To my parents and grandparents.
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Abstract of Dissertation Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

ENVIRONMENTS OF X-RAY SOURCES IN EXTERNAL GALAXIES

By

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Chair: Stephen S. Eikenberry
Major: Astronomy

Star clusters provide a unique opportunity to study both the environments and progenitors associated with compact objects. Star-forming galaxies are abundant in both star clusters and X-ray point sources. The latter are candidates for X-ray binaries (XRBs) containing a compact object left behind after the death of a massive star. I study the environments of compact objects by focusing on X-ray point sources and massive star clusters in the two star-forming galaxies, the Antennae and NGC 1569.

I develop a successful technique for this study using the Antennae. I establish an X-ray/IR astrometric frame tie with an rms positional uncertainty of $\sim 0.5^\prime\prime$. I find 19 IR counterparts within 1.5$^\prime\prime$ of an X-ray source. Performing an IR photometric study, I find that the cluster counterparts are more luminous and massive than the general cluster population in the Antennae. I define the quantity, $\eta$, relating the fraction of observed X-ray sources per unit mass as a function of cluster mass. I find a constant value of $\eta = 6 \times 10^{-8} M_\odot^{-1}$, which I demonstrate indicates more massive clusters are more likely to harbor XRBs only because they have more stars.

Using my IR-to-X-ray frame tie as an intermediary, I match *Chandra* X-ray positions to *HST* optical positions. Applying spectral photometric models to IR/optical counterparts I determine cluster mass, age and metallicity, which further characterize the environments of Antennae XRBs. My analysis also includes a multiwavelength and spectroscopic study of the unusual X-ray source, X-37. After finding an optical and
IR counterpart to this X-ray source, an optical/IR spectrum revealed this source is a background quasar at a redshift of $z = 0.26$.

Extending my study to the dwarf, starburst galaxy, NGC 1569, I produce a frame tie between ground-based, IR and *Chandra*, X-ray images with an rms positional uncertainty of 0.2″. I then identify seven cluster counterparts within 0.6″ of an X-ray source. Unlike the Antennae, I do not find a trend in luminosity or mass for these cluster counterparts. Computing $\eta$ for this galaxy, I find a value of $3.3 \times 10^{-6} \ M_\odot^{-1}$. 
CHAPTER 1
INTRODUCTION

During the past few decades, X-ray observations have revealed a wide range in compact objects from neutron stars and stellar mass black holes to super massive black holes at the centers of galaxies. While there are abundant theories concerning compact object formation, the specifics of their origins remain uncertain. For example, how are compact object properties related to their progenitors mass, angular momentum, kinematics, etc.? Furthermore, what types of stars produce compact objects, under what conditions and in what environments? In this dissertation I will explore some of these issues by investigating the environments of stellar mass compact objects in nearby, <20 Mpc, galaxies. I will also demonstrate that the IR wavelength regime is a powerful tool for this type of investigation.

In this study, I will use X-ray sources to identify compact objects. Many of these X-ray sources are X-ray binaries (XRBs) consisting of a compact object accreting matter from a closely orbiting star. Compact objects are inextricably linked to massive stars. Lada and Lada (2003) showed that these stars preferentially form in young stellar clusters. Massive stars usually end their lives in supernovae, producing a compact remnant. This remnant can be kicked out of the cluster due to dynamical interactions, stay behind after the cluster evaporates, or remain embedded in its central regions. This last case is particularly interesting as the compact object is still in situ, allowing investigations into its origins via the ambient cluster population.

Star-forming galaxies are ideal targets for this work, as they contain many young clusters and X-ray sources. Unlike galactic XRBs, these X-ray sources have more well-determined (or at least uniform) distances, minimizing a major uncertainty in luminosity. Comparing clusters containing XRBs to those without them can contribute statistics on the formation environments of compact objects. Finding lone XRBs can provide insight into their kinematics.
In the past decade, Chandra and XMM observations revealed extremely luminous (10^{39}-10^{42} \text{ ergs s}^{-1}), off-nuclear X-ray point sources, classified as ultra luminous X-ray sources (ULXs), in many nearby galaxies. Given that the Eddington luminosity of neutron stars is \( \sim 10^{38} \text{ ergs s}^{-1} \), ULXs are 10 to 10^4 times more luminous. Assuming luminosity scales as the mass of the compact companion, this implies a mass range much larger than stellar mass black holes (BHs), but smaller than the 10^6 to 10^8 M_\odot ones at the centers of galaxies. Several authors (e.g., Fabbiano, 1989; Zezas et al., 1999; Roberts and Warwick, 2000; Makishima et al., 2000) suggest these massive (100-10,000 M_\odot) compact sources outside galactic nuclei are intermediate mass black holes (IMBHs), a new class of BHs. While IMBHs could potentially explain the observed high luminosities, other theories exist as well, including beamed radiation from a stellar mass BH (King et al., 2001); super-Eddington accretion onto lower-mass objects (e.g., Moon et al., 2003; Begelman, 2002); or supernovae exploding in dense environments (Plewa, 1995; Fabian and Terlevich, 1996). In addition, some background quasars can masquerade as ULXs on the face of a foreground galaxy (Gutiérrez and López-Corredoira, 2005).

An ideal target to begin this investigation is the Antennae galaxies (NGC 4038/4039). This merger is the closest pair of interacting galaxies and contains numerous X-ray sources and star clusters. High resolution X-ray images using Chandra revealed 49 point sources in the Antennae (Zezas et al., 2002a). I will assume a distance to the Antennae of 19.3 Mpc, which implies 10 sources are ultraluminous X-ray sources (ULXS) with X-ray luminosities, \( L_X > 10^{39} \text{ ergs s}^{-1} \). Considering new observations of red giant stars in the Antennae indicate a distance of 13.8 Mpc (Saviane et al., 2004), this ultraluminous X-ray source population could decrease by roughly a half.

HST images of the Antennae display a plethora of star clusters in the spiral arms and bridge region (Whitmore et al., 1999). Broad and narrow band photometric studies indicate many of these clusters are massive, \( \sim 10^6 M_\odot \), and \( \sim 10 \) Myr old (e.g. Whitmore and Zhang, 2002; Mengel et al., 2005). While most clusters are young, Whitmore et al.
(1999) indicate two additional populations: 1) a $\sim$100 Myr population in the northeast quadrant and 2) a $\sim$500 Myr population that most likely formed during the initial encounter. These authors also identified several globular clusters in the field around the Antennae.

Previous X-ray work tried matching X-ray positions directly to the optical (Zezas et al., 2002b). Due to the small field of view of the WFPC2 camera on HST, the authors were unable to locate sources in common and therefore made an absolute astrometric match between Chandra and HST coordinates. Considering the absolute astrometric accuracy of WFPC2 is 0.9″–1.5″ (Biretta, 2000), Zezas et al. (2002b) defined matches as optical sources within 2″ of an X-ray source position. In many case, they found random offsets between clusters and X-ray sources, including ULXs. They suggest many of these X-ray sources are runaway XRBs escaping from their parent cluster. Unfortunately, the chance alignment of unrelated objects is high: their models show 6±2 X-ray sources are false matches with 8±4 optical sources.

In my approach to finding counterparts to X-ray sources in the Antennae, I chose IR, J and Ks images, to make a frame tie to the Chandra X-ray images from Fabbiano et al. (2001). Utilizing the similar dust-penetrating properties of these wavelengths, I demonstrate the power of this approach to finding counterparts to X-ray sources. I then perform a photometric study of these counterparts and compare this to the general population of clusters.

One issue I am particularly interested in is the relationship between the observed XRB frequency and cluster mass. By finding the observed number of XRBs as a function of cluster mass, I can say something about the XRB formation rate in star clusters. Recent theoretical models of young, massive cluster evolution provide a framework for comparison to my observational study. Two in particular, (Oskinova, 2005; Sepinsky et al., 2005), incorporate XRB formation in their models. Oskinova (2005) uses a population synthesis code to study the evolution of X-ray emission in young, massive clusters.
Sepinsky et al. (2005) investigate the role of supernova kicks in XRB expulsion from the parent cluster using the population synthesis code, StarTrack. They also incorporate the XRB formation rate for a range in cluster mass. In this work, I compare my observed number of XRBs per cluster mass in the Antennae to that predicted by these models.

I then extend my analysis to optical wavelengths by fitting X-ray positions to optical, HST positions using my IR frame tie as an intermediary. While a direct optical/X-ray frame tie is difficult, an optical/IR frame tie is substantially easier. Most bright HST sources will show up in the IR, facilitating a coordinate match between them. Incorporating the previously made IR/X-ray frame tie, I can make an astrometric solution across all three wavelengths. Combining $UBV_I$ and $J/K_s$ photometry of cluster counterparts, I fit spectral evolutionary models to these sources to derive masses, ages and metallicities.

My multiwavelength project resulted in an intriguing discovery with respect to the unusual X-ray source, X-37 as designated by Zezas et al. (2002a). At the distance to these interacting galaxies it would have an X-ray luminosity, $L_x = 4.5 \times 10^{39}$ ergs s$^{-1}$, making it a ULX. A previous attempt to match X-ray positions directly to HST positions indicated that this object has a significant ($> 1.0''$) offset from a nearby optical source (Zezas et al., 2002b). This spawned discussions of whether this is a runaway X-ray binary escaping from its parent cluster (Zezas et al., 2002b; Miller et al., 2004; Fabbiano, 2004). But, matching X-ray positions directly to the optical is difficult due to the crowded HST field and image rotation. Here, I use X-37 to demonstrate the power of my frame tie technique and the necessity for followup, spectroscopic observations to ULX counterparts.

I take my multiwavelength program a step further and apply it to the dwarf, starburst galaxy, NGC 1569. This system contains two super star clusters (SSCs) (Arp and Sandage, 1985) and 16 X-ray sources on the face of the galaxy, which range in luminosity from $L_X = \sim 5 \times 10^{33}$–$3 \times 10^{36}$ ergs s$^{-1}$ (Martin et al., 2002). At a distance of 2.2 Mpc (Israel, 1988), it is much closer than the Antennae and allows me to probe much
lower star cluster masses, down to $\sim 1000 \, M_\odot$. Using $J$ and $K_s$ observations acquired with FLAMINGOS on the KPNO 4-m telescope, I carry out a photometric analysis of IR star cluster counterparts to X-ray sources in this galaxy. I then compare the results to the vastly different galactic system of the Antennae.

In my dissertation, Chapters 2 through 4 discuss the Antennae and the multiwavelength properties of counterparts to X-ray sources. In Chapter 5, I present a case study of the multiply wavelength counterpart to the Antennae X-ray source, X-37. I extend my research program to NGC1569 in Chapter 6. Chapter 7 presents a summary and conclusions found from my work.
CHAPTER 2
DEEP NEAR-INFRARED IMAGING AND PHOTOMETRY OF THE ANTENNAE GALAXIES WITH WIRC

The Antennae galaxies, NGC 4038/39 (Arp 244), are probably the best-known example of a pair of interacting galaxies. At a distance of only 19.3 Mpc\(^1\) (Whitmore et al., 1999) the Antennae system has been thoroughly studied over a large range of wavelengths.

Numerous observations that cannot be listed here individually have been made at far-infrared, sub-millimeter and radio wavelengths. They generally agree that most of the emission at longer wavelengths comes from the highly extincted overlap region. The largest molecular complexes have masses of \((3 - 6) \times 10^8 M_\odot\), typically an order of magnitude larger than the largest structures in the disks of more quiescent spiral galaxies (Wilson et al., 2000). These authors also found an excellent correlation between the CO emission and the 15\(\mu\)m emission seen by ISO (Mirabel et al., 1998). Recent mid-IR observations at slightly higher spatial resolutions with Spitzer (Wang et al., 2004) showed that the rate of star formation per unit mass in the active areas is comparable to those in starburst and some ultra-luminous galaxies.

The first deep optical analysis of the Antennae with the Wide Field Camera on HST (Whitmore and Schweizer, 1995) showed over 700 point-like objects. Subsequent observations with WFPC2 (Whitmore et al., 1999) increased the sensitivity by 3 magnitudes in V band and revealed between 800 and 8000 clusters in four age ranges: (i) ages of \(\leq 5\) Myr around the edges of the overlap region and 5 – 10 Myr in the western loop, (ii) ages \(\sim 100\) Myr in the northeastern star formation region, (iii) intermediate-age clusters of \(\sim 500\) Myr and (iv) old globular clusters from the progenitor galaxies. While Whitmore et al. (1999) and Fritze-v. Alvensleben (1999) studied the statistical properties

\(^1\) assuming \(H_0 = 75\text{km}\text{s}^{-1}\text{Mpc}^{-1}\)
of the cluster population, Gilbert et al. (2000) and Mengel et al. (2002) investigated the properties of selected “super star clusters” in greater detail.

X-ray observations with Chandra (Zezas et al., 2002a) revealed 49 sources, including several ultra-luminous X-ray (ULX) sources with X-ray luminosities of $L_X > 10^{39}\text{ erg s}^{-1}$, suggesting these are binary accretion sources.

So far, most studies of the star clusters in the Antennae have been focused on a single wavelength regime with few exceptions: Zhang et al. (2001) studied the relationship between young star clusters and the interstellar medium based on observations ranging from X-rays to the radio wavelengths, and Whitmore and Zhang (2002) correlated optically detected star clusters with their radio counterparts from (Neff and Ulvestad, 2000). Kassin et al. (2003) combined $UBVRJHK$ images to derive extinction maps for the Antennae and found several red clusters.

In this chapter I discuss the initial data analysis before commencing with a detailed investigation of the properties of star clusters associated with X-ray sources in the Antennae in the following three chapters. I present the deep near-infrared observations of NGC 4038/4039 obtained with WIRC and briefly describe the instrument. I then discuss the infrared morphology of the Antennae galaxies, how I identified star clusters and the method used to measure photometry of them.

