All other parameters are identical to those used for model A. The left panels show the appearance of the simulated bubbles to the observer, while the right panels show the normalized apparent radial velocities of the back and front of the bubble, along its major axis. The changing inclination of the bubble induces a strong signature in the component velocity structure.

desired magnitude. We may conclude from these models that the opening angle of the bubble is probably small (i.e., $< 60^\circ$), in order to produce a region of split lines with the extremely uniform observed separation.

A final pair of models were then computed to briefly examine the effects of a linear velocity relationship. In all previous models, the magnitude of the velocity vector was constant, and the direction of each particle's velocity was normal to the surface. (We have run a similar series of models utilizing the radial velocity law. The resulting

Figure 4.16 Monte-Carlo simulations D (upper panels) and E (lower panels) for the southern outflow region in M82. The inclination angle of the bubble is 8° for both simulations. The opening angle of the bubble is 50° in model D and 90° in model E. All other parameters are identical to those used for model A. The left panels show the appearance of the simulated bubbles to the observer, while the right panels show the normalized apparent radial velocities of the back and front of the bubble, along its major axis. The changing opening angle affects the curvature of the physical bubble as well as that of the component velocity structure.

component velocity structures along the bubble axis failed entirely to reproduce the observed uniform component separation. For this reason, we have omitted a more detailed discussion of those models.) Figure 4.17 illustrates this final pair of models (F and G). Model F illustrates velocity vectors normal to the surface, with magnitudes linearly increasing with radius. Model G uses a similar linearly increasing velocity magnitude, but with radially-directed velocity vectors. Clearly the derived velocity structure is entirely dissimilar from that observed. We show these models merely

to emphasize that our simplifying assumption of a constant velocity magnitude is reasonable, and to demonstrate the range of possible configurations.

Figure 4.17 Monte-Carlo simulations F (upper panels) and G (lower panels) for the southern outflow region in M82. The inclination angle of the bubble is 8° and the opening angle is 70° for both simulations. Model F uses velocity vectors directed normal to the surface with magnitudes that linearly increase with distance from the origin. Model G uses velocity vectors directed radially from the origin with magnitudes that follow the same linear law. The left panels show the appearance of the simulated bubbles to the observer, while the right panels show the normalized apparent radial velocities of the back and front of the bubble, along its major axis. The use of a linearly varying velocity, rather than a constant, illustrates the wealth of possibilities in these models.

The final conclusion reached from the Monte-Carlo simulations is that *the rapid divergence of the velocity components in the southern outflow cannot be reproduced by simple manipulations of geometric quantities*. In light of the very different velocity

profiles shown in the final two models (Figure 4.17), it should be kept in mind that this has been an extremely simplistic series of models. Changing environments encountered by the outflowing gas could easily result in a combination of the physical forms found in the simulations. Indeed, in light of the known presence of both a thick disk (Section 4.1) and an extended halo (Section 4.2), it would be difficult to argue in favor of a simplistic model such as those presented.

Consider now the detailed line-splitting morphology (Figure 3.15): Although the line widths become narrower as we approach the nucleus (Figures 3.16 and 3.17), implying perhaps that our dual components are coming even closer together as the bubble approaches its origin, there are at least two arguments suggesting that the line splitting remains relatively constant all the way to the nucleus: First, both the $H\alpha$ and $[N II]$ lines contain a region between 200 and 350 pc south of the nucleus where the lines are closely separated by an amount that is relatively constant with radius ($\Delta v \sim 50$ km/s). (Keep in mind that the radio supernovae distribution in M82 is approximately $5'' \approx 75$ pc thick (Kronberg, Biermann, & Schwab 1985), while the optical image of the disk is much thicker [see Figure 2.3]). Second, the recent spectroscopic work by McKeith *et al.* 1995 detects an identical trend in the split line velocity structure, but they are able to follow the minor axis components well into the nuclear regions, where the components are lost amongst the complex disk emission. The observed line width in these regions is approximately 50 km/s suggesting that the bubble may simply have become filled with optically-emitting gas.

There clearly seem to exist two separate regimes in the southern outflow: the region within approximately 350 pc of the nucleus, where the split line components are separated by approximately 50 km/s, perhaps filling out to a single line 50 km/s in width near the center of the galaxy; and the more distant region beyond 500 pc in which the lines are separated by a much larger constant value of approximately 300 km/s. The inner component is not observed north of the galaxy, assumedly because the split lines cannot be resolved at a sufficiently small radius due to the intervening disk material. Comparison of the line splitting map (Figure 3.15) and the flux maps (Figures 3.10 and 3.11) confirms our identification of two regimes, as the flux level also changes dramatically at a distance of approximately 500 pc from the nucleus, the same radius at which the velocity components rapidly separate.

As our Monte-Carlo simulations demonstrated, these two regimes cannot both be modeled with a single expanding bubble, with or without truncation for the extended injection zone. But consider again Figure 4.12, in which the initial curvature of the

bubble at its origin constitutes the only region in which a model exhibits a divergence of the component velocities comparable in magnitude to the observed increase in separation. Now, as mentioned, if the simulation were to model the entire outflow, the base of the bubble should be truncated to accurately reproduce the spatially extended outflow injection zone. However, since a single model cannot reproduce both the inner and outer regimes, perhaps an *untruncated* bubble is appropriate to model only the outer portion of the velocity structure. The inner portion could then be modeled by a bubble that has been truncated at both ends, forming essentially a tube.

