Chapter 1.
Introduction

Ring galaxies are of great current interest because they offer a unique laboratory to study the processes that occur in more normal galaxies. Formed in the aftermath of a collision between two galaxies, ring galaxies have a relatively simple morphology which allows the interaction to be modeled with some confidence. In this way much can be inferred about the interaction, including the orbital parameters, the mass ratio of the two galaxies, and the time scales for ring formation and dissipation.

Of significant importance, ring galaxies appear to be good systems in which to study at least one mode of star formation since many rings show evidence of both recent interaction and high levels of star formation. For example, Arp 147 has elevated far-infrared emission (Appleton & Struck-Marcell 1987b), strong H II emission (Sargent 1970), and blue spectral colors (Schultz et al. 1990), all of which are indicators of recent active star formation. Thompson & Theys (1978) found the ring in II Zw 466 to be very blue, and Marcum, Appleton & Higdon (1992) found a radial color gradient between the ring and the center of the Cartwheel Galaxy that has been interpreted as an indication of progressive star formation. Thus an understanding of the time for a ring to form and to traverse a region of the galaxy give information about some important time scales for star formation. An understanding of the physical conditions in the ring and the galaxy as a whole will also provide important clues to the process of star formation following the passage of the density wave induced by a collision.

Since this is a physics thesis, as opposed to one from an astronomy department, a brief description of galaxies follows. An overview of colliding galaxies is presented in Sections 1.2 and 1.3 and a more detailed explanation of ring galaxies and a perspective of how this work relates to other investigations in the field is given in Section 1.4.

1.1. Galaxies

For present purposes galaxies can be considered as self-gravitating aggregates of matter with total masses ranging from approximately 10^{40} to 10^{45} grams or, in more common astronomical notation, 10^7 to $10^{12}\,M_\odot$ (solar masses). Stars much like our Sun make up most of the luminous mass in galaxies, but they also contain gas and dust in varying amounts. Galaxies span a large range in linear size, but are on the order of kiloparsecs or tens of kiloparsecs (kpc, 3×10^{21} cm or 3.26×10^3 light years).

Galaxies are conventionally classified into two major types – ellipticals and spirals. Elliptical galaxies derive their name from their appearance in optical photographs and the canonical elliptical galaxy is composed almost entirely of stars, with little, if any, gas and dust. The traditional viewpoint is that the stars in ellipticals were formed at one epoch and have been slowly aging ever since. Individual stars travel on orbits that may be complicated, but the total net angular momentum of ellipticals is small.

The spirals, like our Milky Way are the other major group of galaxies. Spiral galaxies are characterized by having a prominent rotating thin disk which often exhibits superimposed bright spiral arms. The stars in a spiral galaxy are mainly confined to a disk which has a surface brightness that falls off exponentially with radius and a relatively small spherical bulge at the center of the disk. Approximately 10 percent of the mass of a spiral galaxy's disk is in the form of gas, which serves as the raw material from which stars form. The spiral arms shine brightly at optical wavelengths due to the presence of very bright, recently formed groups of massive stars (OB associations) and H II regions — large clouds of hydrogen ionized by the intense ultraviolet radiation field of O and B stars. (The designation H II refers to ionized atomic hydrogen. Neutral atomic hydrogen is denoted H I in the astronomical literature.) The standard model for the spiral features explains them as density waves propagating through the disk (Lin & Shu 1964). The wave pattern speed differs from the disk rotation speed and when rotating gas in the disk overtakes the wave it does so at supersonic speeds, forming shocks and increasing the density. Because active star formation is associated with the spiral arms, it is reasonable to assume that the enhanced density and the presence of shocks are somehow involved in the star formation process, but the details are uncertain. Mouschovias, Shu & Woodward (1974) describe how passage of a shock wave can initiate star formation. Two separate processes can occur: the shock can (1) implode pre-existing clouds (see also Shu et al. 1972) and/or (2) help form clouds via the magnetic Rayleigh-Taylor, or Parker, instability. The discussion in Mouschovias, Shu & Woodward provides a physical explanation for the appearance of OB associations as "beads on a string" along spiral arms. On more quantitative, but less physical, grounds Schmidt (1959) postulated that the star formation rate in galaxies scales as a power, n, of the local gas density. Schmidt and Field and Saslaw (1965) argued for $n \approx 2$, while Kennicutt (1989) finds n=1.3.

The gas distribution in spiral galaxies is not homogeneous; the structure of the interstellar medium (ISM) is extremely complex. In the popular model of of McKee & Ostriker (1977) the ISM consists of three different phases, a hot diffuse medium, dense molecular clouds and a warm medium surrounding the molecular clouds. The hot ISM, with a temperature of approximately 10^5 K fills almost 70 percent of the volume. The details of McKee & Ostriker's model are in dispute, but the model gives a possible general picture of the ISM. Shu et al. (1972) view the ISM as containing H I clouds embedded in a hot, tenuous intercloud medium. Whatever the details, the interstellar medium is supported against gravity by thermal pressure, rotation, and magnetic fields, the latter of which, although extremely weak (μG), can play an important role in determining the equilibrium structure of the gas.