2.1 The Data

2.1.1 Observations

My collaborators, Dr. Bernhard Brandl and Dr. Joseph Carson, obtained near-infrared images of NGC 4038/4039 taken on 2002 March 22 using the Wide-field InfraRed Camera (WIRC) on the Palomar 5-m telescope. At the time of these observations, WIRC was being commissioned and was equipped with an under-sized HAWAII-1 array (prior to installation of the full-sized HAWAII-2 array in September 2002), providing a $\sim 4.7 \times 4.7$-arcminute field of view (FOV) with $\sim 0.25''$ pixels (“WIRC-1K”–see Wilson et al. (2003) for details). Conditions were non-photometric due to patches of cloud passing
through. Typical seeing-limited images had stellar full-width at half-maximum of 1.0″ in $K_s$ and 1.3″ in $J$. We obtained images in both the $J$- (1.25µm) and $K_s$-band (2.15µm) independently. Our observing procedure consisted of a set of 20 randomly dithered pointings controlled by a simple macro. This method produced a large effective FOV and greater redundancy. At each position we took two 7.27 s exposures in the $K_s$-band and eight 29.07 s exposures in the $J$-band. The shorter exposures in $K_s$ accounted for the high sky background flux in this band. The total, on-target exposure resulted in 19.38 s in both $J$ and $K_s$.

2.1.2 Image Morphology

As seen in the $K_s$ band image of the Antennae (Figure 2-1), the two nuclei are the dominant features. In comparison to the optical, the northern nucleus (NGC 4038) appears quite different in the IR than the southern nucleus (NGC 4039). The prominent dust lane across the nucleus of NGC 4038 is lacking in the IR. In the Third Reference Catalogue of Bright Galaxies (de Vaucouleurs, 1991) NGC 4038 is classified as a SB(s)m pec ($B_0^T = 10.59$), while NGC 4039 is classified as SB(s)m pec ($B_0^T = 10.69$). The $K_s$ image clearly shows the spiral structure of NGC 4038, a characteristic of Sb-type galaxies.

The overlap region contains a considerable amount of extinction in the optical and is accentuated by the many dark, dust lanes. The effects of extinction all but disappear in the IR, revealing a multitude of clusters. This is apparent in Figure 2-1, where I compare my $K_s$ image of the Antennae with an optical image of this galaxy pair.

2.1.3 Cluster Identification

I identified IR point sources as compact ‘smudges’ in or near the Antennae. Considering the variety of cluster shapes and complex background, my collaborators and I felt this was the best method to ID cluster candidates for the photometric analysis. While most of these sources are likely associated with the Antennae, I used Table 4 in Whitmore et al. (1999) to identify eight sources which are foreground stars (see Table 2-1). I also identified an additional source as a background quasar and discuss this object.
in Chapter 6 as well as Clark et al. (2005). After removing these nine contaminants from my sample, this left me with 224 clusters.

2.1.4 Photometry

A few sources were extremely faint and I was not able to get accurate photometry on all 224 clusters. Therefore, I performed aperture photometry on 222 clusters in the $J$-band and 221 clusters in the $K_s$-band using a self-written IDL program. I found that the full width at half maximum (FWHM) was 3.5 pixels (0.9") in the $K_s$ image and 4.6 pixels (1.2") in the $J$ band. I used a photometric aperture of 5-pixel radius in $K_s$ band, and 6-pixel radius in $J$ band, corresponding to $\sim 3\sigma$ of the Gaussian PSF.

Background subtraction is both very important and very difficult in an environment such as the Antennae due to the brightness and complex structure of the underlying galaxies and the plethora of nearby clusters. In order to address the uncertainties in background subtraction, I measured the background in two separate annuli around each source: one from 9 to 12 pixels and another from 12 to 15 pixels. Due to the high concentration of clusters, crowding became an issue. To circumvent this problem, I employed the use of sky background arcs instead of annuli for some sources. These were defined by a position angle and opening angle with respect to the source center. All radii were kept constant to ensure consistency. In addition, nearby bright sources could shift the computed central peak position by as much as a pixel or two. If the centroid position determined for a given source differed significantly (> 1 pixel) from the apparent brightness peak due to such contamination, I forced the center of all photometric apertures to be at the apparent brightness peak. For both annular regions, I calculated the mean and median backgrounds per pixel.

Multiplying these by the area of the central aperture, these values were subtracted from the flux measurement of the central aperture to yield 4 flux values for the source in terms of data numbers (DN). Averaging these four values provided me with a flux value for each cluster. I computed errors by considering both variations in sky background, $\sigma_{\text{sky}}$,
and Poisson noise, $\sigma_{adu}$. I computed $\sigma_{sky}$ by taking the standard deviation of the four measured flux values. I then calculated the expected Poisson noise by scaling DN to $e^-$ using the known gain of WIRC ($2 \, e^- \, DN^{-1}$, Wilson et al., 2003) and taking the square root of this value. I added both terms in quadrature to find the total estimated error in photometry.

I then calibrated my photometry using the bright 2MASS star ‘2MASS 12014790-1851156’ at $12^h01^m47.90^s$, $-18^d51^m15.7^s$ which is listed in the 2MASS database with $J = 13.065$, $\sigma_J = 0.02$ mag, and $K_s = 12.771$, $\sigma_{K_s} = 0.02$ mag. This star was in the WIRC FOV for the Antennae observations.

### 2.2 Summary

In this chapter I presented near-IR, $J$ and $K_s$ observations of the Antennae originally acquired by my collaborators, Dr. Bernhard Brandl and Dr. Joseph Carson. I discussed the data reduction, cluster identification and photometry of these sources in this galaxy pair. In the next two chapters I will perform a detailed study of the photometric properties of the IR counterparts to X-ray sources.
Figure 2-1. Antennae, WIRC $K_s$ image on the left and $UBVI$ optical image on the right. Both image are $\sim 4^\prime \times 4^\prime$. Notice the prominent dust lanes in the optical disappear in the IR image.
CHAPTER 3
INFRARED COUNTERPARTS TO CHANDRA X-RAY SOURCES IN THE ANTENNAE

Recently, high resolution X-ray images using Chandra have revealed 49 point sources in the Antennae (Zezas et al., 2002a). I will assume a distance to the Antennae of 19.3 Mpc (for $H_0$=75 km s$^{-1}$ Mpc$^{-1}$), which implies 10 sources have X-ray luminosities greater than $10^{39}$ ergs s$^{-1}$. Considering new observations of red giant stars in the Antennae indicate a distance of 13.8 Mpc (Saviane et al., 2004), I point out this ultraluminous X-ray source population could decrease by roughly a half. Typically, masses of black holes produced from standard stellar evolution are less than $\sim 20 M_\odot$ (e.g., Fryer and Kalogera, 2001). The Eddington luminosity limit implies that X-ray luminosities $> 10^{39}$ ergs s$^{-1}$ correspond to higher-mass objects not formed from a typical star. Several authors (e.g., Fabbiano, 1989; Zezas et al., 1999; Roberts and Warwick, 2000; Makishima et al., 2000) suggest these massive (10—1000 $M_\odot$) compact sources outside galactic nuclei are intermediate mass black holes (IMBHs), a new class of BHs. While IMBHs could potentially explain the observed high luminosities, other theories exist as well, including beamed radiation from a stellar mass BH (King et al., 2001); super-Eddington accretion onto lower-mass objects (e.g., Moon et al., 2003; Begelman, 2002); or supernovae exploding in dense environments (Plewa, 1995; Fabian and Terlevich, 1996).

Compact objects tend to be associated with massive star formation, which is strongly suspected to be concentrated in young stellar clusters (Lada and Lada, 2003). Massive stars usually end their lives in supernovae, producing a compact remnant. This remnant can be kicked out of the cluster due to dynamical interactions, stay behind after the cluster evaporates, or remain embedded in its central regions. This last case is of particular interest to me as the compact object is still in situ, allowing me to investigate its origins via the ambient cluster population. The potential for finding such associations is large in the Antennae due to large numbers of both X-ray point sources and super star clusters; a further incentive for studying these galaxies.
In Chapter 2, I presented $J$ and $K_s$ photometry of $\sim 220$ clusters in the Antennae. My analysis of $(J - K_s)$ colors indicated that many clusters in the overlap region suffer from 9–10 mag of extinction in the $V$-band (Brandl et al., 2005). This result contrasts with previous work by Whitmore and Zhang (2002) who associated optical sources with radio counterparts in the Antennae (Neff and Ulvestad, 2000) and argued that extinction is not large in this system. Here, I continue the analysis of these Antennae IR images by making a frame tie between the IR and Chandra X-ray images from Fabbiano et al. (2001). Utilizing the similar dust-penetrating properties of these wavelengths, I demonstrate the power of this approach to finding counterparts to X-ray sources. By comparing the photometric properties of clusters with and without X-ray counterparts, I seek to understand the cluster environments of these X-ray sources. In §3.1 I discuss the IR astrometric frame tie to Chandra X-ray images. §3.2 explains our matching technique and the photometric properties of the IR counterparts. I conclude with a summary of my results in §3.3.

3.1 Data Analysis

3.1.1 Astrometric Frame Ties

The relative astrometry between the X-ray sources in NGC 4038/4039 and images at other wavelengths is crucial for successful identification of multi-wavelength counterparts. Previous attempts at this have suffered from the crowded nature of the field and confusion between potential counterparts Zezas et al. (2002b). However, the infrared wave band offers much better hopes for resolving this issue, due to the similar dust-penetrating properties of photons in the Chandra and $K_s$ bands. (See also Brandl et al. (2005) for a comparison of IR extinction to the previous optical/radio extinction work of Whitmore and Zhang (2002).) I thus proceeded using the infrared images to establish an astrometric frame tie, i.e. matching Chandra coordinates to IR pixel positions.

As demonstrated by Bauer et al. (2000), I must take care when searching for X-ray source counterparts in crowded regions such as the Antennae. Therefore, my astrometric
frame tie used a simple approach based on solving a two-dimensional linear mapping function relating right ascension and declination coordinates in one image with \( x \) and \( y \) pixel positions in a second image. The solution is of the form:

\[
\begin{align*}
    r_1 &= ax_1 + by_1 + c, \quad (3-1) \\
    d_1 &= dx_1 + ey_1 + f \quad (3-2)
\end{align*}
\]

Here \( r_1 \) and \( d_1 \) are the right ascension and declination, respectively, for a single source in one frame corresponding to the \( x_1 \) and \( y_1 \) pixel positions in another frame. This function considers both the offset and rotation between each frame. Since I am interested in solving for the coefficients \( a-f \), elementary linear algebra indicates we need six equations or three separate matches. Therefore, I need at least three matches to fully describe the rms positional uncertainty of the frame tie.

I first used the above method to derive an approximate astrometric solution for the WIRC \( K_s \) image utilizing the presence of six relatively bright, compact IR sources which are also present in images from the Two Micron All-Sky Survey (2MASS). We calculated pixel centroids of these objects in both the 2MASS and WIRC images, and used the 2MASS astrometric header information to convert the 2MASS pixel centroids into RA and Dec. These sources are listed in Table 3-1. Applying these six matches to my fitting function I found a small rms positional uncertainty of 0.2", which demonstrates an accurate frame tie between the 2MASS and WIRC images.

Using the 2MASS astrometric solution as a baseline, I identified seven clear matches between \textit{Chandra} and WIRC sources, which had bright compact IR counterparts with no potentially confusing sources nearby (listed in Table 3-2). I then applied the procedure described above, using the \textit{Chandra} coordinates listed in Table 1 of Zezas et al. (2002a) (see that reference for details on the \textit{Chandra} astrometry) and the WIRC pixel centroids, and derived the astrometric solution for the IR images in the X-ray coordinate frame.
For the 7 matches, I find an rms residual positional uncertainty of $\sim 0.5''$ which I adopt as my $1\sigma$ position uncertainty. I note that the positional uncertainty is an entirely empirical quantity. It shows the achieved uncertainty in mapping a target from one image reference frame to the reference frame in another band, and automatically incorporates all contributing sources of uncertainty in it. These include, but are not limited to, systematic uncertainties (i.e. field distortion, PSF variation, etc. in both Chandra and WIRC) and random uncertainties (i.e. centroid shifts induced by photon noise, flatfield noise, etc. in both Chandra and WIRC). Thus, given the empirical nature of this uncertainty, I expect it to provide a robust measure of the actual mapping error—an expectation which seems to be borne out by the counterpart identification in the following section.

To further test the accuracy of my astrometric solution I explored the range in rms positional uncertainties for several different frame ties. Specifically I picked ten IR/X-ray matches separated by $<1''$, which are listed in Table 3-3 (see §3.1). Of these ten I chose 24 different combinations of seven matches resulting in 24 unique frame ties. Computing the rms positional uncertainty for each, I found a mean of $0.4''$ with a $1\sigma$ uncertainty of $0.1''$. Considering the rms positional uncertainty for the frame tie used in my analysis falls within $1\sigma$ of this mean rms, this indicates I made an accurate astrometric match between the IR and X-ray.

### 3.2 Results and Discussion

#### 3.2.1 Identification of IR Counterparts to Chandra Sources

I used the astrometric frame tie described above to identify IR counterpart candidates to Chandra X-ray sources in the WIRC $K_s$ image. I restricted my analysis to sources brighter than $K_s \sim 19.4$ mag. This is the $K_s$ sensitivity limit which I define in my photometric analysis below (see §3.2.2.1). Using the $0.5''$ rms positional uncertainty of my frame tie, I defined circles with $2\sigma$ and $3\sigma$ radii around each Chandra X-ray source where I searched for IR counterparts (Figure 3-1). If an IR source lay within a $1.0''$ radius ($2\sigma$) of an X-ray source, I labeled these counterparts as “strong”. Those IR sources between
1.0" and 1.5" (2 – 3σ) from an X-ray source I labeled as “possible” counterparts. I found a total of 13 strong and 6 possible counterparts to X-ray sources in the Antennae. These sources are listed in Table 3-3 and shown in Figure 3-2. Of the 19 X-ray sources with counterparts, two are the Antennae nuclei (Zezas et al., 2002a), one is a background quasar (Clark et al., 2005), and two share the same IR counterpart. Therefore, in my analysis of cluster properties, I only consider the 15 IR counterparts that are clusters. (While X-42 has two IR counterparts, I chose the closer, fainter cluster for my analysis.)