We thereby arrive at a physical model for the southern (and assumedly northern) outflow in M82: The inner 350 pc appear to constitute effectively a flow down a pipe. The outflow is collimated, assumedly by the disk material, and highly inclined to our line of sight, such that the radial component of the flow velocity is only ~ 50 km/s. Beyond 500 pc, however, the collimation is lost and the outflow expands rapidly as a bubble of emission with a front-to-back velocity separation of approximately 300 km/s. The emission line filaments are produced at the interface between the wind and the ambient halo material. Figure 4.18 shows a schematic side-view of the outflow, illustrating these two regimes.

This model clearly explains the increased flux within the collimated region, as a result of the increased density. Since the emission measure of the gas varies as the density squared ($\propto n_e^2$), conservation of mass predicts that the confinement of the material in the inner zone should substantially increase the flux there over that seen in the region of free expansion. These larger densities may also help explain the filling in of the line profiles at very small radii.

Examination of the component velocity structure in the complete velocity maps (Figures 3.13 and 3.14) shows that the expanding bubbles are far from symmetric about the systemic velocity of M82. Rather, one side of each cone appears to lie approximately in the plane of the sky, appearing as emission at the systemic velocity. This component is identified as the low-velocity component (LVC) in the velocity maps. The other component is shifted by approximately 300 km/s relative to the systemic velocity: red-shifted in the north and blue-shifted in the south. This component is identified as the high-velocity component (HVC) in the velocity maps.

Although McKeith *et al.* 1995 reaches precisely the same conclusion from their slit spectra, perhaps even more striking confirmation of the above model is obtained from comparison with recent hydrodynamic outflow models. The first such model

Figure 4.18 A schematic of the derived geometric model for the outflow in M82. The galaxy is viewed from the side, with the observer represented by the eye on the left. The inner regions of the outflow are confined, while the wind expands more freely in a bubble beyond approximately 500 pc. The optical emission line filaments are produced at the wind-halo interface. The bubbles are not perpendicular to the disk, but inclined such that one side of each lies in the plane of the sky, at approximately the systemic velocity.

was developed by Tomisaka & Ikeuchi 1988 as a two-dimensional simulation of the starburst-powered outflow in M82. First and foremost, their model confirmed that supernova rates similar to those seen in starburst galaxies ($\text{SNRt} \sim 0.1$ per year) are sufficient to create large-scale outflows of gas. In addition, these authors proposed an evolution of the outflow which included collimation of the flow at early stages by disk material, eventual breakout of the confined flow at the extremes of the minor axis extent, and eventual extension of the hot wind material up to a few kpc from the nucleus. These arguments lend strong support to the above interpretation

of our observations, as well as to observations of the x-ray halo and molecular gas morphology.

Figure 4.19 The predicted density of the disk, halo, and wind components of model A of Suchkov *et al.* 1994, at an age of 8.3 million years. Each frame is 6×15 kpc in size, with a logarithmic density scale over the range $[-4.5, -1.5]$, $[-3.5, -1.5]$, and $[-4.5, -3.0]$ for the disk, halo, and outflow components, respectively. Note the collimation of the outflow gas by entrained disk material. (Figure adapted from Suchkov *et al.* 1994.)

The extension of this model by the addition of a corotating halo (Tomisaka & Bregman 1993) prefaced the most recent hydrodynamic simulations by Suchkov *et al.* 1994. These models track the development of a galactic wind in a two-component galaxy (disk plus nonrotating halo), from the early stellar wind-dominated stages of the starburst, through to the violent supernovae-powered stage. In addition, these authors model the disk, outflow, and halo components separately, allowing the interactions between these to be examined in great detail. Figure 4.19 shows the predicted density of the disk, halo, and wind components in their primary model. A comparison

of this figure with our flux maps and proposed three-dimensional model is particularly enlightening.

Note first the wind-disk interaction near the base of the outflow in Figure 4.19. The outflow has entrained disk material around itself, dragging higher density material a couple of kiloparsecs above the plane of the galaxy. The regions of densest disk material, near the base of the outflow, actually serves to collimate the outflow beyond the height of the disk itself. The scale height of this collimation is similar to that seen in our observations, ~ 500 pc. The “fingers” of disk material entrained to heights above the collimated zone can be identified with the emission line filaments we observe on the outer walls of the outflow bubble. Note also that the density of the wind material in the collimated zone is extremely high. This density enhancement accounts for the increased flux levels observed near the nucleus in our flux maps (Figure 3.10).

Based on this comparison with hydrodynamic models, we accept the two-zone model for the outflow in M82 proposed in Figure 4.18: As the outflow expands outward from the central starburst zone, the wind material pushes out along the direction of the greatest density gradient – the minor axis. As it expands out of the disk, the wind pushes a layer of disk material before it, entraining additional material around the base of the outflow. This entrained disk gas serves to collimate the flow near the disk. Within this collimated region both the wind and the confining walls are at their densest, with the latter thereby producing the observed bright optical emission. At a height of approximately 350 pc, the density of the entrained disk gas falls rapidly below that required for confinement, and the hot wind rapidly presses outward to produce a conical wind bubble. The remaining entrained disk material is fragmented about the outflow cone, producing the filaments that we observe at optical wavelengths.

There are a number of arguments in favor of the actual wind material consisting of extremely hot gas. The earliest observations of the minor axis concentrations of soft X-rays in M82 (Watson, Stanger, & Griffiths 1984) argued for its origin as thermal emission from a 10^7 K wind. Such a hot gas would not be bound to the galaxy and could therefore expand to the observed enormous spatial extent (~ 6 kpc; Bregman, Schulman, & Tomisaka 1995). The recent discovery that the x-ray distribution implies a partially confined outflow of gas within 1.6 kpc of the disk (Bregman, Schulman, & Tomisaka 1995) supports this interpretation, although the scale length

of the confinement in this case suggests it may be due to the wind-halo interaction, rather than entrained disk material.