The stars in galaxies can also be thought of as a compressible gas, with the kinetic energy of the stars providing support against gravity, analogous to a pressure. Unlike an ordinary gas however, stars form a collisionless system with time scales for significant two-body scattering on the order of the age of the universe or longer (see Binney & Tremaine 1987). Elliptical galaxies are supported by the random motion of their stars while spiral galaxy disks are maintained mainly by the centrifugal force due to rotation.

A rotating disk of stars with no random velocities is extremely susceptible to both local and global instabilities. Toomre (1964) derived a stability parameter, denoted Q, which describes the stability of a disk with respect to local axisymmetric perturbations. A value of Q greater than unity signifies stability and it is estimated that Q has the approximate value 1.5 locally in our galaxy (Binney & Tremaine 1987). Interestingly, n-body computer studies (e.g., Hohl 1972, 1978; Miller 1978) have shown that velocity dispersions far in excess of those observed are needed to stabilize an isolated disk.

An artificially imposed suitable gravitational potential can help hold a disk together and evidence that just such an additional gravitational force may in fact exist is provided by measured rotation velocities in external galaxies. From the observed light distribution in spiral galaxies the gravitational potential can be determined, assuming that light directly traces mass. This method predicts that the circular speed curve should rise from the center of the disk, reach a peak and then fall in a Keplerian fashion in the outer parts of the disk. Observations of doppler-shifted Hα absorption spectral lines from stars in external galaxies show that rotation speeds do not decrease at large radii in the disk. Further, measurements of the doppler shift in the 21- cm spin flip transition in atomic hydrogen reveal the the rotation velocity continues to stay relatively constant at radii far beyond the visible disk. Presently, the most popular solution to this inconsistency is to postulate the existence of a spherical "dark halo" of unseen mass surrounding visible galaxies (see the review articles of Trimble 1987 and Tremaine 1992). The constituent of this "missing mass" (probably better referred to as "missing light") has been conjectured to be anything from massive neutrinos and exotic elementary particles to black holes and "brown dwarfs," would-be stars not massive enough to ignite fusion reactions. Whatever it is, the "dark halo" is believed to interact gravitationally like normal matter, alleviating somewhat the disk instability and rotation curve problems. "Dark matter"is obviously very important for any dynamical study of galaxies.

1.2. Colliding Galaxies

Beyond their intrinsic beauty (Fig. 1.2.1), interacting galaxies are interesting because the time scale for significant changes to occur is probably 10 to 100 times shorter than an isolated galaxy's evolutionary time scale. Therefore it is possible to study cause and effect in colliding galaxies, provided that the precollision structure and orbit of the individual systems can be determined. Collisions which produce ring galaxies are important in this sense since constraints can be put on their orbital elements.

Interactions between neighboring galaxies may play a fundamental role in the evolution of both individual galaxies and groups of galaxies. Collisions can tear galaxies apart or merge systems together. During the epoch of galaxy formation when the universe was much smaller galactic interactions may have been an important factor in shaping the types of galaxies and clusters of galaxies that exist in our universe. It is no longer believed that all galaxies are isolated "island universes" which evolve independently of outside influences.

While the connection between disturbed galactic morphology and the presence of a nearby galaxy had long been noticed (atlases of interacting systems have been published by Arp (1966) and Arp & Madore (1987)), it was not until 1972 that a series of simple, yet elegant, experiments by Toomre & Toomre convincingly showed that "old-fashioned" gravity alone could produce both the long filamentary tails and broad connecting bridges observed in close pairs of galaxies. Subsequent work verified that interactions between more realistic models of galaxies with massive halos and self-gravitating disks could also reproduce morphologies similar to observations (e.g., Barnes 1988). Collisions which occur with the orbit lying in the plane of a galaxy's disk produce different effects depending on the coupling between the angular momentum of the orbit and the rotational angular momentum of the disk (Toomre & Toomre 1972). If the orbital and disk "spin" angular momentum are aligned, long tidal arms are formed due to a resonance which occurs between the two-galaxy orbital period and an individual star's rotation period within its own disk. If the two angular momenta are antiparallel much less damage is done to the galaxies.

Figure 1.2.1: Examples of two interacting galaxy systems from the Arp-Madore atlas (Arp & Madore 1987). At top is an interacting triplet of galaxies. Below is the famous ring galaxy known as the Cartwheel.