I then attempted to estimate the level of “contamination” of these samples due to chance superposition of unrelated X-ray sources and IR clusters. This estimation can be significantly complicated by the complex structure and non-uniform distribution of both X-ray sources and IR clusters in the Antennae, so I developed a simple, practical approach. Given the < 0.5" rms residuals in our relative astrometry for sources in Table 3-2, I assume that any IR clusters lying in a background annulus with radial size of 2.0"–3.0" (4 – 6σ) centered on all X-ray source positions are chance alignments, with no real physical connection (see Figure 3-1). Dividing the total number of IR sources within the background annuli of the 49 X-ray source positions by the total area of these annuli, I find a background IR source surface density of 0.02 arcsecond$^{-2}$ near Chandra X-ray sources. Multiplying this surface density by the total area of all “strong” regions (1.0" radius circles) and “possible” regions (1.0"–1.5" annuli) around the 49 X-ray source positions, I estimated the level of source contamination contributing to my “strong” and “possible” IR counterpart candidates. I expect two with a 1σ uncertainty of +0.2/-0.1 of the 13 “strong” counterparts to be due to chance superpositions, and three with a 1σ uncertainty of +0.5/-0.3 of the six “possible” counterparts to be chance superpositions.

---

1 Found using confidence levels for small number statistics listed in Tables 1 and 2 of Gehrels (1986).
This result has several important implications. First of all, it is clear that I have a significant excess of IR counterparts within 1.0″ of the X-ray sources–13, where I expect only two in the null hypothesis of no physical counterparts. Even including the “possible” counterparts out to 1.5″, I have a total of 19 counterparts, where I expect only five from chance superposition. Secondly, this implies that for any given “strong” IR counterpart, I have a probability of ∼85% (11/13 with a 1σ uncertainty of 0.3¹) that the association with an X-ray source is real. Even for the “possible” counterparts, the probability of true association is ∼50%. These levels of certainty are a tremendous improvement over the X-ray/optical associations provided by Zezas et al. (2002b), and are strong motivators for follow-up multi-wavelength studies of the IR counterparts. Finally, I can also conclude from strong concentration of IR counterparts within ∼1″ of X-ray sources that the frame tie uncertainty estimates described above are reasonable.

Figure 3-3 is a 4.3′ × 4.3′ $K_s$ image of the Antennae with X-ray source positions overlaid. I designate those X-ray sources with counterparts using red circles. Notice that those sources with counterparts lie in the spiral arms and bridge region of the Antennae. Since these regions are abundant in star formation, this seems to indicate many of the X-ray sources in the Antennae are tied to star formation in these galaxies.

3.2.2 Photometric Properties of the IR Counterparts

3.2.2.1 Color magnitude diagrams

Using the 219 clusters that had both $J$ and $K_s$ photometry, I made $(J - K_s)$ versus $K_s$ color magnitude diagrams (Figure 3-4). I estimated a sensitivity limit by first finding all clusters with signal-to-noise ∼ 5σ. The mean $J$ and $K_s$ magnitudes for these clusters were computed separately and defined as cutoff values for statistical analyzes. This yielded 19.0 mag in $J$ and 19.4 mag in $K_s$. I note that the X-ray clusters are generally bright in the IR compared to the general population of clusters. While the IR counterpart for one X-ray source (X-32) falls below my $J$-band sensitivity limit, its $K_s$ magnitude is still above the $K_s$ cutoff. Therefore, I retained this source in our analysis.
I then broke down the X-ray sources into three luminosity classes (Figure 3-4). I took the absorption-corrected X-ray luminosities, \( L_X \), as listed in Table 1 of Zezas et al. (2002a) for all sources of interest. These luminosities assumed a distance to the Antennae of 29 Mpc. I used 19.3 Mpc (for \( H_0 = 75 \) km s\(^{-1}\) Mpc\(^{-1}\)) instead and so divided these values by 2.25 as suggested in Zezas et al. (2002a). I defined the three X-ray luminosities as follows: Low Luminosity X-ray sources (LLXs) had \( L_X < 3 \times 10^{38} \) ergs s\(^{-1}\), High Luminosity X-ray sources (HLXs) were between \( L_X \) of \( 3 \times 10^{38} \) ergs s\(^{-1}\) and \( 1 \times 10^{39} \) ergs s\(^{-1}\), while \( L_X > 1 \times 10^{39} \) ergs s\(^{-1}\) were Ultra-Luminous X-ray Sources (ULXs). In Figure 3-4 I designate each IR counterpart according to the luminosity class of its corresponding X-ray source. There does not appear to be a noticeable trend in the IR cluster counterparts between these different groupings.

### 3.2.2.2 \( K_s \) luminosity

To further study the properties of these IR counterparts, I calculated \( M_{K_s} \) for all IR clusters. I calculated reddening using the observed colors, \((J - K_s)_{\text{obs}}\), (henceforth the “color method”). Assuming all clusters are dominated by O and B stars, their intrinsic \((J - K_s)\) colors are \( \sim 0.2 \) mag. Approximating this value as 0 mag, this allowed me to estimate \( A_{K_s} \) as \( \simeq (J - K_s)_{\text{obs}}/1.33 \) using the extinction law defined in Cardelli et al. (1989, hereafter CCM). Since these derived reddenings are biased towards young clusters, older clusters will have abnormally high \( K_s \) luminosities.

For IR counterparts to X-ray sources, I also computed X-ray-estimated \( A_{K_s} \) using the column densities, \( N_H \), listed in Table 5 of Zezas et al. (2002a). Here, \( N_H \) is derived by fitting both a Power Law (PL) and Raymond-Smith (RS Raymond and Smith, 1977) model to the X-ray spectra. Using the CCM law, \( A_{K_s} \) is defined as \( 0.12 A_V \). Taking \( A_V = 5 \times 10^{-22} \) mag cm\(^2\) \( N_H \), I could then derive \( A_{K_s} \).

Then I compared \( A_{K_s} \) calculated using the “color method” to \( A_{K_s} \) found using the above two \( N_H \) models. I found the “color method” matched closest to \( N_H(PL) \) for all
except one (the cluster associated with Chandra source 32 as designated in Zezas et al. (2002b)).

In Figure 3-5, I plot histograms of the distribution of $K_s$-band luminosity, $M_{K_s}$. Figure 3-5 displays all clusters as well as over plotting only those with X-ray counterparts. Notice that the clusters with associated X-ray sources look more luminous. To study whether this apparent trend in luminosity is real, I compared these two distributions using a two-sided Kolmogorov-Smirnov (K-S) test. In my analysis, for statistical purposes, I only included clusters below $M_{K_s} < -13.2$ mag. Restricting my study to sources with “good” photometry, I first defined a limit in $K_s$, 18.2 mag, using the limiting $J$ magnitude, 19.0 mag as stated above, and, since the limit in $K_s$ is a function of cluster color, the median $(J - K_s)$ of 0.8 mag. Subtracting the distance modulus to the Antennae, 31.4 mag, from this $K_s$ limit, I computed our cutoff in $M_{K_s}$. Since all clusters with X-ray sources fall below this cutoff, our subsample is sufficient to perform a statistical comparison.

The KS test yielded a D-statistic of 0.37 with a probability of $3.2 \times 10^{-2}$ that the two distributions of clusters with and without associated X-ray sources are related. Considering the separate cluster populations as two probability distributions, each can be expressed as a cumulative distribution. The D-statistic is then the absolute value of the maximum difference between each cumulative distribution. This test indicates that those clusters with X-ray counterparts are more luminous than most clusters in the Antennae.

### 3.2.2.3 Cluster mass estimates

Whitmore et al. (1999) found 70% of the bright clusters observed with the Hubble Space Telescope have ages <20 Myr. Therefore, in this study I will assume all clusters are typically the same age, ~20 Myr. This allows me to make the simplifying assumption that cluster mass is proportional to luminosity and ask: Does the cluster mass affect the propensity for a given progenitor star to produce an X-ray binary? I estimated cluster mass using $K_s$ luminosity ($M_{K_s}$). Since cluster mass increases linearly with flux (for
an assumed constant age of all clusters), I converted $M_{K_s}$ to flux. Using these data as binned in the $M_{K_s}$ histogram (Figure 3-5), I calculated an average flux per bin. By computing the fraction of clusters per average flux, I am in essence asking what is the probability of finding a cluster with a specific mass. Since those clusters with X-ray sources are more luminous, I expect a higher probability of finding an X-ray source in a more massive cluster. As seen in Figure 3-6, this trend does seem to be true. Applying a KS-test between the distributions for all clusters and those associated with X-ray sources for clusters below the $M_{K_s}$ completeness limit defined in the previous section, I find a D-statistic of 0.66 and a probability of $7.2 \times 10^{-3}$ that they are the same. Hence, the two distributions are distinct, indicating it is statistically significant that more massive clusters tend to contain X-ray sources.

While I assume all clusters are $\sim$20 Myr above, I note that the actual range in ages is $\sim$1–100 Myr (Whitmore et al., 1999). Bruzual-Charlot spectral photometric models (Bruzual and Charlot, 2003) indicate that clusters in this age range could vary by a factor of roughly 100 in mass for a given $K_s$ luminosity. Thus, I emphasize that the analysis above should be taken as suggestive rather than conclusive evidence, and note that in Chapter 4 (see also Clark et al., 2007b) I explore this line of investigation and the impacts of age variations on the result in depth.

### 3.2.2.4 Non-detections of IR counterparts to X-ray sources

To assess whether my counterpart detections were dependent on reddening or their intrinsic brightness, I found limiting values for $M_{K_s}$ for those X-ray sources without detected IR counterparts. I achieved this by setting all clusters $K_s$ magnitudes equal to my completeness limit defined for the CMDs (19.4 mag; see §3.2.2.1) and then finding $M_{K_s(lim)}$ for each using $A_{K_s}$ calculated for that cluster. Since $M_{K_s(lim)}$ is theoretical and only depends on reddening, I could now find this limit for all X-ray sources using an $A_{K_s}$ estimated from the observed $N_H$ values. Thus I considered all IR counterparts (detections) and those X-ray sources without a counterpart (nondetections). If nondetections are
due to reddening there should not exist a difference in $M_{K_s(lim)}$ between detections and nondetections. In contrast, if nondetections are intrinsically fainter, I expect a higher $M_{K_s(lim)}$ for these sources. In the case of detections, I considered reddening from both the “color method” and the $N_H(PL)$ separately. I could only derive nondetections using $N_H(PL)$ reddening. Figure 3-7 shows $M_{K_s(lim)}$ appears higher for all nondetections. To test if this observation is significant, I applied a KS-test to investigate whether detections and nondetections are separate distributions. I found a D-statistic of 0.82 and probability of $8.8 \times 10^{-6}$ that these two distributions are the same using the “color method” for detections. Considering the $N_H(PL)$ reddening method for detections instead, the D-statistic drops to 0.48 and the probability increases to $3.9 \times 10^{-2}$. Since both tests indicate these distributions are distinct, the observed high $M_{K_s(lim)}$ for nondetections seems to be real. This leads to the conclusion that these sources were undetected because they are intrinsically IR-faint, and that reddening does not play the dominant role in nondetections.

I summarize these statistics in Table 3-4. Here I calculated the mean $K_s$, $(J - K_s)$, and $M_{K_s}$ for three different categories: 1) all clusters, 2) clusters only connected with X-ray sources, and 3) these clusters broken down by luminosity class. I also include uncertainties in each quantity. Notice that the IR counterparts appear brighter in $K_s$ and intrinsically more luminous than most clusters in the Antennae, although there is no significant trend in color. I also summarize the above K-S test results in Table 3-5.

### 3.3 Conclusions

I have demonstrated a successful method for finding counterparts to X-ray sources in the Antennae using IR wavelengths. I mapped Chandra X-ray coordinates to WIRC pixel positions with a positional uncertainty of $\sim 0.5\arcmin$. Using this precise frame tie I found 13 “strong” matches ($< 1.0''$ separation) and 5 “possible” matches ($1.0'' - 1.5''$ separation) between X-ray sources and IR counterparts. After performing a spatial and photometric analysis of these counterparts, I reached the following conclusions:
1. I expect only 2 of the 13 “strong” IR counterparts to be chance superpositions. Including all 19 IR counterparts, I estimated 5 are unrelated associations. Clearly, a large majority of the X-ray/IR associations are real.

2. The IR counterparts tend to reside in the spiral arms and bridge region between these interacting galaxies. Since these regions contain the heaviest amounts of star formation, it seems evident that many of the X-ray sources are closely tied to star formation in this pair of galaxies.

3. A $K_s$ vs. $(J - K_s)$ CMD reveal those clusters associated with X-ray sources are brighter in $K_s$ but there does not seem to be a trend in color. Separating clusters by the X-ray luminosity classes of their X-ray counterpart does not reveal any significant trends.

4. Using reddening derived $(J - K_s)$ colors as well as from X-ray-derived $N_H$, I found $K_s$-band luminosity for all clusters. A comparison reveals those clusters associated with X-ray sources are more luminous than most clusters in the Antennae. A KS-test indicates a significant difference between X-ray counterpart clusters and the general population of clusters.

5. By relating flux to cluster luminosity, simplistically assuming a constant age for all clusters, I estimated cluster mass. Computing the fraction of clusters per average flux, I estimated the probability of finding a cluster with a specific mass. I find more massive clusters are more likely to contain X-ray sources, even after I normalize by mass.

6. I computed a theoretical, limiting $M_{K_s}$ for all counterparts to X-ray sources in the Antennae using X-ray-derived reddenings. Comparing detections to non-detections, I found those clusters with X-ray source are intrinsically more luminous in the IR.