There are difficulties with this argument, however. The hydrodynamic simulations of Tomisaka & Bregman 1993 and Suchkov *et al.* 1994 both include derivations of the observed x-ray flux from their models. In both cases, the derived wind temperature is an order of magnitude larger than that used by Watson, Stanger, & Griffiths 1984. This 10^8 K gas does not thermally emit as strongly in the x-ray band, producing insufficient soft and hard X-rays to account for the observations. Also, an analysis of the x-ray energetics shows that this emission represents at most a few percent of the proposed starburst injection energy, suggesting that perhaps it plays a more cursory role in the outflow. Finally, the most convincing evidence comes from our spatial analysis of the optical and x-ray maps, shown in Figure 3.22. In this image, the X-rays and optical emission are clearly correlated across the field. At large scales, we see that the x-ray flux drops at a radius of approximately 500 pc, as does the optical emission. But also on scales as small as 10 pixels (150 pc), the x-ray and optical emission appears reasonably well correlated.

These observations lend support to the x-ray emission mechanism suggested by several authors (e.g., Chevalier & Clegg 1985; Suchkov *et al.* 1994): the soft X-rays arise from shocked disk and halo material, possibly in the form of clouds. These same shocked regions could also produce the observed optical emission, accounting for the correlation between the X-rays and the $H\alpha$ emission. It might seem difficult, however, to shock and thereby excite halo gas at the large distances from M82 at which X-rays are observed. The rapid decrease in the $H\alpha$ luminosity of the filaments does not allow their detection at such extreme distances either. Perhaps instead we have a hybrid model: The wind near the nucleus is extremely hot, and its emission (both optical and x-ray) is therefore dominated by shocks at interfaces with disk and halo gas clouds. As the wind expands and cools, however, the portion of the x-ray emission produced from thermal radiation increases. The observations and simple models of Bregman, Schulman, & Tomisaka 1995 derive an x-ray temperature at large radii of only $\sim 2 \times 10^6$ K, suggesting perhaps an increased role of thermal emission at those radii.

On the other hand, observations with the Ginga x-ray satellite have made the startling discovery of faint x-ray emission extending several *tens* of kiloparsecs from M82 (Tsuru *et al.* 1990). The hydrodynamic simulations of Tomisaka & Bregman 1993 model this emission as shock-excited in nature, assuming that the outflow is

much older ($\sim 5 \times 10^7$ years). The radial decrease in the wind pressure and density may indeed allow the wind shock to propagate to extremely large distances from its starburst origins.

We must therefore conclude that a large portion of the x-ray emission, particularly beyond the optical line-emitting zone, originates with the primary shock front of the wind. Nevertheless, the final clue to decipher the importance of shocks versus thermal emission in the inner outflow region of M82 can be found by comparing the observed optical line ratios with those predicted by models of various emission mechanisms. Recall our optical observations in Figures 3.18 and 3.19. The $[\text{N II}]/\text{H}\alpha$ ratio is spectacularly uniform and low in the outflow region; values of 0.3-0.6 are typical. We must be careful, however, as the line ratios in the split regions should be determined individually for each component. In this case, the line ratios of the components reveal similar low ratios across the outflow bubble, except in the inner collimated zone, where higher line ratios are seen (~ 1.0), particularly in the low-velocity component (LVC). Recall also the $[\text{O III}]/\text{H}\alpha$ line ratios in Figures 3.20 and 3.21. Unlike the $[\text{N II}]/\text{H}\alpha$ ratio, the $[\text{O III}]/\text{H}\alpha$ ratio exhibits a strong radial gradient: the ratio increases from a value of approximately 0.03 at the center to 0.08 at a distance of ~ 750 pc.

A primary issue here is the question of the importance of shock excitation for the optical filaments. Although the limited number of line diagnostics at our disposal severely limits our analysis, we can nevertheless make a rough assessment of the influence of shocks. As a first step, we can compare the observed line ratios with the emission-line galaxy classifications of Veilleux & Osterbrock 1987. If we examine their Figure 1 (reproduced in Figure 4.20), we see that a $[\text{N II}]/\text{H}\alpha$ ratio of 0.5 (-0.3 dex) rests just inside the line separating H II region-like objects from AGN; except in the case of a strong $[\text{O III}]/\text{H}\beta$ ratio. The ratio lies directly in the region of starburst galaxies, at slightly higher ratios than most cooler H II regions and H II region models. This immediately suggests an emission mechanism such as photoionization for the filaments, particularly near the nucleus, where the $[\text{O III}]/\text{H}\alpha$ ratio is lower. This comparison certainly makes no statement regarding shock excitation, however.

In the last twenty years, a large number of shock models have appeared in the literature which predict the emission characteristics of shocks at a range of velocities (e.g., Shull & McKee 1979; Binette, Dopita, & Tuohy 1985). In most cases, these velocities are below the several hundred km/s range in which we are interested. We will compare with some very recent work by Dopita & Sutherland 1995, in which are computed a series of shock models with velocities in the range of 150-500 km/s.