Even though Toomre & Toomre used only a restricted three-body method in which a galaxy is modeled as a point mass surrounded by massless test particles, they nonetheless realized that one of the important effects of a strong interaction would be to transfer energy from the two body orbit of the galaxies' centers of mass into the internal dynamics of the individual galaxies. They speculated that two galaxies could merge via this process and that the result might be the formation of an elliptical galaxy. Models of merging galaxies have indicated that, in fact, the transfer of energy occurs very quickly (Toomre 1977; White 1978, 1979; Negroponte & White 1983; Roos & Norman 1979; Miller & Smith 1980; Gerhard 1981; Farouki & Shapiro 1982; Villumsen 1982; Barnes 1988, 1992). Penetrating collisions of galaxies on subparabolic orbits merge within a few passages and even systems on parabolic and mildly hyperbolic orbits are doomed to coalesce. There are both proponents and opponents of the idea that elliptical galaxies are formed by the collision of spiral galaxies and the issue is still not settled (see Tremaine 1981), although it does seem that at least some galaxies are the product of mergers. Strong interactions would be expected to be important in dense clusters of galaxies (Roos and Norman 1979) and in the early universe when the average separation between galaxies was smaller. Fried (1988) has estimated that the average non-field galaxy has experienced at least one significant interaction during the age of universe.

Other effects attributed to galaxy interactions include the generation of "grand design" spirals similar to the galaxy M51 (Howard & Byrd 1990; Hernquist 1990), the presence of "shells," ripples, and "boxy isophotes" in SOs and elliptical galaxies (Schweizer 1980; Hernquist & Quinn 1988), "dumbbell" galaxies (Valentijn & Casertano 1988), polar ring galaxies (Athanassoula & Bosma 1985), loss of gas to a cluster medium (Mair et al. 1988; Müeller, Mair & Hillebrandt 1989) and equatorial ring galaxies (Lynds & Toomre 1976). It has been suggested that interactions can supply fresh gas to the central sources of non-thermal emission in Seyfert galaxies and quasars (Sanders et al. 1988; Byrd et al. 1987; Hernquist 1989). Harwitt et al. (1987) and Harwitt & Fuller (1988) suggest that some of the excess infrared flux could be due to direct emission from shock heated regions. Good review articles are available by Barnes &

Hernquist (1992, 1993), Schweizer (1986), and Barnes, Hernquist & Schweizer (1991). Further details are contained in these articles and the references cited therein.

1.3. Star Formation in Interacting Galaxies

Collisions between galaxies do more than induce morphological changes; any gas present in a galaxy will be affected in ways that can lead to a number of phenomena. Larson & Tinsley (1978) provided evidence that anomalously high star formation rates are associated with interacting galaxies. Larson & Tinsley found, based on optical observations, that morphologically disturbed galaxies have a large scatter in colors when compared to normal spirals. When interpreted using models of galaxy star formation rates and stellar evolution, this scatter is consistent with bursts of star formation lasting as short as 2×10^7 years involving up to 5 percent of the galaxy's mass. In addition, they found that the galaxies at the earlier stages of interaction, as indicated by the absence of long tidal tails, have colors consistent with the most recent bursts.

Subsequent observations at many wavelengths have confirmed that enhanced star formation appears to be taking place in many, but not all, morphologically disturbed pairs of galaxies (Bushouse 1986, 1987; Condon et al. 1982; Joseph et al. 1984; Joseph & Wright 1985; Keel et al. 1985; Kennicutt et al. 1987; Hummel 1981; Fabbiano, Feigelson & Zamorani 1982).

The most striking observational evidence for increased star formation comes from infrared studies (see Soifer et al. 1987). The Infrared Astronomical Satellite (IRAS) sky survey detected many bright infrared galaxies where they show up mainly at 60 and 100 microns. Infrared selected samples of galaxies tend to overwhelmingly pick out interacting systems. Sanders et al. (1988) found that approximately two-thirds of IRAS galaxies with $L_{FIR} > 10^{11}\,\mathrm{L}_\odot$ and all with $L_{FIR} > 5 \times 10^{11}\,\mathrm{L}_\odot$ are in interacting pairs. These systems radiate up to 99 percent of their total luminosity in the far infrared, whereas the value for normal galaxies is on the order of 50 percent. It is thought that most of the infrared radiation is coming from dust grains heated by ultraviolet radiation emitted by young, massive O and B stars which are still embedded in their embryonic clouds of dust and gas. Bushouse, Lamb & Werner (1988) found that a sample of optically selected disturbed pairs have a factor of two infrared luminosity increase, on average, when compared to a sample of normal spiral galaxies. They also noticed that the most strongly interacting systems show the most extreme values of infrared excess.

Much of the enhanced star formation appear to be located in the central regions of the galaxies, particularly for galaxies which appear to be merging (Soifer et al. 1987). The problem of transporting large amounts of disk gas to the nucleus has been addressed by, e.g., Noguchi (1988), Byrd et al. (1986), Hernquist (1989), Hernquist & Barnes (1991). The formation of a nuclear bar appears to provide the torque necessary to remove angular momentum from gas.

While a link between interactions and bursts of star formation seems clear, the mechanism by which star formation occurs is poorly understood at best. Qualitatively, it is expected that interactions between the interstellar media of the two galaxies (eg. Jog & Solomon 1992) or the perturbed medium of a single galaxy help initiate gravitational collapse of clouds (e.g., Young et al. 1986), which leads to star formation.