In the next chapter in which I explore the effects of cluster mass on XRB formation rate (Clark et al., 2007a), I will investigate the effects of age on cluster luminosity and hence our cluster mass estimates.
Table 3-1: Common Sources Used for the 2MASS/WIRC Astrometric Frame Tie

<table>
<thead>
<tr>
<th>Description</th>
<th>RA (2MASS)</th>
<th>Dec (2MASS)</th>
<th>$J$ $^a$</th>
<th>$K_s$ $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bright Star</td>
<td>12:01:47.90</td>
<td>-18:51:15.8</td>
<td>13.07(0.01)</td>
<td>12.77(0.01)</td>
</tr>
<tr>
<td>Southern Nucleus</td>
<td>12:01:53.50</td>
<td>-18:53:10.0</td>
<td>13.45(0.05)</td>
<td>12.50(0.03)</td>
</tr>
<tr>
<td>Cluster 1</td>
<td>12 01 51.66</td>
<td>-18 51 34.7</td>
<td>14.84(0.01)</td>
<td>14.24(0.01)</td>
</tr>
<tr>
<td>Cluster 2</td>
<td>12 01 50.40</td>
<td>-18 52 12.2</td>
<td>14.98(0.02)</td>
<td>14.06(0.01)</td>
</tr>
<tr>
<td>Cluster 3</td>
<td>12 01 54.56</td>
<td>-18 53 04.0</td>
<td>15.05(0.03)</td>
<td>14.27(0.02)</td>
</tr>
<tr>
<td>Cluster 4</td>
<td>12 01 54.95</td>
<td>-18 53 05.8</td>
<td>16.52(0.01)</td>
<td>14.66(0.01)</td>
</tr>
</tbody>
</table>

$^a$ Units are magnitudes, from WIRC photometry. Values in parentheses indicate uncertainties.

Table 3-2: Common Sources Used for the Chandra/WIRC Astrometric Frame Tie

<table>
<thead>
<tr>
<th>Chandra Source ID $^a$</th>
<th>RA (Chandra)</th>
<th>Dec (Chandra)</th>
<th>$K_s$ $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>12 01 50.51</td>
<td>-18 52 04.80</td>
<td>15.66(0.02)</td>
</tr>
<tr>
<td>10</td>
<td>12 01 51.27</td>
<td>-18 51 46.60</td>
<td>14.66(0.01)</td>
</tr>
<tr>
<td>24</td>
<td>12 01 52.99</td>
<td>-18 52 03.20</td>
<td>13.55(0.11)</td>
</tr>
<tr>
<td>29</td>
<td>12 01 53.49</td>
<td>-18 53 11.10</td>
<td>12.50(0.03)</td>
</tr>
<tr>
<td>34</td>
<td>12 01 54.55</td>
<td>-18 53 03.20</td>
<td>14.27(0.02)</td>
</tr>
<tr>
<td>36</td>
<td>12 01 54.81</td>
<td>-18 52 14.00</td>
<td>15.92(0.01)</td>
</tr>
<tr>
<td>37</td>
<td>12 01 54.98</td>
<td>-18 53 15.10</td>
<td>16.16(0.01)</td>
</tr>
</tbody>
</table>

$^a$ ID numbers follow the naming convention of Zezas et al. (2002a).

$^b$ Units are magnitudes, from WIRC photometry. Values in parentheses indicate uncertainties.
Table 3-3: Potential IR Counterparts to Chandra X-Ray Sources

<table>
<thead>
<tr>
<th>Chandra Src ID</th>
<th>RA</th>
<th>Dec</th>
<th>$\Delta \alpha$</th>
<th>$\Delta \delta$</th>
<th>J</th>
<th>$K_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(arcsec)</td>
<td>(arcsec)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;Strong&quot; Counterparts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.............</td>
<td>12:01:50.51</td>
<td>-18:52:04.77</td>
<td>0.29</td>
<td>0.04</td>
<td>16.21(0.01)</td>
<td>15.66(0.02)</td>
</tr>
<tr>
<td>10............</td>
<td>12:01:51.27</td>
<td>-18:51:46.58</td>
<td>0.24</td>
<td>0.31</td>
<td>15.57(0.01)</td>
<td>14.66(0.01)</td>
</tr>
<tr>
<td>11............</td>
<td>12:01:51.32</td>
<td>-18:52:25.46</td>
<td>0.34</td>
<td>0.03</td>
<td>18.27(0.01)</td>
<td>17.37(0.08)</td>
</tr>
<tr>
<td>20............</td>
<td>12:01:52.74</td>
<td>-18:51:30.06</td>
<td>0.11</td>
<td>0.38</td>
<td>18.48(0.04)</td>
<td>17.78(0.02)</td>
</tr>
<tr>
<td>24............</td>
<td>12:01:52.99</td>
<td>-18:52:03.18</td>
<td>0.07</td>
<td>0.82</td>
<td>14.37(0.11)</td>
<td>13.55(0.11)</td>
</tr>
<tr>
<td>26............</td>
<td>12:01:53.13</td>
<td>-18:52:05.53</td>
<td>0.27</td>
<td>0.87</td>
<td>15.95(0.01)</td>
<td>14.71(0.15)</td>
</tr>
<tr>
<td>29............</td>
<td>12:01:53.49</td>
<td>-18:53:11.08</td>
<td>0.20</td>
<td>0.25</td>
<td>13.45(0.05)</td>
<td>12.50(0.03)</td>
</tr>
<tr>
<td>33............</td>
<td>12:01:54.50</td>
<td>-18:53:06.82</td>
<td>0.11</td>
<td>0.99</td>
<td>16.71(0.08)</td>
<td>16.45(0.07)</td>
</tr>
<tr>
<td>34............</td>
<td>12:01:54.55</td>
<td>-18:53:03.23</td>
<td>0.02</td>
<td>0.39</td>
<td>15.05(0.03)</td>
<td>14.27(0.02)</td>
</tr>
<tr>
<td>36............</td>
<td>12:01:54.81</td>
<td>-18:53:13.99</td>
<td>0.11</td>
<td>0.50</td>
<td>16.60(0.03)</td>
<td>15.92(0.01)</td>
</tr>
<tr>
<td>37............</td>
<td>12:01:54.98</td>
<td>-18:53:15.07</td>
<td>0.13</td>
<td>0.10</td>
<td>17.55(0.02)</td>
<td>16.16(0.01)</td>
</tr>
<tr>
<td>39............</td>
<td>12:01:55.18</td>
<td>-18:52:47.50</td>
<td>0.18</td>
<td>0.03</td>
<td>17.10(0.07)</td>
<td>15.71(0.04)</td>
</tr>
<tr>
<td>42............</td>
<td>12:01:55.65</td>
<td>-18:52:15.06</td>
<td>0.73</td>
<td>0.40</td>
<td>17.13(0.03)</td>
<td>16.27(0.06)</td>
</tr>
<tr>
<td>&quot;Possible&quot; Counterparts</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>15.............</td>
<td>12:01:51.98</td>
<td>-18:52:26.47</td>
<td>1.09</td>
<td>0.84</td>
<td>16.63(0.04)</td>
<td>15.95(0.02)</td>
</tr>
<tr>
<td>22............</td>
<td>12:01:52.89</td>
<td>-18:52:10.03</td>
<td>0.70</td>
<td>1.20</td>
<td>15.77(0.01)</td>
<td>15.13(0.06)</td>
</tr>
<tr>
<td>25............</td>
<td>12:01:53.00</td>
<td>-18:52:09.59</td>
<td>0.87</td>
<td>0.76</td>
<td>15.77(0.01)</td>
<td>15.13(0.06)</td>
</tr>
<tr>
<td>32............</td>
<td>12:01:54.35</td>
<td>-18:52:10.31</td>
<td>0.92</td>
<td>1.39</td>
<td>20.30(0.45)</td>
<td>16.84(0.03)</td>
</tr>
<tr>
<td>35............</td>
<td>12:01:54.77</td>
<td>-18:52:52.43</td>
<td>0.42</td>
<td>0.92</td>
<td>16.76(0.02)</td>
<td>14.88(0.04)</td>
</tr>
<tr>
<td>40............</td>
<td>12:01:55.38</td>
<td>-18:52:50.53</td>
<td>0.61</td>
<td>1.24</td>
<td>16.21(0.02)</td>
<td>15.27(0.04)</td>
</tr>
</tbody>
</table>

a ID numbers follow the naming convention of Zezas et al. (2002a)

b Chandra coordinates with an uncertainty of 0.5″ (Zezas et al., 2002a)

c Positional offsets in units of seconds of arc from the Chandra coordinates to the WIRC coordinates of the proposed counterpart

d Units are magnitudes, from WIRC photometry. Values in parentheses indicate uncertainties in the final listed digit.
Table 3-4: Summary of Potential IR Counterpart Properties.

<table>
<thead>
<tr>
<th>Category</th>
<th>$\bar{K}$</th>
<th>$\sigma_K$</th>
<th>$(J - K)$</th>
<th>$\sigma_{(J-K)}$</th>
<th>$\bar{M_K}$</th>
<th>$\sigma_{M_K}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>all clusters</td>
<td>16.72</td>
<td>0.08</td>
<td>0.82</td>
<td>0.03</td>
<td>-15.33</td>
<td>0.09</td>
</tr>
<tr>
<td>X-ray sources</td>
<td>15.72</td>
<td>0.27</td>
<td>0.95</td>
<td>0.11</td>
<td>-16.30</td>
<td>0.35</td>
</tr>
<tr>
<td>LLX</td>
<td>15.85</td>
<td>0.36</td>
<td>0.84</td>
<td>0.11</td>
<td>-16.16</td>
<td>0.39</td>
</tr>
<tr>
<td>HLX</td>
<td>15.09</td>
<td>0.37</td>
<td>1.13</td>
<td>0.28</td>
<td>-17.14</td>
<td>0.54</td>
</tr>
<tr>
<td>ULX</td>
<td>16.82</td>
<td>0.55</td>
<td>0.88</td>
<td>0.02</td>
<td>-14.67</td>
<td>0.51</td>
</tr>
</tbody>
</table>

$^a$ Uncertainties in each value.
Table 3-5: Summary of KS-Test Results.

<table>
<thead>
<tr>
<th></th>
<th>Probability $^a$</th>
<th>D $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{K_s}$</td>
<td>3.2 $\times$ 10^{-2}</td>
<td>0.37</td>
</tr>
<tr>
<td>Cluster Mass</td>
<td>9.6 $\times$ 10^{-2}</td>
<td>0.40</td>
</tr>
<tr>
<td>$M_{K_s,\text{lim}}$ (CM) $^c$</td>
<td>8.8 $\times$ 10^{-6}</td>
<td>0.82</td>
</tr>
<tr>
<td>$M_{K_s,\text{lim}}$ (NH) $^c$</td>
<td>3.9 $\times$ 10^{-2}</td>
<td>0.48</td>
</tr>
</tbody>
</table>

$^a$ Probability distributions are the same.

$^b$ Kolmogorov-Smirnov D-statistic.

$^c$ CM: “color method” for detections, NH: $N_H$(PL) method for detections. See text for details.
Figure 3-1. IR counterpart to X-36 overlaid with areas of positional uncertainty centered on the X-ray source position. Black: 1.0″ radius circle for strong sources, red: 1.0″–1.5″ annulus for possible sources, and blue: 2.0″–3.0″ annulus used to estimate background source contamination.
Figure 3-2. Subimages highlighting X-ray positions for all X-rays sources with IR counterparts. Positional error circles are 1.0′′ in radius. Image field-of-view is 10.0′′×10.0′′ and north is up. I label “strong” matches in black and “possible” matches in red.
Figure 3-3. $K_s$-band image of the Antennae showing positions of X-ray sources. The field-of-view is 4.3′×4.3′. Red circles designate those sources with IR counterparts. Notice these tend to reside in the spiral arms and bridge region between the galaxies.
Figure 3-4. (upper left) $(J - K_s)$ vs. $K_s$ CMD for all clusters with photometry. In each of the three plots, the dashed line shows my cutoff for statistical analyzes. (upper right) Here clusters with X-ray counterparts are designated. Note that one IR counterpart falls below my sensitivity limit. Since its $K_s$ magnitude is still above the $K_s$ cutoff, I retained this source in my analysis. (lower right) These clusters are broken down by their luminosity class. LLX: $L_X < 3 \times 10^{38}$ ergs s$^{-1}$, HLX: $3 \times 10^{38}$ ergs s$^{-1} < L_X < 1 \times 10^{39}$ ergs s$^{-1}$, and ULX: $L_X > 1 \times 10^{39}$ ergs s$^{-1}$. 
Figure 3-5. $M_K$ histogram for all clusters. Binned by 0.2 magnitudes. Dashed line shows cutoff for statistical analyzes.
This figure is the same as Figure 3-5, except that I have plotted $M_{K_s}$ versus the number of clusters per bin divided by the mean flux in that bin. Arguing that mass is proportional to flux, this graph shows the probability of finding a cluster with a given mass.
Figure 3-7. Theoretical, $M_{K(\text{lim})}$ histograms for all X-ray sources with counterparts, detections, and those without, nondetections, using bins of 0.2 magnitudes. For detections, reddening computed using $N_H(PL)$ (top) and “color method” (bottom).
CHAPTER 4
A FIRST ESTIMATE OF THE X-RAY BINARY FRACTION AS A FUNCTION OF
STAR CLUSTER MASS IN A SINGLE GALACTIC SYSTEM

In Chapter 3 I performed an extensive study of the XRB environments in the Antennae galaxies using Chandra X-ray images and J and $K_s$ IR images (Brandl et al., 2005, henceforth Paper I). In this chapter I will expand on this study by exploring the relationship between XRBs and cluster mass in the Antennae (see also Clark et al., 2007a).

Recent theoretical models of young, massive cluster evolution provide a framework for comparison to my observational study. Two in particular, (Oskinova, 2005; Sepinsky et al., 2005), incorporate XRB formation in their models. Oskinova (2005) use a population synthesis code to study the evolution of X-ray emission in young, massive clusters. Sepinsky et al. (2005) investigate the role of supernova kicks in XRB expulsion from the parent cluster using the population synthesis code, StarTrack. They also incorporate the XRB formation rate for a range in cluster mass. I will compare my observations of the XRB formation rate in the Antennae to those predicted by these models.

I begin this chapter by defining a quantity, $\eta$, relating the XRB fraction to cluster mass in the Antennae (§4.1). In my analysis, I estimate cluster mass using $K_s$ luminosity, which depends non-trivially on the assumed cluster age. I explore cluster age/luminosity relations and their impact on my mass estimates in §4.2. I then compare $\eta$ to the measured value predicted by theoretical cluster evolutionary models and present conclusions in §4.3.