Figure 4.20 Reddening-corrected $[\text{O III}]/\text{H}\beta$ vs. $[\text{N II}]/\text{H}\alpha$ for a selection of H II regions (circles), H II region models (lines), starburst galaxies (triangles), and AGN (filled polygons). The logarithmic $[\text{N II}]/\text{H}\alpha$ ratio of -0.3 that we observe in the wind of M82 places it just within the H II region-like portion of the figure, except where the $[\text{O III}]/\text{H}\beta$ ratio is very high. The emission characteristics of starburst galaxies place them in the same region of the plot. (Plot taken from Veilleux & Osterbrock 1987.)

Comparison of our $[\text{N II}]/\text{H}\alpha$ line ratio with their Figure 2 (reproduced in Figure 4.21) shows that a ratio in the observed range could certainly be derived from excitation by shocks with velocities throughout the modeled range. However, the deprojected wind filament velocity must certainly be near the extreme high end of their modeled velocity range, in which case their models then demand a high $[\text{O III}]/\text{H}\beta$ ratio ($\gtrsim 1$).

Based upon these comparisons, we may suggest that the optical filament emission is, at least partially, due to photoionization of the sides of the cavity created by the outflow. The hot gas in the wind itself would be quite transparent to the UV

Figure 4.21 Reddening-corrected $[\text{O III}]/\text{H}\beta$ vs. $[\text{N II}]/\text{H}\alpha$ grids for a selection of high-velocity shock models. Observations of Seyfert galaxies are shown as open circles; LINERs are shown as filled circles. The grid labeled 'Shock Only' includes only the emission from the shock, while the grid labeled 'Shock + Precursor' includes the contribution of preshock ionization. Emission characteristics of shocks with velocities of 150–500 km/s are computed. The observed velocity of the wind in M82 is at the upper end of this range. (Plot taken from Dopita & Sutherland 1995.)

ionizing photons from the starburst region, allowing the entrained disk and halo gas to be illuminated directly. The issue is complicated, however. For example, the component $[\text{N II}]/\text{H}\alpha$ ratio maps display a higher ratio in the collimated region of the wind, just above the starburst. Comparison with the models of Dopita & Sutherland 1995 suggests that these higher ratios could arise from shocks with velocities of 300–500 km/s. In this case, however, the predicted $[\text{O III}]/\text{H}\beta$ ratios are low, matching exactly the trend we see in our $[\text{O III}]/\text{H}\alpha$ map. A complex combination of shock and photoionization is probably a more reasonable model for the emission in the violent

collimated zone, where the disk gas is being entrained and drawn upward by the hot wind just as it leaves the luminous starburst region. Similarly, at large radii, the high observed value of the $[\text{O III}]/\text{H}\alpha$ ratio could imply a more important role for shocks there as well, although this is less certain.

Finally, we should note that the tipped nature of the outflow cones probably places the systemic side of each cone more directly in the path of the photoionizing radiation from the central starburst. This can easily explain the higher fluxes seen in the low-velocity components of the wind in terms of a photoionization mechanism. It is difficult, but not impossible, to explain the differences in the component fluxes using models of shock excitation. Nevertheless, observations at additional wavelengths are clearly required to more accurately constrain the excitation mechanisms in the outflowing gas.

4.4 M82: Synthesis

We now summarize the results derived in this chapter:

Disk: The almost edge-on disk of M82 exhibits normal rotation but a convoluted appearance, with highly obscured regions as well as bright stellar clusters. These are the first indication of the starburst phenomenon taking place in the central 500 pc of the galaxy. A large population of small bright radio supernovae are resolved as well. The starburst, probably initiated by a close encounter with M81 some 10^8 years ago, now fuels the galactic wind via its stellar winds and supernovae. The starburst in M82 may be waning, based on comparisons of supernovae at several epochs.

The molecular gas in the disk is arranged in a torus, interior to which is a similar torus of ionized gas that forms the core of the starburst. The “eyes” observed in our data are the cross section of this ring. This ionized torus is expanding outward into the molecular ring, maintaining a “self-propagating starburst”. Although the entire central starburst region has been filled with the hot wind gas, the ring also assists in collimation of the flow along the minor axis. Portions of the disk material, including molecular gas, are entrained by the outflow and dredged up around it, ultimately becoming the optical emission line filaments on the surface of the wind bubbles.

Finally, line ratios indicate that the disk contains a diffuse ionized medium (DIM), similar to that seen in NGC 891 and other galaxies. The observed enhanced $[\text{N II}]/\text{H}\alpha$

ratio is understood as the result of mixing layers produced by turbulence from the interaction of supernovae remnants with cold disk gas.

Halo: The halo is observationally detected as an exponential distribution of dust-scattered radiation from the disk and outflow regions. Observed line widths in the halo imply electron temperatures far greater than a gas emitting thermally at $H\alpha$. The density of electrons in the halo is far too low to account for the scattered flux, even with very small grain size distributions. The lifetime of the halo dust is longer than that of the outflow, although dust actually coincident with the hot wind has probably been destroyed. The most reasonable source for the dust in the halo may be metal-rich gas extracted from the disk during the encounter with M81.

Outflow: Kinematic observations, simple stellar wind models, and Monte-Carlo simulations of the velocity structure in the galactic wind in M82 suggest a two-zone model. Within approximately 350 pc of the disk, the outflow appears cylindrical and collimated by the large amounts of entrained disk material. Beyond this radius, the bubbles expand rapidly in cones, dragging the disk material out as filaments which are observed at optical wavelengths. The cones are tilted such that the near side of the northern cone and the far side of the southern cone are approximately in the plane of the sky. These portions of the cones, referred to as the low-velocity component (LVC), are brighter, due to more direct illumination by the starburst nucleus. The high-velocity component (HVC) is red-shifted in the north and blue-shifted in the south by approximately 300 km/s relative to the LVC. This two-zone model for the outflow is supported by recent hydrodynamic simulations as well.