Most studies of this phenomenon have assumed that collisions between individual gas clouds are of primary importance in the production of new stars (Olson & Kwan 1990a, 1990b; Scalo & Struck-Marcell 1986, Noguchi & Ishibashi 1986). When clouds collide in these simulations, dissipation occurs and gas is turned into stars in some prescribed manner. Olson & Kwan create stars when strong cloud collisions occur, Noguchi uses all collisions to form stars, and Scalo & Struck-Marcell assume that the star formation rate is a nonlinear function of cloud mass so that clouds can coalesce before becoming stars. Cloud collision parameterizations are also a popular means for studying large-scale star formation in general (Levinson & Roberts 1981; Roberts & Hausman 1984; Hausman & Roberts 1984; Combes 1988; Scalo & Struck-Marcell 1986).

While these studies are instructive in parameterizing some aspects of the interactions, they suffer in that the physics of interstellar cloud collisions is largely unknown;

the degree of "stickiness," the star formation efficiency, and the final state of the cloud are free parameters (see Lattanzio et al. 1985 for simulations of cloud collisions). It is not at all clear that the rate of cloud collisions is the dominant mediator of large-scale star formation in interacting systems and the variance in results from various investigations seems to argue against it. Appleton & Struck-Marcell (1988); Appleton, Schombert & Robson (1992); Noguchi & Ishibashi (1986); and Olson & Kwan (1990a, 1990b) all cite observations to support their viewpoints. Mihos, Richstone & Bothun (1991) claim to be unable to match observations using a cloud collision model and the Schmidt Law.

It is contended here that a likely trigger for producing bursts of high-mass extranuclear star formation is the compressions and shocks that form in a continuous background interstellar medium. Shocks can implode pre-existing clouds and provide a perturbation to initiate the formation of large cloud complexes via the Parker instability. This mechanism was proposed by Mouschovias et al. (1974) in the context of star formation due to the passage of a spiral arm shock (see also Roberts 1969) and explains the spacing of large star forming regions in the spiral arms of external galaxies, often described as "beads on a string" (see also Woodward 1976). A similar structure is seen in collisionally excited ring galaxies (e.g., Theys & Spiegel 1976), in which a strong circular density wave is expanding in the disk (Lynds & Toomre 1976). The magnetic field configuration in interacting systems might be expected to become quite disrupted, but even in the absence of the magnetic instability discussed by Mouschovias et al. the results of calculations presented here show the presence of what is believed to be a Rayleigh-Taylor instability in the interstellar medium of ring galaxies which could serve to gather embedded clouds into large complexes.

Alternate theories exist for the formation of giant molecular clouds (see Elmegreen 1991) and Larson (1988) argues against the importance of shocks in regulating the star formation process. Levinson & Roberts (1981) contended that shocks could not form in the hot, diffuse intercloud medium argued for by McKee & Ostriker (1977) because of the high sound speed in such a medium. Field (1986) argues that observations indicate that there exists a warm, 10^4 K H I medium with a filling factor of approximately 0.5, in which the sound speed is considerably less. In either case, shocks in interacting systems can reach great enough velocities that the intercloud medium may play a larger role in mediating the star formation process, as compared to normal spiral galaxies.

The criterion for star formation used by Jog & Solomon (1992) and Jog & Das (1992) is in somewhat the same spirit as that of Mouschovias et al. in that cloud-intercloud interactions are important for star formation. Jog & Solomon's contention that stars only form in the overlap regions between two gas-rich disk galaxies seems too conservative, though, and it shown in Chapter 4 and Gerber, Lamb & Balsara (1992) that shocks can form during an interaction between a gas-rich disk galaxy and a gas-free elliptical.

If the Mouschovias, Shu & Woodward mechanism for triggering star formation is assumed, as a first approximation, the detailed substructure of the ISM can be ignored and the large scale structure can be modeled using a single-fluid representation. By locating the shock fronts and large-scale density enhancements, likely regions of active star formation can be deduced.

1.4. Ring Galaxies

Both theoretical and observational evidence indicates that a ring galaxy can be formed by the collision of two galaxies, providing that at least one was originally a disk galaxy. If one galaxy strikes the other's disk at near normal incidence and near its center, much of the disk is transformed into an expanding ring. Theoretical studies have confirmed that ring formation is the natural outcome of such a collision (Lynds & Toomre 1976; Appleton & Struck-Marcell 1987b; Struck-Marcell & Lotan 1990; Struck-Marcell & Higdon 1993; Hernquist & Weil 1993; Huang & Stewart 1988.) Observationally, Theys & Spiegel (1976) found that bright ring galaxies usually have a nearby second galaxy aligned with the apparent minor axis of the ring (15 of the 16 companions to ring galaxies studied by Theys & Spiegel lie within 25° of the minor axis of the ring. See also Few & Madore 1986). Further study has found that vigorous star formation is taking places in these rings (Higdon 1992; Few, Madore & Arp 1982; Theys & Spiegel 1976; Thompson & Theys 1978; Appleton & Struck-Marcell 1987b; Fosbury & Hawarden 1977; Marcum, Appleton & Higdon 1992; Schultz et al. 1991; Jeske 1986).