4.1 XRB-to-Cluster Mass Fraction

In Chapter 3 I used $K_s$ luminosity to estimate cluster mass, which assumes that all clusters are the same age. I then demonstrated that XRBs are more common in more massive clusters in the Antennae (see §3.2.2.3 and Figure 3-6).

This result is not surprising as star cluster mass increases, so does the number of massive stars in it. Through stellar evolution, a certain fraction of these stars will die
in supernova explosions, leaving behind neutron star or black hole remnants. In turn, a fraction of these stellar remnants will retain/acquire a mass-donating companion star, becoming a detectable XRB. Thus, through sheer numbers of stars in more massive clusters, I expect a greater likelihood of finding XRBs in them. This leads me to two interesting questions: 1) quantitatively, what range in cluster masses tend to harbor XRBs and 2) is there some intrinsic property of massive cluster physics that favors the production of XRBs, beyond simple scaling with mass?

For the first time, I am able to answer these questions for the Antennae galaxies. Never before has there existed a large enough sample of IR-to-X-ray associations to allow meaningful statistics. In my approach to answer these questions I explore the relationship between the number of X-ray detections per unit mass as a function of cluster mass in the Antennae. I can formalize this expression in the following equation:

\[ N_X(M_c) = N_{Cl}(M_c) \cdot \eta(M_c) \cdot M_c \]

Here, \(N_X(M_c)\) is the number of detected X-ray sources with an IR cluster counterpart, \(N_{Cl}(M_c)\) is the number of detected clusters, and \(\eta(M_c)\) is the fraction of X-ray sources per unit mass, all as a function of cluster mass, \(M_c\).

If \(\eta(M_c)\) increases or decreases over a range in \(M_c\), this means there could be something peculiar about massive cluster physics to favor or suppress XRB formation. In contrast, a constant \(\eta(M_c)\) across all \(M_c\) would indicate that more massive clusters are more likely to have an XRB simply because they have more stars.

While \(\eta(M_c)\) is a powerful tool in studying XRB formation rates, it requires that I know the mass of each star cluster. However, extrapolating the masses of the Antennae clusters from my photometric data required models that called for estimates of ages and metallicities. While I successfully constrained these inputs and determined cluster masses (see below and §4.2), I first sought to compute \(\eta(M_c)\) in terms of a purely observable
quantity–flux. Calculating $\eta(M_c)$ as a function of $K_s$-band flux, $\eta(F_{K_s})$, allowed me to investigate non-model dependent trends in $\eta(M_c)$.

I calculated $\eta(F_{K_s})$ for clusters with a $K_s$-band luminosity brighter than the -13.2 mag cutoff using bin sizes of $F_{K_s} = 4 \times 10^6$ (Figure 4-1). This bin size was small enough to show a trend in $\eta(F_{K_s})$, but large enough to contain at least two clusters with X-ray sources, allowing me to assign error bars to each value of $\eta(F_{K_s})$. The errors plotted on the graph are uncertainties in the mean value of $\eta(F_{K_s})$ added in quadrature with the Poisson uncertainty in each bin. Due to the small sample size per bin, I computed these uncertainties using the small number statistics formulae described in Keeping (1962).

Figure 4-1 shows that $\eta(F_{K_s})$ is roughly consistent with a constant value of $5.4 \times 10^{-8} F_{K_s}^{-1}$ with an uncertainty of $\sigma_\eta = 1.8 \times 10^{-8} F_{K_s}^{-1}$.

In essence, $\eta(F_{K_s})$ is comparing two different mass distributions, $N_{Cl}(F_{K_s})$, the mass distribution for all clusters in the Antennae and $N_X(F_{K_s})/F_{K_s}$, the mass distribution for clusters with X-ray sources, normalized by flux. If there is a constant number of X-ray sources per unit cluster mass as suggested by Figure 4-1, then these two mass distributions should be the same. We can further corroborate this result by comparing $N_X(F_{K_s})/F_{K_s}$ and $N_{Cl}(F_{K_s})$ using a two-sided Kolmogorov-Smirnov (KS) test. The KS-test yielded a D-statistic of 0.75 and a probability of 0.107 that they are related.

Considering the separate cluster mass populations as two probability distributions, each can be expressed as a cumulative distribution. The D-statistic is then the absolute value of the maximum difference between each cumulative distribution. This test quantitatively demonstrates that there is nothing peculiar about massive clusters in the Antennae with associated XRBs. I also computed the Pearson $r$ linear correlation coefficient between $N_X(F_{K_s})/F_{K_s}$ and $N_{Cl}(F_{K_s})$, finding a value of 0.99. Since a value of 1 means a perfect linear fit, this value of $r$ further substantiates the observed relationship in $\eta(F_{K_s})$.

I then converted $\eta(F_{K_s})$ into the more conventional units of solar mass. Selecting the mass-normalized $M_{K_s}$ listed in the Bruzual-Charlot (BC) cluster evolutionary
models (Bruzual and Charlot, 2003) for a 20 Myr cluster as a typical value in the Antennae (Whitmore et al., 1999), I converted the model $M_{K_s}$ to $F_{K_s}$ using the standard relationship between luminosity and flux. Multiplying $\eta(F_{K_s})$ by $F_{K_s}$ I converted $\eta(F_{K_s})$ to solar masses: assuming a cluster metallicity of $z = 0.02$, $\eta = 5.8 \times 10^{-8} M_\odot^{-1}$ with an uncertainty of $\sigma_\eta = 7.9 \times 10^{-9} M_\odot^{-1}$, while assuming a metallicity of $z = 0.05$, $\eta = 7.9 \times 10^{-8} M_\odot^{-1}$ with an uncertainty of $\sigma_\eta = 1.2 \times 10^{-8} M_\odot^{-1}$.

While I assumed all clusters are $\sim$20 Myr old, I note that the actual range in ages should be $\sim$1–100 Myr (Whitmore et al., 1999). The BC models indicate that clusters in this age range could vary by a factor of as much as 100 in mass for a given $K_s$ luminosity. Since $\eta$ is a function of mass, incorrectly assigning cluster ages has the potential to significantly impact $\eta$. In the next section, I explore how differences in cluster age can affect the value of $\eta$.

### 4.2 Effects of Age

I investigated the effect differences in cluster age has on $\eta$ by assuming three individual age distributions for the Antennae clusters: an instant burst in which all clusters are the same age, a uniform distribution, and a distribution of the form, $dN/d\tau \propto \tau^{-1}$ (Fall et al., 2005). In each case, I assumed all clusters have solar metallicity ($z = 0.02$) (Whitmore et al., 1999).

In the instant burst case, I assigned the same age to describe all clusters and picked several such values in the range 1–100 Myr. Applying the BC models, I produced several different cluster mass distributions. For each distribution I computed a mean $\eta$ (Figure 4-2). The mean for these values is $\eta_{\text{instant}} = 4.7 \times 10^{-8} M_\odot^{-1}$ with a standard deviation of $\sigma_{\text{instant}} = 1.8 \times 10^{-8} M_\odot^{-1}$. Comparing $\eta_{\text{instant}}$ to $\eta$ computed assuming constant cluster ages of 20 Myr ($\eta_{20}$) and 100 Myr ($\eta_{100}$) shows that both $\eta_{20}$ and $\eta_{100}$ fall within $\sim 1\sigma$ of $\eta_{\text{instant}}$ and that all three values of $\eta$ differ by less than a factor of two (Figure 4-5).

Next, I assumed a uniform age distribution for my Antennae cluster sample. Picking ages at random from a uniform distribution between 1–100 Myr, I assigned an age to
each cluster in my sample. Applying the BC models, I computed each cluster’s mass based on the assigned age, produced a mass distribution, and then calculated a mean $\eta$. Performing a Monte Carlo (MC) simulation, I recreated cluster mass distributions 10,000 times, producing a large sample of $\eta$’s with a mean of $\eta_{\text{uniform}} = 3.2 \times 10^{-8} \, M_{\odot}^{-1}$ and $\sigma_{\text{uniform}} = 7.4 \times 10^{-9} \, M_{\odot}^{-1}$ (Figure 4-3). While there is at least a 1σ difference between $\eta_{\text{uniform}}$ and $\eta_{20}$, a uniform age distribution is not the most applicable to the Antennae. As demonstrated by Fall et al. (2005), most of the clusters in this galaxy pair are young, with a median cluster age of $\sim 20$ Myr.

A more realistic approach is assuming the cluster ages are defined by a power law (PL): $dN/d\tau \propto \tau^{-1}$ (Fall et al., 2005). These authors derived their relationship using HST $UBVI\alpha$ observations of $\sim 11,000$ clusters. Fitting BC models to photometry of each cluster, they generated an age distribution. In my analysis I picked ages at random according to this distribution. Mirroring the procedure used for the uniform distribution case above, I created a sample of 10,000 $\eta$ values. I found a mean for this sample of $\eta_{PL} = 5.2 \times 10^{-8} \, M_{\odot}^{-1}$ and a $\sigma_{PL} = 9.5 \times 10^{-9} \, M_{\odot}^{-1}$. Interestingly, $\eta_{PL}$ falls well within 1σ of $\eta_{20}$ (Figure 4-3). This is not surprising considering most clusters are $\sim 20$ Myr old. Furthermore, it illustrates that by assuming an instant burst of 20 Myr, as I did initially, will not significantly affect my results, since $\eta_{20}$ and $\eta_{PL}$ vary by a factor of less than two.

In a final scenario, I used the cluster ages listed in the electronic table available through Mengel et al. (2005) to fit ages to 144 clusters in my sample, including all 15 clusters associated with X-ray sources. Mengel et al. (2005) derived ages by using three age indicators—$UBVI$ and $K_s$ broadband photometry to break the age/reddening degeneracy, $H\alpha$ and $Br\gamma$ emission to identify clusters less than 7 Myr, and CO band-head absorption from narrow-band images for clusters $\sim 10$ Myr. They then fit these data to theoretical spectra for ages $< 500$ Myr using a $\chi^2$ minimization technique (for details, see Mengel et al., 2005).
Following the method discussed in §4.1, I used the BC models to convert $M_{K_s}$ to mass for those clusters with Mengel et al. (2005) age estimates. Using cluster bins of $3 \times 10^6 M_\odot$ in mass, I computed three values for $\eta(M_\odot)$ (see Figure 4-4). The errors plotted on the graph are uncertainties in the mean value of $\eta(M_\odot)$ added in quadrature with the Poisson uncertainty in each bin. Again, I used the small number statistic formulae in Keeping (1962) to compute these errors. I found a mean in $\eta(M_\odot)$ of $5.8 \times 10^{-8} M_\odot^{-1}$ and $\sigma_\eta = 1.9 \times 10^{-8} M_\odot^{-1}$.

I summarize my age analysis in Figure 4-5. Comparing the distributions in $\eta$ for the instant burst, uniform and power law age distributions, all values for $\eta$ are within a factor of two. Even if I assume an instant burst of 10 Myr, $\eta$ differs by no more than a factor of four (see Figures 4-2 and 4-3). These relatively small variations indicate cluster age has little effect on $\eta$ and hence my results.

My observed lack of dependence between $\eta$ and an assumed cluster age distribution is not surprising considering the recent work in Fall (2006). These authors discussed how the cluster mass distribution in the Antennae is independent of the cluster age distribution. Since $\eta$ depends on this mass distribution, my small range in $\eta$ corroborates the results in Fall (2006).

### 4.3 Comparison with Models

Through the quantity $\eta$, my investigation showed that the XRB formation rate per unit mass is independent of cluster mass in the Antennae. I estimated cluster mass by fitting BC spectrophotometric models to cluster $M_{K_s}$, assuming all clusters are $\sim 20$ Myr. Recognizing that this method depends on cluster age, I explored how different assumptions for the Antennae cluster age distribution will affect $\eta$ and showed that $\eta$ varies by less than a factor of four. This small variation in $\eta$ demonstrated that this quantity does not strongly depend on the assumed age distribution of clusters in the Antennae.
I now proceed by comparing my observed value for $\eta = 6 \times 10^{-8} M_\odot^{-1}$ (z = 0.02) to that predicted by models of young, massive clusters. Specifically, I chose the theoretical work of Oskinova (2005) and Sepinsky et al. (2005).

In a recent study presented in Oskinova (2005), the author modeled X-ray emission from young, massive star clusters, assuming a closed system with constant mass, no dynamics and all stars are coeval, with cluster metallicities of either z = 0.02 or z = 0.008. These models predict $\sim 2\text{-}5\%$ of all OB stars in a cluster should produce high mass X-ray binaries (HMXBs). In the models in Oskinova (2005), all clusters are assumed to have masses of $M_{cl} = 10^6 M_\odot$ with stellar masses ranging from 1–100 $M_\odot$. Considering the Salpeter initial mass function (IMF) of the form $\xi(M) = M_0 M^{-2.35}$ and defining stars with masses $> 8 M_\odot$ as “OB stars”, for our purposes here, I estimated 6% of all stars in the model clusters are OB stars. Therefore, $1\text{-}3 \times 10^{-3}$ of all stars in a cluster with an initial mass of $3 \times 10^6 M_\odot$ (set by the Salpeter IMF) should produce an XRB. Since the Salpeter IMF implies there are $7 \times 10^5$ stars in a cluster, then these stars should produce $7\text{-}22 \times 10^3$ XRBs–orders of magnitude greater than the $\sim 49$ observed in the Antennae. In fact, only 15 of these sources are associated with clusters. Expressing $\eta$ as a fraction of XRBs-to-cluster mass, the models in Oskinova (2005) suggest $\eta$ ranges from $3\text{-}7 \times 10^{-4} M_\odot^{-1}$. These values are greater by at least a factor of 1000 from my estimates for $\eta$.