Analysis of the $[N II]/H\alpha$ and $[O III]/H\alpha$ line ratio maps suggests that photoionization by the central starburst plays a major role in the filament emission. However, the observed spatial distribution of the x-ray halo, which presumably originates with the hot wind, correlates with the optical emission, suggesting that shocks may play a role as well. Recent high-velocity shock models confirm this.

Caveats: Although the above model satisfies many of the observational constraints revealed by the detailed Fabry-Perot observations, as well as a number of observational and theoretical considerations from the literature, we now briefly review a few outstanding inconsistencies.

First, the proposed two-zone model for the wind, including axisymmetric cylindrical and conical components, is clearly a simplistic approach that allows straightforward modeling. The actual situation in M82, and even in a number of hydrodynamical simulations (e.g., Suchkov *et al.* 1994), involves a much more complicated geometry, including sidelobes, possible regions of wind breakout, etc. For this reason, detailed application of the model to M82 reveals a number of complications. For example, an axisymmetric bubble with velocity vectors perpendicular to the bubble's surface, such as that used in our Monte-Carlo simulations, will exhibit a radial velocity component that is at a maximum down the main axis of the bubble and decreases toward the projected bubble edges. As can be seen from the velocity maps (Figures 3.13 and 3.14), this behavior is not seen in the Fabry-Perot observations. Rather, the observed radial velocity appears uniform across the bubble, suggesting perhaps that the cone is broken or only partial. A similar effect is seen in the line splitting map, Figure 3.15, as well.

Another difficulty with the model proposed herein can be found in the total velocity maps (Figures 3.13 and 3.14). Note that regions south of the disk are moving at almost uniformly negative radial velocities. After accounting for the rotation of the disk, and perhaps even a rotating halo, this velocity trend remains, particularly to the east. Clearly the proposed conical outflow would not encompass such a large region, suggesting a more spherical outflow, perhaps involving halo material. As mentioned previously, such spherical behavior is anticipated by a few observations in the literature, particularly those at radio continuum wavelengths (e.g., Seaquist & Odegard 1991). In this picture, the high-velocity component may consist of fingers of denser material ejected along the minor axis by the outflow. Alternatively, the fits at the eastern edge of the disk have a lower signal-to-noise ratio, suggesting that this trend may simply be the result of data analysis problems.

As a final caveat, note that the ratio maps of the low- and high-velocity components differ in their northern-most regions, corresponding to the hypothesized collimated zone of the wind. It is difficult to explain the increased brightness of $H\alpha$ at the northern tip of the HVC, although arguments concerning $H\alpha$ -bright knots and tilting of the collimated region relative to the disk may provide solutions. In any case, more detailed comparisons of this and additional models with the maps from the line fits, and especially with the data itself, should yield new insight into the outflow observed in M82.

Chapter 5

Future Directions and Objects of Interest

In this chapter I will briefly outline several future directions in which the work described in this thesis can be expanded. The high spectral and spatial resolution of an imaging Fabry-Perot, and particularly its ability to obtain spectra across a wide two-dimensional field of view, make it perhaps the instrument best suited for the study of galactic-scale winds. As noted in this thesis, galactic outflows involve high velocity motions across a wide field; a field which is often made complex by the superposition of normal galactic emission. For this reason, most galactic winds have been discovered and observed via minor-axis emission, which is necessarily seen most clearly in galaxies which are close to edge-on. With the use of a Fabry-Perot, it should be now possible to observe galactic winds in even face-on galaxies, resolving and separating various emission components from both a wind and the nuclear and H II region components of the galaxy itself. With the capability to perform accurate spectrophotometry, the Fabry-Perot is an exceptional choice for such observations.

Nonetheless, at present Fabry-Perot observations of galactic winds are few in number. For M82, the prototypical galactic wind system, there are only three Fabry-Perot observations in the literature (Williams, Caldwell, & Schommer 1984; Bland & Tully 1988; this thesis), consisting of only two separate data sets! The paucity of published Fabry-Perot observations in extragalactic work in general has been due primarily to a lack of sufficient software and reduction methods suited to the large data sets obtained with a Fabry-Perot. As a significant portion of this thesis has been directed toward the development of algorithms and techniques to alleviate this problem, it is fitting to end this thesis with a discussion of other galactic wind candidates which would be well-suited to future Fabry-Perot studies. In light of the conclusions reached herein concerning M82, a number of physical predictions can be made as well.

5.1 NGC 253

The galaxy NGC 253 is a large (50×20 kpc [Beck, Hutschenreiter, & Wielebinski 1982]), highly-inclined ($i \sim 78^\circ$ [Demoulin & Burbidge 1970]) gas- and dust-rich spiral system located at a distance of approximately 3 Mpc (e.g., Sandage & Tammann 1975). A picture of the galaxy is reproduced in Figure 5.1. Twenty-five years ago, NGC 253 was shown to contain highly non-circular motions in the central regions (Demoulin & Burbidge 1970). It was also known to be an extremely intense infrared source (Rieke & Low 1975), suggesting high levels of star formation. Spectral observations since then have confirmed the presence of an outflow from the nuclear regions via the telltale signature of split emission lines (e.g., Ulrich 1978). Additional kinematic studies of this object have been performed (e.g., Beck, Lacy, & Geballe 1979), including simple imaging Fabry-Perot observations (Pence 1980; Pence 1981), but little work exists with the combination of high spatial resolution and wide field coverage necessary to model the wind accurately.