The ring galaxies discussed here are completely different from the normal spiral galaxies with rings. In the latter case, the rings are believed to be a long-lived feature caused by the interaction between rotating disk gas and a central bar (Gallagher & Wirth 1980, Schwarz 1981) or the static structures of Zaspel (1992). The original idea of Freeman & de Vaucouleurs (1974) that ring galaxies are produced by a collision between a disk galaxy and an intergalactic gas cloud is no longer believed relevant to most observed rings (e.g., Joy et al. 1988, Jeske 1986).

In the following sections a description of how a ring galaxy forms is given, followed by a synopsis of some observations of ring galaxies, and a summary of previous theoretical work on ring systems.

1.4.1. Kinematics of Ring Formation

The mechanism by which a ring galaxy forms can best be demonstrated by studying a simple idealized situation that still contains the relevant physics. Consider a coplanar system of massless test particles (stars) all moving in circular orbits in a central gravitational potential. In any reasonable galactic potential individual stellar orbits are stable to small radial perturbations, following which the particles execute harmonic oscillations about their initial radii at a frequency (known as the epicycle frequency) that varies with radius and is a function only of the potential.

If a fast, small intruder passes through the disk parallel to its rotation axis the intruder will have little effect except to impart a radially varying radial velocity impulse to the disk particles. After the collision the stars begin oscillating about their equilibrium positions with the same initial phase, but since the epicycle frequency decreases

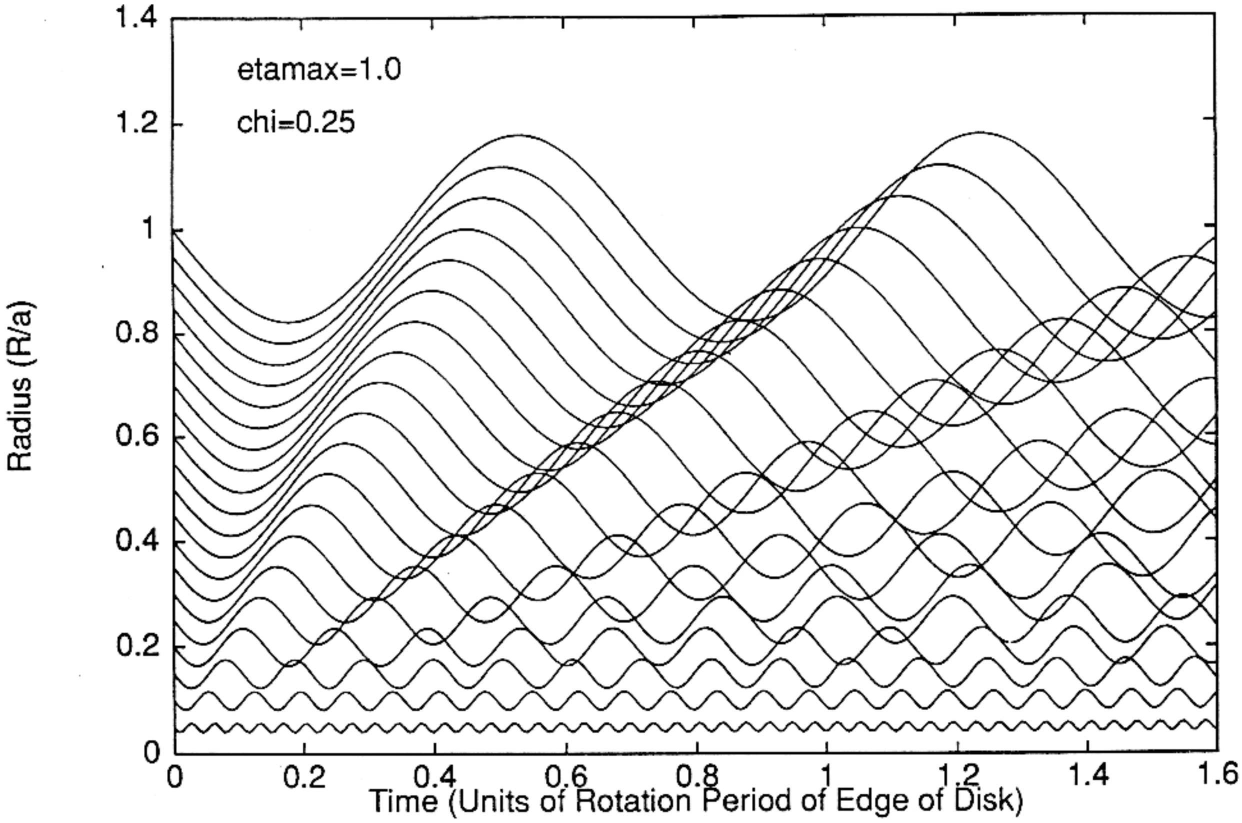

Figure 1.4.1: Radial oscillations of a sample of equally spaced points following an inwardly directed radial velocity impulse. A singular isothermal sphere potential is used for illustrative purposes; the qualitative behavior would be similar in a more realistic galactic potential. The oscillation frequency varies with radius, which produces orbital crowding and an outward moving ring. The meaning of the parameters etamax, chi and a are explained in Chapter 2.