Clearly, this predicts a much larger formation rate of compact object binaries than what I observed in the Antennae. Oskinova (2005) note that they were unable to detect HMXBs in three massive ($\sim 10^4 M_\odot$) clusters which they predict should contain between 1-3 HMXBs. If my observed value for $\eta$ accurately describes the formation rate of HMXBs, then it is not surprising that Oskinova (2005) fail to find any. As pointed out by these authors, future modeling of HMXB formation is needed to understand the discrepancy between the predictions and observations of XRB populations in starburst galaxies.

In another study, Sepinsky et al. (2005) use the binary evolution and population synthesis code, StarTrack (Belczynski et al., 2002), to investigate the rate of XRB
formation and ejection from young, massive clusters. This program tracks stellar parameters such as radius, luminosity, mass and core mass. The simulations are stopped at the formation of a compact object. The models include mass transfer in binaries and include transient XRBs. Sepinsky et al. (2005) consider cluster masses ranging from $5 \times 10^4 \, M_\odot$ to $5 \times 10^6 \, M_\odot$ and cluster ages from 1 to $\sim 20$ Myr and compute the average number of XRBs within 1–1000 pc of the cluster center.

Considering the typical cluster age in the Antennae is 20 Myr, Sepinsky et al. (2005) predict a $5 \times 10^4 \, M_\odot$ cluster should contain 0.13 XRBs, while 15 XRBs should reside in a $5 \times 10^6 \, M_\odot$ cluster. Here I assume that an XRB is associated with a cluster if it is within 100 pc. This separation is equivalent to $1.0''$ at the distance of the Antennae (for $H_0=75$ km s$^{-1}$ Mpc$^{-1}$), which is my criteria for an XRB-cluster association (Chapter 3). These model predictions for XRB detections assume a limiting X-ray luminosity of $L_X = 5 \times 10^{35}$ ergs s$^{-1}$, but the observed limiting luminosity in the Antennae is $2 \times 10^{37}$ ergs s$^{-1}$. Using the X-ray luminosity function (XLF) for the Antennae defined in Zezas and Fabbiano (2002), I scaled the XRB results of Sepinsky et al. (2005) to estimate what these models would predict for the observed number of XRBs in the Antennae clusters. Using a XLF power law slope of $\alpha = -0.45$ (Zezas and Fabbiano, 2002), the models predict 0.02 XRBs are observed in a $5 \times 10^4 \, M_\odot$ cluster, while 2.7 XRBs should be seen in a $5 \times 10^6 \, M_\odot$ cluster, at the luminosity limits of the X-ray observations. Expressing these model results as a fraction of XRBs-to-cluster mass, I can directly compare them to my observed value for $\eta$ in the Antennae. Doing so, Sepinsky et al. (2005) predict $\eta$ ranges from $4 \sim 5 \times 10^{-7} \, M_\odot^{-1}$, at least a factor of 10 higher than my predictions for $\eta$. As mentioned by Sepinsky et al. (2005), several caveats exist for their models including: 1) assumed binary fraction of unity which could lead to over estimates of the mean number of XRBs per cluster, 2) the stellar, power-law IMF can affect the XRB fraction per cluster, and 3) changes in the half-mass radius can strongly influence the median XRB distance from the cluster.
These factors could potentially explain the discrepancies between their models and my observations.

4.4 Summary and Conclusions

In this chapter I introduced the quantity, $\eta$, relating the fraction of X-ray sources per unit mass as a function of cluster mass. Applying this function to the Antennae, I revealed several important environmental implications for the X-ray sources in the Antennae. Specifically, $\eta$ predicts a far different relationship between XRB formation and cluster mass than that predicted by Oskinova (2005) and is broadly consistent with that predicted by Sepinsky et al. (2005). Clearly, future cluster modeling with particular emphasis on the relationship between the number of XRBs in a galaxy and the galactic cluster environment is essential to explain my current observations. In addition, I plan to extend my observational study to additional starburst galaxies. I can then address whether $\eta$ depends on an individual galaxy or is constant for all galactic environments.
Figure 4-1. This figure displays $\eta(F_{K_s})$ plotted versus $M_{K_s}$. The bins are $F_{K_s} = 4 \times 10^6$ in size and designated by the histogram. Error bars are the uncertainties in the mean value of $\eta$ added in quadrature with the Poisson uncertainty in each bin. The dotted line is the mean of the four $\eta(F_{K_s})$ values.
Figure 4-2. Assuming an instant burst of star formation in the Antennae, I plot the mean value of $\eta$ for a range in ages between 1 - 100 Myr. Notice the factor of $\sim 4$ range in $\eta$ as well as the degeneracy in $\eta$ in this age range. Error bars are uncertainties in $\eta$. 
Figure 4-3. Comparison between uniform and PL Monte Carlo simulations of $\eta$. The peaks of each distribution vary by a factor of $\sim 2$ in $\eta$, indicating $\eta$ does not significantly change when I assume different age distributions for the Antennae. I also plot the values of $\eta$ for instantaneous bursts at four different ages.
Figure 4-4. Here $\eta(M_\odot)$ is plotted versus cluster mass in units of $M_\odot$. In this case, I computed cluster mass using ages provided by Mengel et al. (2005) (see §4.2). The bins are $M_\odot = 3 \times 10^6 M_\odot$ in size and designated by the histogram. Error bars are the uncertainties in the mean value of $\eta$ added in quadrature with the Poisson uncertainty in each bin. The dotted line is the mean value of the three $\eta(M_\odot)$. 
Figure 4-5. Here I summarize how age affects $\eta$, assuming four different age distributions for the Antennae clusters: instant burst (a), uniform (b), power law (c) and derived ages by Mengel et al. (2005) (d). Each value is the mean $\eta$ and includes 1-\(\sigma\) error bars. See text for details. Also included is $\eta$ for an instant starburst of 20 Myr (e) and 100 Myr (f).
CHAPTER 5
MULTIWAVELENGTH STUDY OF CHANDRA X-RAY SOURCES IN THE ANTENNAE

The numerous X-ray point sources and young, massive star clusters in the Antennae makes this galaxy pair an ideal laboratory for studying the environments of X-ray binaries (XRBs). Chandra observations revealed 49 X-ray point sources ranging in luminosity from $10^{38} - 10^{40}$ ergs s$^{-1}$ (Zezas et al., 2002a). While most are XRBs with either a black hole or neutron star, those sources with $L_X > 10^{39}$ ergs s$^{-1}$ are more unusual objects classified as ultraluminous X-ray sources (ULXs). Some theories suggest these ULXs are intermediate mass black holes with masses from 10 – 1000 $M_\odot$ (e.g., Fabbiano, 1989; Zezas et al., 1999; Roberts and Warwick, 2000; Makishima et al., 2000), but there remains a considerable amount of controversy concerning their origins (e.g., King et al., 2001; Moon et al., 2003; Plewa, 1995).

Compact objects tend to be associated with massive star formation, which some theories suggest is predominant in young stellar clusters (Lada and Lada, 2003). In my previous chapters on the Antennae I found a close association between compact objects and clusters, identifying 15 possible IR counterparts to X-ray sources. Many of these counterparts reside in the spiral arms and “bridge” region of the Antennae – locations predominant in massive star formation. Those X-ray sources without counterparts could be compact objects that escaped their parent cluster or remained behind after their cluster evaporated. In Chapter 3, I suggest a third possibility, that some X-ray sources do have counterparts, but these are too faint to see in the IR images.

In this chapter, I extend my study to optical wavelengths using HST images of the Antennae. The higher sensitivity of HST will allow me to search for additional counterparts to X-ray sources. In addition, combining multi-band photometry in the optical and IR, I can use spectral evolutionary models to measure cluster properties. In §5.1 I discuss my IR observations and analysis of optical HST archival images. I describe
my photometric analysis of counterpart cluster properties in §5.2. I summarize my results in §5.3.

5.1 Observations and Data Analysis

5.1.1 Infrared and Optical Imaging

I base this study in part on IR $J$ (1.25 $\mu$m) and $K_s$ (2.15 $\mu$m) band images of the Antennae. My collaborators and I initially analyzed these images in Brandl et al. (2005) and report the details of their reduction in that work. In summary, I acquired 20-minute total exposures in each filter using the Wide-field InfraRed Camera (WIRC) on the Palomar 5-m telescope during the night of 22 March, 2002.

I supplemented the IR wavelengths with optical HST images (Whitmore et al., 1999) obtained from the HST archive. This data set consists of images in the following filters: F336W($U$), F439W($B$), F555W($V$), and F814W($I$). Those authors also included narrow band, F658N images centered on the redshifted H$\alpha$ line at the distance to the Antennae. I used the F658N filter to derive reddening and ages for some optical counterparts (see §3.2).

In my efforts to understand the environments of the Antennae X-ray sources, I extended my frame tie between the IR and X-ray discussed in Chapter 3 to optical, HST images. Tying Chandra X-ray coordinates directly to HST positions is nontrivial due to field crowding in the HST images. Instead, I used my excellent frame tie between the IR and X-ray as an intermediary. Initially, I identified 12 sources in common with the IR and optical. Again, using the mapping method described in Chapter 3, I matched IR pixel positions to HST right ascension and declination. Due to image rotation between the WF and PC cameras I made separate frame ties between the IR and each camera field. Image rotation also exists between filters, which forced me to make additional frame ties between the $I$-band image and each of the other four bands. In all cases, the rms positional uncertainty was less than 0.6”. Applying my IR-to-optical astrometric fits to
previously derived IR x/y pixel positions of X-ray sources, I found the HST positions for all Chandra X-ray sources.

Using the IR as an intermediary between the optical and X-ray frame tie has many advantages over direct optical/X-ray matches. First, the IR penetrates dust in similar ways to X-rays, facilitating the identification of counterparts to X-ray sources. Furthermore, while bright IR sources may be obscured in the optical, the converse is generally untrue—any bright HST source shows up prominently in the IR images, enabling an excellent optical/IR frame tie, and thus closing the astrometric loop at all wavelengths. Previous attempts to match X-ray and optical positions produced many possible counterparts, but with poor accuracy—as many as 75% of the matches are chance coincidences (Zezas et al., 2002a).

5.1.2 Identification of Optical Counterparts to Chandra Sources

As I did in Chapter 3, I defined circular areas of positional uncertainty centered on each X-ray source position. Specifically, an inner aperture with a radius of 1.0″ and two outer annuli, one from 1.0″–1.5″ and another from 2.0″–3.0″. Due to the highly crowded HST fields I often found multiple sources within the central aperture, forcing me to deviate from my criteria used in Chapter 3 to define counterpart candidates. I narrowed my selection criteria by defining “strong” matches as those X-ray sources with only one match to an optical source in the central aperture and only ~ 1 source in the outer annulus. “Possible” matches were those X-ray sources with matches to two optical sources within the central aperture and only ~ 2 sources in the outer annulus. Using these criteria, I identified 13 I-band counterparts to 10 X-ray sources, seven “strong” matches and three “possible” matches to six I-band counterparts. Five of these 10 X-ray sources did not have previously identified counterparts in the IR. Using the V-band HST image, I found an additional three counterparts to two X-ray sources, a “strong” match and a “possible” match to two V-band. Both of these X-ray sources did not have counterparts in the IR. I list all optical counterparts in Table 5-1. Comparing optical source positions, I
identified all of these counterparts across both the $V$ and $I$ bands. Of all 12 X-ray sources with optical counterparts, one is the southern nucleus and another is a background quasar (see Chapter 6 and Clark et al., 2005). Therefore, in my analysis of cluster properties, I only considered the optical cluster counterparts to the remaining 10 X-ray sources. In Figure 5-1 I display subimages of all X-ray sources with optical counterparts.

Using the technique developed in Chapter 3, I attempted to estimate the level of “contamination” of these samples due to chance superpositions of unrelated X-ray sources and optical clusters. First, I calculated an optical source density by counting the number of sources in the outer, $2.0''$–$3.0''$ annulus around each cluster counterpart candidate and divided this by the total area of these annuli. Multiplying this density by the total area of positional uncertainty around the “strong” and “possible” optical counterparts, I estimated the level of source contamination contributing to my sample of optical counterpart candidates. I expect five with a $1\sigma$ uncertainty of $+0.5/-0.3$ of the seven “strong” counterparts to be due to chance superpositions, and five with a $1\sigma$ uncertainty of $+0.6/-0.4$ of the six “possible” counterparts to be chance superpositions. Clearly these statistics indicate the majority of my optical counterparts are chance superpositions and further demonstrates the difficulty of making such matches in the crowded, HST images of the Antennae.

I also increased my sample by considering the optical equivalents to the previously identified 15 IR cluster counterparts (Chapter 3). These additional optical matches were identified using the IR-to-optical astrometric frame tie to match IR counterpart positions to HST positions. While in many cases a single IR counterpart split into multiple optical counterparts, I labeled these conglomerations as a positive match. I found optical counterparts to all IR cluster counterparts, increasing my total number of X-rays

\footnote{1 Found using confidence levels for small number statistics listed in Tables 1 and 2 of Gehrels (1986)}
sources with counterparts to 22. Figure 5-2 displays subimages of those counterparts to X-ray sources seen across all six IR and optical bands. Figure 5-3 is an I-band image of the Antennae showing the positions of all counterpart candidates to X-ray sources.

5.1.3 Photometry

I performed aperture photometry on my X-ray cluster counterpart sample using two techniques. One method employed the same sized aperture across all wavelengths to estimate cluster colors, while a second method used apertures defined by the image point spread function (PSF) to find photometric magnitudes.

5.1.3.1 Constant aperture photometry

In this work, I fit spectral evolutionary models to cluster colors. Following the photometric procedure defined in Whitmore et al. (1999), I performed photometry on all optical counterpart clusters using constant apertures across all bands. This method gave me accurate measurements of cluster colors, since color indices are defined using magnitudes measured within same-sized apertures. (But, as Whitmore et al. (1999) points out, there may be an error of a few tenths of a magnitude in total magnitude.) For those counterparts only seen in the optical, I picked a central aperture with a radius of 4 pixels and a sky background annulus from 10–15 pixels. These are with respect to the WF chips. In terms of the PC chip, these radii translate to 3 and 7–10 pixels for the central aperture and background annulus, respectively.