Although the spatial extent of the outflow ($\sim 30''$) is significantly smaller than that seen in M82, the observed velocity characteristics are very similar: velocities increasing with radius to ~ 300 km/s, reasonably constant line splitting by ~ 300 km/s, and a roughly conical morphology of the outflow region (Ulrich 1978). The presence of a massive halo in NGC 253 has been suggested theoretically by the models of Pence 1980 and others, as well as observationally (Beck, Hutschenreiter, & Wielebinski 1982). However, it is unclear how large of a role interaction with the halo plays in this outflow, because of the much smaller ratio between the outflow and host galaxy dimensions.

Perhaps the most impressive confirmation of the outflow in this galaxy has been the x-ray observations, which clearly show a diffuse component extending from the nucleus to the southeast (Fabbiano & Trinchieri 1984). (The outflow in NGC 253 is only seen south of the disk, possible due to obscuration of northern outflow by the intervening disk.) As in the case of M82, this x-ray wind is reasonably aligned with the optical emission, although the poor resolution of the observations makes a stronger statement impossible.

More recent observations of NGC 253 include HST imaging observations of the core of the galaxy, which clearly resolve the starburst nucleus into several massive star clusters (Watson *et al.* 1994). Although NGC 253 is second only to M82 in its reputation as a galactic wind system, it clearly awaits more detailed analysis. The

Figure 5.1 An image of the large nearby spiral galaxy NGC 253 at optical wavelengths. The central $30''$ – $60''$ is known to exhibit signs of a galactic wind. (Photo taken from Ferris 1982, courtesy of the Hale Observatories.)

projection of the entire outflow region on the disk of the galaxy suggests very strongly that only with spatially complete Fabry-Perot observations will we be able to clearly parameterize and model the wind phenomenon in this system. The opportunity to confirm the predictions of the extensive observations and modeling of M82 in another nearby system are a strong motivation for such observations as well.

5.2 NGC 3079

Although the edge-on spiral galaxy NGC 3079 (Figure 5.2) is much more distant than either M82 or NGC 253 ($D \sim 17$ Mpc [Tully, Shaya, & Pierce 1992]), its nuclear regions contain a galactic-scale outflow that has been studied in greater detail than any other, except the wind in M82. Known to be a strong infrared source (Rice *et al.* 1988), NGC 3079 also contains a bright molecular ring or disk (e.g., Sofue & Irwin 1992) and both radio (e.g., Seaquist, Davis, & Bignell 1978) and x-ray (e.g., Fabbiano,

Kim, & Trinchieri 1992) emission concentrated along the minor axis. Although the infrared emission implies high levels of star formation in the central regions of the galaxy, LINER-like nuclear spectra (Heckman 1980) suggest the presence of an active nucleus (AGN) as well. Optical kinematic studies have detected loops and filaments along the minor axis of the galaxy (Ford *et al.* 1986), as well as extremely complex non-circular motions near the nucleus, which are interpreted as a large-scale bipolar outflow (Filippenko & Sargent 1992).

Figure 5.2 An image of the spiral galaxy NGC 3079 at optical wavelengths. An extremely energetic expanding bubble has been detected near the active nucleus of this system. (Photo taken from the Digitized Sky Survey.)

These studies have culminated with the detailed Fabry-Perot observations and analysis of NGC 3079 by Veilleux *et al.* 1994. The model developed by these authors contains many features common to the winds seen in M82 and NGC 253, although the energetics are more impressive: The “outflow” in NGC 3079 appears to consist of an

expanding ovoidal bubble approximately one kpc in size, containing complex motions with velocities that range over 2000 km/s. Although comparable in mass and size, the kinetic energy associated with this bubble may well be an order of magnitude larger than that of the wind in M82. In addition, high $[\text{N II}]/\text{H}\alpha$ ratios (> 1) imply a more important role for shocks in the NGC 3079 wind, as might be expected from the influence of an active nucleus.

5.3 NGC 1808

NGC 1808 is another relatively nearby ($D \sim 11$ Mpc [Tully, Shaya, & Pierce 1992]) spiral galaxy which has been known for some time to contain minor axis filaments similar to those seen in M82 (e.g., Garrison & Walborn 1974). These spectacular dust-laden arcs and streamers are seen in Figure 5.3, taken from Phillips 1993. Despite their projection on the disk of the galaxy, these filaments have been shown to almost certainly extend to ~ 3 kpc above the plane of the disk (Véron-Cetty & Véron 1985), suggesting a nuclear wind mechanism. As in the case of NGC 253, signs of a corresponding outflow on the opposite side of the galaxy have not been found, although the moderate inclination of NGC 1808 ($\sim 57^\circ$ [Reif *et al.* 1982]) makes an optical detection unlikely.

Recent optical kinematical analyses of the filaments (Forbes, Boisson, & Ward 1992; Phillips 1993) find velocities similar to those seen in M82 ($\sim 400 - 700$ km/s deprojected), and high $[\text{N II}]/\text{H}\alpha$ ratios suggestive of shock excitation (although N and O abundance enhancements may also exist [Phillips 1993]). A much smaller scale outflow is also seen in the central ~ 50 pc (Phillips 1993), suggesting that NGC 1808 is a “minor” example of the far-infrared galaxy (FIRG) class, in which several objects exhibit starburst-driven wind phenomena (e.g., Heckman, Armus, & Miley 1987; Armus, Heckman, & Miley 1990). This classification is somewhat disturbed, however, by occasional observations which seem to detect signs of a Seyfert nucleus (e.g., Véron-Cetty & Véron 1985; Saikia *et al.* 1990).