with increasing radius, particles in the inner parts of the disk reach their turning points and begin to move outward while stars in the outer parts of the disk are still moving inward. The result is that particles crowd together at certain radii and form an outward propagating density wave in the shape of a ring (see Fig. 1.4.1).

1.4.2. Observations of Ring Galaxies

Observed rings often appear elliptical with bright knots, reminiscent of giant H II regions seen in the arms of spiral galaxies. A galaxy that can be implicated as the intruder usually lies near the apparent minor axis of the ring (Theys & Spiegel 1976). Most rings have a bright nucleus inside the ring, but some rings are apparently empty although faint emission is usually detected between the nucleus and the ring. Outside the ring the surface brightness can fall to sky background levels quickly (Thompson & Theys 1978, Appleton 1993). The line of sight velocity differences between the ring and the intruder suggest that the time since close approach in many bright systems is on the order of 10^8 yr, approximately equal to a disk rotation period for a "typical" spiral galaxy. The number ratio of ring galaxies to spiral galaxies is about 0.002 (Athanassoula & Bosma 1985).

Theys and Spiegel (1976, hereafter TS) and Few and Madore (1986, hereafter FM) grouped ring galaxies into morphological categories. TS defined ring, or R, galaxies to be ones that appear elliptical without a central nucleus, to differentiate them from the more normal spiral galaxies that sometimes exhibit ring structure in their inner disk regions. TS separated these R systems into three subgroups: RE – crisp elliptical rings with empty interiors, RN – elliptical rings with off-center nuclei, and RK – rings with a single, prominent knot in the ring. The system of FM separates ring galaxies into two groups: P-type – crisp, knotty structure with often a displaced nucleus and, O-type – smooth structure and a centrally located nucleus. FM found that P-type rings had a significant excess of companions lying with two ring diameters. However, they concluded that O-type ring systems were likely not products of collision. A classification scheme based on the appearance of the nucleus has been suggested by Faundez-Abans et al. (1992), but they included all types of rings and the groupings do not seem useful for studies of interacting ring systems.

Vigorous star formation is apparently taking place in many of the rings. From UBV photometry measurements, TS found that ring galaxies were generally blue, similar in color to disks of spiral galaxies. The colors are consistent with a model in which the ring underwent a burst of star formation 10^8 years ago.

Thompson and Theys (1978) found that the knots in the ring of the RE galaxy VII Zw 466 had blue colors, similar to the extreme end of the blue "normal" spiral galaxies. In contrast, a knot that appears to be on the inner side of the ring has a redder color, consistent with it being the remnant nucleus of a spiral galaxy. Their photometry also revealed that the colors interior to the ring, as well as between the knots in the ring, are bluer than normally seen in galaxies on a large scale.

Observations of the asymmetrical ring galaxies Arp 147 (Schultz et al. 1990, 1991) and II Zw 28 (TS) suggest that a remnant nucleus can be displaced so far from the center that it may appear in the bright side of the ring.

Appleton & Struck-Marcell (1987) discovered that 20 of 26 galaxies from the data sets of TS and FM were detected by IRAS, with an average $L_{FIR} = 1.2 \times 10^{10}\,\mathrm{L}_\odot$, which is two to six times greater than the average for most galaxy types (ie., normal galaxies) in the Shapley-Ames sample of de Jong et al. (1984). The mean blue luminosity of the ring galaxy sample is $L_B = 1.4 \times 10^{10}(100/H_0)^2\,\mathrm{L}_\odot$, in accord with the mean of interacting galaxies in the Arp Atlas of Interacting Galaxies in general (Keel et al. 1985). The ratio L_{FIR}/L_B is a factor of two higher for Appleton & Struck-Marcell's sample than for normal spirals, which they interpret as a signature of significant emission from OB stars. These results are consistent with those found by Bushouse, Lamb & Werner (1988) in a study of optically selected interacting systems.

The galaxy AM 0644-741 has a large, knotty, elliptical ring with a nucleus quite offset along the major axis (Arp & Madore 1987). Few, Madore & Arp (1982) successfully fit measured velocity data to an expanding, rotating ring model. The galaxy II Hz 4 is similar to AM 0644-741 and was velocity mapped by Lynds & Toomre (1976), who fit the kinematics and morphology with a simple n-body model in their seminal paper.