In the case of those cluster counterparts seen across all six IR and optical bands, I defined a constant photometric aperture as \( \sim 3\sigma \) of the \( J \)-band Gaussian PSF, where the full width at half maximum (FWHM) is 1.2". The background annulus had a radius of \( \sim 6–10\sigma \) of the PSF. Considering \( HST \) resolved many of the IR sources into multiple components, this large photometric aperture encompassed these conglomerations. Since I expect that these sources are part of the same, larger structure with similar ages and metallicities, it is appropriate to include photometry of them in spectral evolutionary models.
5.1.3.2 PSF aperture photometry

As I discuss in §5.2.1, I estimated cluster mass assuming mass is proportional to cluster flux and only used the $V$ and $K_s$ bands. Therefore, I chose a more precise technique to derive cluster magnitudes, specifically defining photometric apertures as $\sim 3\sigma$ of the Gaussian PSF. I also used this method to measure $I$ magnitudes for optical counterparts listed in Table 5-1. The FWHM in these bands are 0.18″ in $V$, 0.21″ in $I$, and 0.9″ in $K_s$. Thus, the aperture radii are 2.5 pixels in $V$ and 2.6 pixels in $I$ for WFC, and 5 pixels in $K_s$ for WIRC. I did not find cluster counterparts on the PC chip field and did not consider photometric parameters for this field.

I compensated for the crowded field in the Antennae by measuring sky background in two separate annuli, from $\sim 6$–10$\sigma$ of the Gaussian PSF. In addition, I divided the annuli into arcs for exceptionally crowded regions. Multiplying the mean and median sky background in each annulus by the area of the central aperture and then subtracting this from the central aperture flux yielded four separate flux measurements for the source. I then averaged these four values to give me the source flux. When computing errors, I considered variations in the sky background, $\sigma_{sky}$, and Poisson noise, $\sigma_{adu}$. To calculate $\sigma_{sky}$ I found the standard deviation of the four flux values for each source. Dividing the mean source flux by the instruments gain and then taking the square root of these, we found $\sigma_{adu}$. The known gain for WIRC is 2 $e^-$ DN (Wilson et al., 2003)$^2$, while Whitmore et al. (1999) used a gain of 7 $e^-$ DN for $HST$. Both $\sigma_{sky}$ and $\sigma_{adu}$ were added in quadrature to yield a total error in flux, $\sigma_{flux}$.

I used a bright, 2MASS star to establish the $K_s$ magnitude zeropoint. I derived $HST$ F555W and F814W magnitudes using zero points listed in Table 28.1 of the $HST$ Data Handbook (Voit, 1997). Applying color transformations defined in Holtzman et al.

$^2$ At the time of the Antennae observations, WIRC was equipped with a Hawaii-1 1K×1K detector and this is the gain for it.
1995), I converted F555W and F814W magnitudes to Johnson V and I magnitudes, respectively. I expressed errors in magnitude, $\sigma_m$, as $\sigma_{\text{flux}}$ divided by the mean flux. In the case of the optical filters, $\sigma_m$ consists of the additional errors in the zeropoint and color transformations, all of which were added in quadrature.

5.2 Results and Discussion

5.2.1 Spectral Evolutionary Models

After performing photometry on all X-ray source counterparts, I threw out nine that had bad photometry. I defined “bad photometry” as those sources with negative fluxes in any of the six bands ($UBVIJ$ and $K_s$). In many cases this occurred due to poor sky subtraction in exceptionally crowded regions of the Antennae. Furthermore, some faint optical counterparts were only seen in the $V$ and $I$ bands and thus was not able to get photometry across all four optical bands for them. Thus I continued further analysis on 16 counterparts to X-ray sources. These 16 clusters consist of nine sources seen in all six filters, four with only $UBVI$ photometry and three containing solely $V$ and $I$ magnitudes (see Table 5-2). I fit Bruzual-Charlot (BC; Bruzual and Charlot, 2003) spectral evolution models to the cluster magnitudes available for each source to determine mass, age and metallicity. These parameters gave me a more complete understanding of XRB environments in the Antennae. While it is uncertain which strictly optical counterparts are associated with an X-ray source, I proceeded separately with analysis of them as well and interpreted their derived properties as suggestive of the nearby X-ray source’s environment.

As discussed in §5.1.2, those clusters identified as strictly optical counterparts are not necessarily believable as accurate matches to X-ray sources. Therefore, I urge caution in interpreting the model results for these counterpart candidates.

Before performing the model fits, I de-reddened all magnitudes using $A_V$ derived from X-ray measured column densities, $N_H$ (Zezas et al., 2002a, Table 5). Zezas et al. (2002a) fit two separate models to their X-ray spectra to compute $N_H$; a Raymond-Smith
(RS; Raymond and Smith, 1977) model and a power law (PL) model. I chose to compute reddening using $N_H(PL)$ because this provided a closer match to reddening calculated using $(J - K_s)$ cluster colors (see Chapter 3). Applying the following equation, $A_V = 5 \times 10^{-22} \text{ mag cm}^2 N_H$, I found $A_V$. Inserting $A_V$ in the reddening law defined in Cardelli et al. (1989, hereafter CCM), I found the reddening in all six bands.

I estimated the error in reddening, $\sigma_A$, by also computing reddening in each filter using the extinction law defined in Rieke and Lebofsky (1985). Comparing these values to the reddening computed using the CCM law, I defined the difference in reddening as $\sigma_A$. Adding $\sigma_A$ and $\sigma_m$ in quadrature, I computed a total error in de-reddened magnitude, $\sigma_M$.

Plotting the cluster de-reddened magnitudes, I produced a pseudo spectral energy distribution (SED). Iteratively shifting the BC model SEDs, I found a best fit to the cluster SEDs by minimizing $\chi^2$ (see Figure 5-4). I also introduced reddening in the cluster SEDs. By iteratively picking values for $A_V$ in the range 0.0–3.0 mag and in steps of 0.1 mag, I selected the $A_V$ that contributed to my best model fit. I defined goods fits as those models within one of the best fit $\chi^2$ sum ($\Sigma \chi^2 + 1$). The resulting fits gave me a range in metallicity, age, and reddening for each cluster. Each fit is listed in Table 5-2.

The shift in magnitude between model and data ($\Delta$) gave me a mass estimate for each IR/optical counterpart. $\Delta$ contains information on the distance modulus and mass of the cluster. Subtracting off the known distance modulus to the Antennae, $m_d = 31.4$ mag, I was left with a difference in luminosity between my cluster and a 1 $M_\odot$ cluster as listed by the BC models. Converting this difference into a change in flux gave me the cluster mass in solar masses. Before computing this change in flux, I renormalized the luminosity difference, expressing it in terms of magnitudes instead of colors. For fits only to the optical bands, I renormalized the luminosity difference to $M_V$, while I used $M_{K_s}$ for fits across all bands.
5.2.2 Estimating $A_V$ From H$\alpha$ Equivalent Widths

Three X-ray sources, X-17, X-27 and X-48, only had optical cluster counterparts and did not have X-ray-measured $N_H$. Therefore, I could neither use $(J - K_s)$ nor $N_H$ to find cluster $A_V$. Since my fitting technique to the BC models requires knowledge of $A_V$, I needed a separate method to find the properties of these three cluster counterparts.

I chose to adapt a method outlined in Whitmore and Zhang (2002) to analyze this trio of clusters. As these authors point out, there exists a degeneracy between reddening and age for clusters with $A_V > 1$ mag; the reddening vector can intersect the BC evolutionary track in multiple locations. I was able to break this degeneracy by using H$\alpha$ equivalent widths (EWs) to estimate cluster age.

Before measuring the H$\alpha$ EWs from the narrow band F658N HST image, I estimated the continuum level in our three sources using scaled $I$ fluxes. I converted the resulting continuum-subtracted H$\alpha$ flux to units of energy using the following relation: $4.2 \times 10^{15}$ ergs s$^{-1} = 1$ DN s$^{-1}$.

Applying the PHOTFLAM keywords listed in Table 28.1 of the HST Data Handbook (Voit, 1997), I computed H$\alpha$ EWs. I list my measured EWs in Table 5-3. Fitting these H$\alpha$ EWs to Starburst99 spectral evolution models (Leitherer et al., 1999), I found cluster ages. These models consist of evolution tracks for five different metallicities ranging from $z = 0.001$–0.04. Thus, I calculated five separate age estimates for each of my three clusters.

Next, I produced three separate color-color plots overlaid with BC evolutionary tracks (Figure 5-5). Using equations 1 and 2 in Whitmore and Zhang (2002) I corrected for excess H$\alpha$ emission seen in the $V$ and $I$ bands and define these corrected magnitudes as $V_{cor}$ and $I_{cor}$, respectively. Based on the H$\alpha$ EW-predicted ages alone, I determined all three clusters are < 20 Myr. Since there is little discrimination between cluster color and age in the $(V - I_{cor})$ vs. $(B - V)$ plot, I only used the $(B - V_{cor})$ vs. $(U - B)$ and $(V - I_{cor})$.

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vs. \((U - B)\) plots to estimate cluster age. Tracing the reddening vector backwards from each cluster’s colors, I searched for the intersection with the BC models that matched closest to the age predicted by the cluster’s Hα EW. Repeating this analysis for a range in metallicities, I searched for the best match in age predicted by the two evolutionary track models. I found a \(z = 0.008\) provides the best fit for the cluster counterparts to X-17 and X-27. I did not find a reasonable fit to X-48’s counterpart. This cluster lies below the BC models in color and its reddening vector never intersects the model. Therefore, I excluded this cluster counterpart from further analysis.

After deriving age and metallicity for the cluster counterparts to X-17 and X-27, I estimated their mass. Comparing the clusters’ observed \((V - I)\) to the intrinsic \((V - I)\), I calculated \(A_V\) using the CCM extinction law. I then used \(A_V\) and the distance modulus to the Antennae, \(m_d = 31.4\) mag, to find each cluster’s \(V\) luminosity, \(M_V\). Comparing \(M_V\) to \(M_V\) listed in the BC models for a 1.0 \(M_\odot\) cluster with the same age and metallicity, I found each clusters mass in solar masses. I summarize the properties for these two clusters in Table 5-3.

In the plots displayed in Figure 5-6, I include the cluster counterparts discussed in §5.1.4 where I fit BC models to cluster colors to find their properties. Notice the reasonably good agreement for most of the clusters. Only two of these clusters, with the X-ray sources X-34 and X-46, are outliers. Since I could only fit \(UBVI\) photometry to these clusters, it is understandable that they have a wide range in ages.

I summarize the results from all model fits in Figure 5-6. These model fits indicated a wide range in cluster properties. Only considering those cluster counterparts seen across all six IR and optical bands, I found ages between \(\sim 10^6 - 10^8\) Myr. Masses ranged from \(10^5 - 10^7\) \(M_\odot\), with most \(\sim 10^6\) \(M_\odot\). The mean metallicity was \(z = 0.047\) with a range from \(z = 0.004 - 0.050\). This is consistent or slightly higher than solar metallicity, which is the value Whitmore et al. (1999) assumed in their analysis. Finally, I did not find a trend between these cluster properties and the luminosities of their associated X-ray sources.
If I include the (less reliable) cluster counterparts only seen in the optical, I found ages between $\sim 10^6 - 10^{10}$ Myr, a range in masses of $\sim 10^3 - 10^8$ M$_\odot$, and metallicities from $z = 0.0001 - 0.05$.

5.3 Conclusions

Using my initial IR-to-X-ray frame tie as an intermediary, I produced an accurate frame tie between *Chandra* X-ray coordinates and optical *HST* positions, achieving a positional uncertainty of less than 0.6″. After producing this astrometric match, I searched for optical counterparts to X-ray sources and performed a multiwavelength photometric study of these counterparts. In my analysis, I reached the following conclusions:

1. I identified 8 “strong” matches (X-rays sources with $\sim 1$ optical counterpart within a 1.0″ radius) and 4 “possible” matches (X-ray sources with $\sim 2$ optical counterparts within a 1.0″ radius). Of these 12 matches, seven are not seen in my IR study of the Antennae (Chapter 3). Considering the “strong” matches to eight X-ray sources, I estimated five of their optical counterparts are chance alignments. In the case of the “possible” matches to four X-ray sources, I estimated five of their optical counterparts are chance alignments. These large numbers indicated most of my identified optical counterparts are not necessarily believable and I interpreted the photometric properties of these counterparts as only a suggestive description of the environments of the nearby X-ray sources.

2. I found all 15 IR cluster counterparts present in the *HST* images. In many cases, the high resolution and increased sensitivity of *HST* split the IR sources into individual components. I expect that conglomerations are all part of the same, larger structure with approximately the same age and metallicity. Therefore, I included these groupings in my photometric study of cluster counterparts to X-ray sources.

3. Using a $\chi^2$-minimization technique, I fit BC models to nine cluster counterparts across all six, $UBVIJK_s$ bands and four cluster counterparts across the four $UBVI$ optical bands. An additional three strictly optical counterparts lacked X-ray-derived
$N_H$; a quantity necessary to estimate reddening. Therefore, I combined BC model fits to
cluster colors and Starburst99 model fits to cluster Hα equivalent widths to characterized
these clusters’ properties.

Since I was uncertain if the strictly optical counterparts are real, I considered model
results across all optical and IR bands separately from models fits to only optical bands.
The BC model fits across all bands indicated the X-ray-source-associated clusters are
$10^5$–$10^7$ M$_\odot$ in mass, $\sim 10^6$–$10^8$ Myr in age, with metallicities of $z \approx 0.05$.