As expected, confirmation of the outflow has been provided at x-ray wavelengths as a spatial concentration of soft X-rays along the projected minor axis (Dahlem, Hartner, & Junkes 1994). Indicators of a kinematic bar and high levels of star formation are also observed (e.g., Saikia *et al.* 1990; Phillips 1993). The nuclear starburst and associated outflow were probably instigated by an encounter of NGC 1808 with

Figure 5.3 An image of the nearby spiral galaxy NGC 1808, shown as the ratio of broadband B and R images. Darker regions are redder in color. North is up; east to the left. The narrow filaments and arcs in the central kiloparsec are evidence for a dusty large-scale nuclear outflow. The inset illustrates one particular filament which seems to curve back toward the disk. (Image taken from Phillips 1993.)

the galaxy NGC 1792, which shows signs of heavy star formation throughout its disk (Dahlem *et al.* 1990).

Although excellent imaging and spectroscopic studies have been made (e.g., Phillips 1993), the spatial and kinematic extent of the few slit spectra available strongly recommend a Fabry-Perot approach. The low levels of $H\alpha$ emission associated with the outflow (Phillips 1993) may be difficult to detect, but the complications induced by the projection of the filaments onto the disk of the galaxy may require Fabry-Perot data to deconvolve the wind from other galaxy emission. In light of the low observed $[N II]/H\alpha$ ratio in M82, confirmation of the higher ratios in NGC 1808 could prove extremely interesting as well.

Chapter 6

Conclusions

The theory and observations of galactic-scale winds have developed immensely in the ten years since the first basic model by Chevalier and Clegg. Current hydrodynamic simulations are pushing the observations for increased detail in both spatial and spectral domains. This thesis serves to help bridge that gap by comparing, for the first time, wide-field imaging Fabry-Perot spectrophotometry of the prototype galactic wind galaxy, M82, with the predictions of basic wind, bubble, ionization, and scattering models. We have treated the galaxy as three separate components (disk, halo, and outflow), emphasizing that many of the observable outflow phenomena are associated with the interactions between these components.

The disk of M82 houses the starburst nucleus which both powers and illuminates the outflow. The morphology of the star-forming complexes at the core of the starburst is that of a torus, with hot ionized gas and self-propagating star formation present on the inner side of the torus, expanding outward into cooler molecular gas. The torus helps to collimate the hot starburst gas which fills the inner regions of the galaxy into a bipolar wind along the minor axis of the disk. Portions of the disk material are entrained by this wind and dredged high above the plane, where the gas is radiated by the bright starburst nucleus to generate the observed optical filaments. The disk also exhibits enhanced $[\text{N II}]/\text{H}\alpha$ ratios, suggesting the presence of a diffuse ionized medium (DIM), which arises from the turbulent mixing of hot supernovae remnants with cooler disk gas.

The halo of M82 is modeled as a slowly rotating, spherical distribution of dust, which scatters the disk and outflow radiation. Models of intrinsic halo emission and electron scattering fail to match our observations.

The outflow of M82 consists of two zones: an inner zone near the disk in which the outflowing gas is well-collimated, primarily by the entrained disk material, and an outer zone, where the wind passes beyond the collimating material and expands outward in broad cones. These cones are tilted relative to the line of sight, producing low- and high-velocity components on each side of the disk. Current hydrodynamic

wind models support this two-zone model. The relative emission line strengths of $H\alpha$, [N II], and [O III] indicate a significant role for photoionization in the excitation of the optical filaments which surround the hot wind. However, shock models suggest that there may also be an excitation component due to shocks at the wind/halo interface.

In Chapter 5, we briefly examined a few other galactic wind systems, to investigate ways in which these results of this thesis might be applied more generally. We are left with the realization that the power of the Fabry-Perot interferometer now allows us to examine large-scale outflows in galaxies with unprecedented detail. Future projects of great interest in this field include mapping the extent of the optical emitting gas; how far along the minor axis does it really extend, and how well does it track the x-ray emission? Spatial maps at additional wavelengths, such as [O I], will help answer the question of shocks versus photoionization. Deep halo observations will yield clues to the wind/halo interface, where much of the physics behind galactic winds occurs. Clearly the imaging Fabry-Perot interferometer, when coupled with the analysis techniques described in this thesis, is well-suited to the study of galactic winds. The next few years should prove to be an exciting time for the field of galactic winds.

Appendix A

Line fitting

Perhaps the most difficult task associated with the analysis of imaging Fabry-Perot data is that of fitting the spectra across the entire field of view. The fitting is complicated by both the very large number of spectra and the almost certain variation in the fit characteristics across the wide field. The former demands high levels of automation in the fitting procedure, while the latter requires a certain degree of flexibility. As an example, the $H\alpha$ + $[N\ II]$ data reduced for this thesis contained over 60,000 spectra, of which approximately half held sufficient flux for the emission lines to be fit. However, about 4,000 of those spectra contained multiple velocity components in the lines of $H\alpha$, $[N\ II]$, or both, and several hundred spectra were saturated and could not be fit at all. Clearly a fitting technique is required which is capable of automatically fitting large numbers of spectra, subject to broad parameters and restrictions specified by the user. `xzplot` is a Fabry-Perot analysis and visualization tool that has been developed by the author for precisely this purpose.