The southern ring galaxy A0035, dubbed the Cartwheel galaxy, is perhaps the best-studied ring system (see Fig. 1.2.1). It has a bright clumpy outer ring with many H II regions (Fosbury & Hawarden 1977), an inner ring, and a slightly off-center nucleus. In between the nucleus and the ring are a number of radial spoke-like features, hence the name Cartwheel.

Fosbury and Hawarden (1977), estimate a mass of $4 \times 10^{11}\,\mathrm{M}_\odot$ for the nucleus and a mass of ionized gas in the ring $\gtrsim 1.2 \times 10^{8}\,\mathrm{M}_\odot$. H$\alpha$ imagery by Higdon (1992) shows that a strong burst of star formation is confined to the outer ring, confirming the earlier results of Fosbury and Hawarden. Both studies infer that 3×10^{6} OB stars are producing the observed flux. Marcum, Appleton & Higdon (1992) find a near infrared and optical radial color gradient in the disk behind the ring, implying an aging stellar population which formed as the expanding ring moved past. Further, Marcum et al. noted a lack of a ring in the K band which, together low metallicities as measured by Fosbury & Hawarden, suggested that the Cartwheel was a very gas rich disk with little original background stellar population. If this is true, the Cartwheel may be an interesting object, but not prototypical of ring galaxies.

Neutral hydrogen has been detected in the Cartwheel and Higdon (1992) finds an anti-correlation between Hα or 20 cm continuum and the H I distribution, evidence that the starburst is affecting the neutral gas in the ring. The velocity fields are found to be consistent with a rotational velocity of $254\,\mathrm{km\,s^{-1}}$ and expansion velocity of $20\,\mathrm{km\,s^{-1}}$ in the ring. This rotational velocity agrees with that of Fosbury & Hawarden, but the latter's value of radial expansion was $89\,\mathrm{km\,s^{-1}}$. No emission lines have been detected from the spokes in the Cartwheel galaxy, indicating a lack of an interstellar medium excited by high-mass stars.

Ghigo, Wardle & Cohen (1983) did not detect X-rays from any of the ring galaxies in their sample of nine systems. However, their own model indicates that the expected X-ray flux should be below their detection limit. Suspected sources of X-rays are supernova explosions and shocked gas, both of which are expected to found in regions of active star formation.

1.4.3. Previous Theoretical Investigations

Lynds & Toomre (1976) demonstrated that galaxy-galaxy collisions could produce rings and that the basic mechanism for ring formation was the crowding of stellar orbits following passage of the intruder. They proposed that the ring structure in II Hz 4 was caused by this mechanism and were able to get a good fit to the observed morphology using a simple, largely kinematic model. Lynds & Toomre noted that toroidal flows were present in the ring and that interstellar material could be swept up in the ring, enhancing the star formation rate. They also commented that the lateral displacement of the nucleus could give it the ability to hide behind the ring when viewed from an oblique angle.

Huang & Stewart (1988) studied ring formation using a three- dimensional particle-mesh code (see Chapter 2). They used a gravitating stellar disk, a massive halo and a companion 0.4 the mass of the target galaxy, which was forced to move at constant "escape" velocity throughout the experiment. They concluded that near central collisions produce the O-type rings of Few & Madore (1982) with peaks in density which lag behind the corresponding peaks in radial velocity. Huang & Stewart also found that the inclusion of a "live" self-gravitating halo increases the ring expansion rate and leads to narrower rings and arcs. Central collisions inclined at 30° to the disk produced similar results to normal collisions. Lynds & Toomre and Toomre (1978) reported that penetrations within 15 percent of the disk radius and inclined at less than 45° were necessary to make good rings. Huang & Stewart managed to make rings with highly inclined encounters, as did Appleton & James (1990).

The formation of rings in cold disks perturbed by a low-mass companion was interpreted in the context of mathematical caustics by Struck-Marcell & Lotan (1990). In this picture the intruder gives stars in the disk a radial perturbation, following which the stars execute epicyclic motion about their original orbit. Crowding of orbits occurs at certain radii and where orbits cross one another, formally infinite density enhancements, or caustics, are formed. Many concurrent rings in the same disk can be formed as the oscillators drift in and out of phase. Struck-Marcell (1990) extended this work to include a small departure for axisymmetry and found that a wide variety of caustic forms were created.

Appleton & Struck-Marcell (1987b) and Struck-Marcell and Appleton (1987) studied the response of gas cloud to a perturbation caused by the passage of a small, low-mass companion (companion mass 1/5 that of the target galaxy). They excluded completely the gravitational influence of stellar density wave and concentrated on the behavior of gas clouds, which can grow by coalescence, shrink due to collisional shredding, and form stars. Clouds above a certain threshold mass are broken up and the fragments accelerated by stellar winds, H II regions and supernova explosions. This cloud-fluid approach, in the limit of short cloud lifetimes, yields a star formation rate that deviates from the Schmidt law (Schmidt 1959). Early in the collision, star formation becomes depressed near the density maximum, but later peaks at the location of the density maximum in the ring. Star formation is always depressed behind the ring due to a mean cloud mass decrease, not due simply to the presence of less gas behind ring. After passage of the ring, material falls back toward the center, having lost angular momentum from cloud-cloud interactions, and forms a second, inner ring. When Struck-Marcell & Appleton used a cloud collision time scale approximately the same as cloud lifetimes, they found that if the target galaxy was initially near a critical cloud collision rate, or critical gas mass density, even a small intruder could induce a large burst of star formation in the outer ring. If the galaxy was not near critical, a small intruder would make a burst in the second, inner ring. Although they did not explicitly study the effects of a collision with a large companion, Struck-Marcell & Appleton noted that such a collision would produce large-amplitude waves which would drive coalescence on short time scale and sweep up material. They also inferred that gas might be driven out of disk vertically.

A mechanism for producing ring systems without an apparent companion was proposed by Luban-Lotan & Struck-Marcell (1989). They pointed out that dynamical friction (the mechanism of transferring translational motion into internal motion) could produce a damped oscillatory capture of the companion while rings were still present in the disk.

Theys & Spiegel (1977) were particularly interested in studying the breakup of rings into clumps or beads. They numerically simulated gas particles that were to be interpreted as clouds, starting with a non-expanding rotating ring in equilibrium, and found that the ring broke up into beads in 10^8 years. However, they noted, referring to work of Ostriker & Peebles (1973), that the development of knots was likely to be slowed by the presence of a halo.

Theys & Spiegel proposed that their RE class of ring galaxies were formed as the result of a galaxy collision in which a substantial portion of the nucleus was torn out of the host galaxy. The loss of binding energy caused the rest of the nucleus to disperse. Using a model with axisymmetric, equally spaced rings with no velocity dispersion, they found that the rings formed "a sort of funnel with the nucleus at the narrower opening." They added dissipation and found that the nucleus can be dislodged, producing an RE galaxy. Theys & Spiegel tried a series of further experiments with more realistic galaxy models, but their disk had unrealistically high velocity dispersions for stability reasons, which washed out most of the ring structure.

Two models of the Cartwheel galaxy which include a representation of a gaseous ISM have recently been proposed by Struck-Marcell & Higdon (1993) and Hernquist & Weil (1993). In both cases the gas compression accompanying the ring amplifies pre-existing inhomogeneities into self-gravitating clumps which are sheared into spoke-like features. Both groups contend that both dissipation and self-gravity are necessary to produce the spokes. Struck-Marcell & Higdon believe that their model and observations contradict the colliding cloud star formation models of Olson & Kwan (1990a,b) and Noguchi & Ishibashi (1986).

Chatterjee (1984, 1986) has related ring parameters to the change in energy delivered in an impulsive encounter.

1.5. Objectives of This Investigation

In this thesis the response of a disk galaxy when it interacts with another galaxy is studied. The restriction is made to collisions in which a spherical gas-free galaxy, referred to as the "intruder" or "companion," encounters the disk of a second galaxy at near normal incidence, producing rings and arcs in the disk.

The ultimate goal of this investigation, of which this thesis is only the beginning, is to build a link between numerical models and observations of actively star forming regions in interacting galaxies. Ring galaxies provide a good laboratory for this study since strong constraints can be put on the orbital history of the two galaxies — only certain collisions produce rings.

Regions of high gas density and shock formation in the disk will be identified as potential sites for enhanced star formation rates. Since the resulting morphology correlates with initial conditions, these models provide the first step toward determining how certain physical conditions relate to enhanced star formation rates. Generic results and the physical mechanisms that underlie them are sought as primary goals. The obvious extension of this study is to use the insight gained here to make detailed models of specific observed systems.

Only large scale phenomena are considered here since the numerical method and computational resources limit resolution length scales to approximately the kiloparsec scale.

Specifically, the objectives of this study are:

- Create models of steady-state galaxies which can be used as a initial states for collision simulations.
- Study the formation of ring galaxies and how an increasing impact parameter affects the resulting morphology. Understand why these morphologies develop with the help of a simple analytic model.

- Incorporate a representation of the interstellar medium into a numerical model in a state-of-the-art manner, paying special attention to the morphology of the gas and noting differences between the behavior of stars and gas.
- Locate regions of increased gas density and shocks. Measure time scales over which these increases occur and find generic features of the collisions.
- Compare these results with observed ring galaxies in a generic sense. Correlate the location of shocks and high density in the models with observed regions of active star formation.

Subsequent chapters of this thesis are arranged thusly:

- Chapter 2. An analytic, kinematic model is developed which provides insight into the ring and arc formation process.
- Chapter 3. The numerical methods are discussed and the non-trivial construction of steady-state galaxy models is described.
- Chapter 4. Results of the collision simulations are presented. An axisymmetric collision is discussed in detail, followed by a presentation of a series of four collisions at increasing impact parameters. The numerical and analytic models are compared.
- Chapter 5. A brief summary of results and future prospects is given.