Based upon the `zplot` software developed by Jonathan Bland-Hawthorn, `xzplot` allows the user to display grids of spectra from a Fabry-Perot cube, with options for overlaying other spectra, spectral fits, and contoured images. An individual spectrum may be scaled, binned, fit, cosmic-ray cleaned, or masked entirely from the analysis. Figure A.1 shows a grid of spectra displayed by `xzplot`, illustrating several of its features.

`xzplot` provides three methods of scaling each displayed spectrum: With no scaling, the values for each spectrum are plotted from zero to the maximum value in the current grid. With scaling activated, each spectrum is plotted between the minimum and maximum values for the entire spectral grid. Finally, autoscaling may be performed, in which case each spectrum is individually scaled between its own minimum and maximum values. The values in each spectrum may be multiplied by a sequence of weights, as well.

To increase the signal-to-noise level, spectra may be spatially binned, with the option to specify integral binning factors in both the X and Y dimensions indepen-

Figure A.1 A grid of spectra from the central regions of M82, displayed by the xzplot software. The spectra have been overlaid in specific regions with spectral fits and a contour map of the compressed data cube. Spectra not shown have been masked from the analysis.

dently. The spectra are combining using either a mean or a median function. Binning along the spectral axis is also supported.

xzplot has been optimized for fitting the large numbers of spectra in Fabry-Perot data. It supports both interactive fitting, in which the user selects a linear continuum and the emission or absorption features to be fit, and automatic fitting, in which a spectrum is fit with initial parameters computed from neighboring spectral fits. In a typical application, the user would fit a few representative spectra manually, specifying the initial values for the continuum and up to ten Gaussian features. The automated mode would then be used to fit the remaining spectra, using the final fit parameters of nearby spectra as initial values for new fits. Finally, the user reviews the automated fits, often by looking at spatial maps of the final parameters, and manually re-fits any problematic spectra. In both manual and automated modes, a nonlinear Levenberg-Marquardt algorithm (e.g., Press *et al.* 1992) is used to converge on a fit.

Other features of `xzplot` include point-and-click removal of cosmic rays from spectra and the ability to overlay a contour map of an image on the spectral grid. Other spectra and spectral fits may be overlaid as well. A very useful option is the specification of an image mask, with which the user may specify spectra to be eliminated from the analysis (e.g., saturated spectra, low signal-to-noise spectra). If a spectrum is masked, it will not appear in the display of the spectral grid, and it will not be used for spectral fitting or binning.

The user interface for `xzplot` is based upon features of `splot` and `specplot` from IRAF, `zplot` from Zodiac, and Supermongo, a plotting package from Robert Lupton. As the Supermongo libraries are used for plotting, support is provided for a large number of graphics devices, including Tektronix terminals, PostScript printers, and Encapsulated PostScript. `xzplot` may also be used non-interactively to generate a plot, including all mask and overlay features.

Future developments of `xzplot` include fitting of Lorentzian and Voigt profiles, graphics display interaction, and porting the software from its current host processing system, Zodiac, to the more commonly used IRAF image analysis system. This port will include integration of the software with the IRAF graphical user interface.

Appendix B

Acronyms and Variables

B.0.1 Acronyms

The following acronyms are used throughout this work:

ADS	Astrophysics Data System
ADU	analog-digital unit
AGN	active galactic nucleus/nuclei
ASIAS	Astrophysics Science Information and Abstract Service
CCD	charge-coupled device
CFHT	Canada-France-Hawaii telescope
DIM	diffuse ionized medium
FIRG	far-infrared galaxy
FSR	free spectral range (of an etalon)
FWHM	full width at half maximum
HIFI	Hawaii Imaging Fabry-Perot Interferometer
HRI	High-Resolution Imager (ROSAT)
HVC	high-velocity component
IC	International Catalogue
IMF	initial mass function
IPAC	Infrared Processing and Analysis Center
ISM	interstellar medium
LINER	low-ionization nuclear emission-line region
LMC	Large Magellanic Cloud
LVC	low-velocity component
NASA	National Aeronautics and Space Administration
NED	NASA/IPAC Extragalactic Database
NGC	New General Catalogue

NOAO	National Optical Astronomy Observatories
QSO	quasi-stellar object
ROSAT	Röntgensatellit
SFRt	star formation rate
SMC	Small Magellanic Cloud
SN	supernova
SNR	supernova remnant
SNRt	supernova rate (commonly SNR)

B.0.2 Variables

The following variables are used throughout this work. If a variable is not defined at the point of its use in the text, it may be assumed to have the following meaning:

l	distance between etalon plates (μm)
n	order of interference
z	etalon gap setting
λ	wavelength ($\text{\AA}$)
μ	index of refraction between etalon plates
θ	angle between light ray and optical axis
p_μ	pixel size (μm)
t	exposure time (sec)
$\Delta\lambda$	free spectral range (FSR) ($\text{\AA}$)
Δz	free spectral range (FSR)
Δz_0	on-axis free spectral range (FSR)
N_R	reflective finesse
Λ_v	velocity resolution (km/s)
R_λ	resolving power
$\delta\lambda$	sampling increment ($\text{\AA}$)
f_{cam}	camera focal length (mm)
f_{coll}	collimator focal length (mm)
f_{tel}	telescope focal length (mm)
m_H	mass of Hydrogen atom (g)
m_e	mass of electron (g)
e	charge of electron (C)
σ	cross section (cm^2)

c	speed of light (km/s)
c_s	speed of sound (km/s)
n_e	electron density (cm^{-3})
T_e	electron temperature (K)
P	gas pressure (erg cm^{-3})
ρ	gas density (g cm^{-3})

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