While I can use multiwavelength photometry to describe cluster properties, there
remains some uncertainty in these characteristics due to errors in magnitude and model
limitations. In future work, I plan to acquire spectra of Antennae cluster counterparts and
refine estimations of their properties.
Table 5-1: Potential Optical Counterparts to Chandra X-Ray Sources

<table>
<thead>
<tr>
<th>Chandra Src ID (^a)</th>
<th>RA (^b)</th>
<th>Dec (^b)</th>
<th>(\Delta \alpha) (^c) (arcsec)</th>
<th>(\Delta \delta) (^c) (arcsec)</th>
<th>(V) (^d)</th>
<th>(I) (^d)</th>
<th>IR CP (^e)</th>
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<tr>
<td>18.............</td>
<td>12 01 52.39</td>
<td>-18 52 06.85</td>
<td>0.21</td>
<td>0.00</td>
<td>24.96(0.08)</td>
<td>23.58(0.10)</td>
<td>no</td>
</tr>
<tr>
<td>27.............</td>
<td>12 01 53.44</td>
<td>-18 51 54.83</td>
<td>0.59</td>
<td>0.18</td>
<td>23.54(0.06)</td>
<td>23.42(0.07)</td>
<td>no</td>
</tr>
<tr>
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<td>12 01 53.49</td>
<td>-18 53 11.08</td>
<td>0.35</td>
<td>0.12</td>
<td>18.12(1.10)</td>
<td>16.65(0.06)</td>
<td>yes</td>
</tr>
<tr>
<td>34.............</td>
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<td>-18 53 03.23</td>
<td>0.55</td>
<td>0.52</td>
<td>18.75(0.06)</td>
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</tr>
<tr>
<td>37.............</td>
<td>12 01 54.98</td>
<td>-18 53 15.07</td>
<td>0.13</td>
<td>0.04</td>
<td>20.74(0.02)</td>
<td>19.64(0.02)</td>
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<tr>
<td>45.............</td>
<td>12 01 56.47</td>
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<td>0.03</td>
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<td>12 01 56.99</td>
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</tr>
<tr>
<td>“Possible” CP (^e)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>-18 51 52.02</td>
<td>0.13</td>
<td>0.24</td>
<td>22.79(0.03)</td>
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<td>no</td>
</tr>
<tr>
<td>25.............</td>
<td>12 01 53.00</td>
<td>-18 52 09.59</td>
<td>0.40</td>
<td>0.16</td>
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<td>21.64(0.25)</td>
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<tr>
<td>35.............</td>
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<td>0.50</td>
<td>0.45</td>
<td>23.00(0.04)</td>
<td>21.18(0.03)</td>
<td>yes</td>
</tr>
<tr>
<td>43.............</td>
<td>12 01 55.71</td>
<td>-18 52 32.16</td>
<td>0.43</td>
<td>0.46</td>
<td>25.10(0.07)</td>
<td>24.54(0.10)</td>
<td>no</td>
</tr>
</tbody>
</table>

\(^a\) ID numbers follow the naming convention of Zezas et al. (2002a)
\(^b\) Chandra coordinates with an uncertainty of 0.5\(^\prime\) (Zezas et al., 2002a)
\(^c\) Positional offsets in units of seconds of arc from the Chandra coordinates to the WIRC coordinates of the proposed counterpart.
\(^d\) Units are magnitudes, from HST PSF photometry. Values in parentheses indicate uncertainties in the final listed digit.
\(^e\) CP stands for counterpart.
Table 5-2: Bruzual-Charlot Model Fits

<table>
<thead>
<tr>
<th>Chandra Src ID</th>
<th>Log($L_X$)</th>
<th>$z$</th>
<th>Log(Age/yr)</th>
<th>$A_V$</th>
<th>Log(M/$M_{\odot}$)</th>
<th>$\chi^2$</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>UBVJIK$_S$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>38.30</td>
<td>0.0200–0.0200</td>
<td>7.08–7.44</td>
<td>0.0–0.1</td>
<td>6.35–6.71</td>
<td>0.65</td>
<td>0.52</td>
</tr>
<tr>
<td>10</td>
<td>37.83</td>
<td>0.0500–0.0500</td>
<td>7.22–7.34</td>
<td>0.0–0.1</td>
<td>6.39–6.55</td>
<td>0.33</td>
<td>0.80</td>
</tr>
<tr>
<td>11</td>
<td>39.51</td>
<td>0.0080–0.0500</td>
<td>6.64–8.01</td>
<td>0.0–1.4</td>
<td>5.02–5.98</td>
<td>0.16</td>
<td>0.94</td>
</tr>
<tr>
<td>15</td>
<td>38.05</td>
<td>0.0500–0.0500</td>
<td>7.22–7.49</td>
<td>0.0–0.4</td>
<td>6.33–6.69</td>
<td>0.31</td>
<td>0.81</td>
</tr>
<tr>
<td>20</td>
<td>38.30</td>
<td>0.0500–0.0500</td>
<td>6.72–7.48</td>
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<td>4.88–5.70</td>
<td>0.48</td>
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<td>33</td>
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<td>6.64–8.41</td>
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<td>5.44–6.93</td>
<td>4.1e-3</td>
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</tr>
<tr>
<td>36</td>
<td>37.65</td>
<td>0.0200–0.0500</td>
<td>6.66–7.70</td>
<td>0.0–1.1</td>
<td>5.35–6.43</td>
<td>0.06</td>
<td>0.99</td>
</tr>
<tr>
<td>40</td>
<td>37.76</td>
<td>0.0500–0.0500</td>
<td>6.68–6.72</td>
<td>0.0–0.6</td>
<td>5.87–6.08</td>
<td>0.95</td>
<td>0.31</td>
</tr>
<tr>
<td>42 b</td>
<td>39.79</td>
<td>0.0500–0.0500</td>
<td>6.74–6.78</td>
<td>0.0–0.2</td>
<td>5.18–5.29</td>
<td>0.51</td>
<td>0.63</td>
</tr>
<tr>
<td>UBVJ</td>
<td>34</td>
<td>0.0001–0.0500</td>
<td>6.50–10.30</td>
<td>0.0–0.9</td>
<td>5.30–8.16</td>
<td>0.91</td>
<td>0.26</td>
</tr>
<tr>
<td>46</td>
<td>38.37</td>
<td>0.0001–0.0500</td>
<td>7.91–9.32</td>
<td>0.0–0.9</td>
<td>4.21–4.93</td>
<td>0.12</td>
<td>0.83</td>
</tr>
</tbody>
</table>

$^a$ ID numbers follow the naming convention of Zezas et al. (2002a)

$^b$ Due a one-sided age range, BC fits increased to $\Sigma \chi^2 + 1.921$

Table 5-3: X-17 and X-27 Cluster Counterpart Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>X-17 cluster</th>
<th>X-27 cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_\alpha$ EW</td>
<td>1.42</td>
<td>1.94</td>
</tr>
<tr>
<td>Log (age/yr)</td>
<td>7.01</td>
<td>6.69</td>
</tr>
<tr>
<td>$\Delta$ Log(age/yr)$^a$</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>$A_V$</td>
<td>2.61</td>
<td>1.26</td>
</tr>
<tr>
<td>Log (mass/$M_{\odot}$)</td>
<td>4.41</td>
<td>3.69</td>
</tr>
</tbody>
</table>

$^a$ Difference in age between that determined using reddening vector intersection to BC model and $H_\alpha$ EW.
Figure 5-1. Subimages highlighting optical counterparts to X-ray sources. Positional error circles with 1.0′′ radii centered on X-ray source positions are in yellow. Blue circles are centered on cluster counterparts and have 0.3′′ radii equivalent to the $I$-band photometric aperture. I label those X-ray sources with possible counterparts using a ‘*’. All images are 6.0″×6.0″.
Figure 5-2. Subimages highlighting optical counterparts to X-ray sources with IR cluster counterparts. Positional error circles with 1.0" radii centered on X-ray source positions are in yellow. Red circles are centered on cluster counterparts and have 1.3" radii equivalent to the $K_s$-band photometric aperture. I label those X-ray sources with possible counterparts using a '*' . All images are 6.0"×6.0".
Figure 5-3. *I*-band Antennae *HST* image (Whitmore et al., 1999) showing positions of X-ray sources. North is up and east is to the left. Blue circles are optical counterparts identified in this paper. Red squares are optical counterparts to X-ray sources with IR cluster counterparts identified in Chapter 3.
Figure 5-4. Example of a good $\chi^2$ fit between a cluster counterpart and a BC model. I include the derived cluster properties and the quality of the fit parameters. In the lower graph, notice the small residuals between the model and data.
Figure 5-5. Color-color and Hα equivalent width plots used to determine ages for the cluster counterparts to X-17, X-27 and X-48 (crosses). Dashed lines are reddening vectors extending from cluster colors to BC models. Notice reddening vector from X-48 counterpart does not intersect BC model, indicating a poor fit. I indicate this cluster with a circle in the lower left plot. Also included in these plots are clusters whose properties I determined using χ²-fitting to BC models. I fit $UBVIK_s$ magnitudes to clusters indicated by diamonds and $UBVI$ magnitudes to clusters indicated by triangles. Solid lines in lower left plot indicate ranges in cluster age.
Figure 5-6. Summary of results from $\chi^2$ fitting to BC models. I fit the BC models to $UBVIJ_K$ photometry (⋄’s), and $UBVI$ photometry (△). Error bars are ranges in cluster parameters for models within one of the best fit $\chi^2$ sum. I also include the two clusters I analyzed using Hα EWs (+’s). I divide these plots by X-ray source luminosity into three separate regions: LLX: $L_X < 3 \times 10^{38}$ ergs s$^{-1}$, HLX: $3 \times 10^{38}$ ergs s$^{-1} < L_X < 1 \times 10^{39}$ ergs s$^{-1}$, and ULX: $L_X > 1 \times 10^{39}$ ergs s$^{-1}$. Notice there is no obvious trend between cluster properties and the luminosity of the associated X-ray source. Note: Those strictly optical counterparts to X-ray sources are not necessarily accurate matches and these cluster properties do not conclusively describe their nearby X-ray source’s environment.
CHAPTER 6
THE ULTRALUMINOUS X-RAY SOURCE X-37 IS A BACKGROUND QUASAR IN
THE ANTENNAE GALAXIES

Ultraluminous X-ray sources (ULX) are typically defined as point sources with
X-ray luminosities > 10^{39} \text{ ergs s}^{-1}. Einstein (Long and van Speybroeck, 1983; Helfand,
1984; Fabbiano, 1989) and ROSAT (Roberts and Warwick, 2000; Colbert and Ptak,
2002) observations revealed many of these objects in nearby galaxies. Recent Chandra
observations indicate the Antennae (NGC 4038/4039) contain 9 ULXs (Zezas et al., 2002a,
assuming here and hence forth \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \)), the largest number discovered so
far in a single galaxy (Fabbiano et al., 2003).

One X-ray source in the Antennae that has received considerable attention in
the literature is X-37, as designated by Zezas et al. (2002a). At the distance to these
interacting galaxies (19.3 Mpc) it would have an X-ray luminosity, \( L_X = 4.5 \times 10^{39} \text{ ergs s}^{-1} \),
making it a ULX. A previous attempt to match X-ray positions directly to HST positions
indicated that this object has a significant (> 1.0''') offset from a nearby optical source
(Zezas et al., 2002b). This spawned discussions of whether this is a runaway X-ray binary
escaping from its parent cluster (Zezas et al., 2002b; Miller et al., 2004; Fabbiano, 2004).
But, matching X-ray positions directly to the optical is difficult due to the crowded HST
field and image rotation.

In Chapter 3 (see also Clark et al., 2007b) I demonstrated that the IR is a powerful
method for finding counterparts to X-ray sources. This wavelength regime has similar
dust penetrating properties to X-rays, facilitating counterpart identification. In Chapter
5 I matched X-ray and optical HST positions with high precision by using the IR frame
tie as a go-between. Here I use X-37 to demonstrate the success of my method and show
the importance of obtaining follow-up spectra of counterparts to ULX candidates. §6.1
describes spectroscopic observations of the counterpart to X-37 and briefly discusses
my analysis of the IR and optical images. I summarize my results and present the
implications of this discovery in §6.2.
6.1 Observations and Data Analysis

6.1.1 Infrared and Optical Images

I continue with analysis of the IR and optical images of the Antennae by focusing on the particularly interesting counterpart to the X-ray source, X-37. Using the astrometric frame tie discussed in Chapter 3, I identified a bright, $K_s = 16.2$ mag source $0.3 \pm 0.5''$ from the X-ray position of X-37 (see Figure 6-1). Note that this contradicts previous reports of a significant offset between X-37 and the star cluster candidate, and independently eliminates any need for the hypothesis that this X-ray source is a runaway X-ray binary (Zezas & Fabbiano 2002; see also Miller et al. 2004a and Fabbiano et al. 2003). Using this astrometric frame tie between the X-ray and optical, HST images discussed in Chapter 5, I found an optical source $0.6 \pm 0.6''$ from the X-ray position of X-37 (Figure 6-1)–again, an insignificant offset.

6.1.2 Spectroscopy

My collaborator, Micol Christopher, acquired an optical spectrum of X-37 on March 7, 2003, using the Low Resolution Imaging Spectrograph (Oke et al., 1995, LRIS) on Keck I. He observed this source in two separate slitmasks with a 400 lines mm$^{-1}$ grating and blaze wavelength of 8500 Å, yielding a total wavelength coverage on the red side of 5600-9400 Å. Seeing throughout the observations was $\sim 0.8''$. He observed X-37 for a total of 6000 seconds between the two masks with typical single exposure times of 600 seconds.

He reduced the spectrum with a combination of standard IRAF procedures and IDL code using the NeAr arc-lamp spectrum for wavelength calibration. He used the standard star Feige 67 to flux calibrate the spectrum.

He extracted spectra of the X-37 counterpart from each individual exposure in a 1.8'' (approximately 2 FWHM) region centered on the emission peak. A background spectrum extracted from a region 2'' removed from the counterpart was sufficient for removing the night sky lines. I point out the blended lines, H$\alpha$/[NII] at $\sim 6600$ Å and the [SII] pair at $\sim 6750$ Å, observed at the redshift of the Antennae (Figure 6-2). These spectral features
are at approximately the same levels in the on-source and background spectra, suggesting that they are likely diffuse emission from the Antennae and not associated with X-37.

After presenting this spectrum to my colleagues, Dr. Fred Hamann and Dr. Vicki Sarajedini, they noted the broad emission lines characteristic of a quasar. We then looked for other spectral features to confirm this classification. The realization that the broad line at 8296 Å was red-shifted Hα prompted a search for additional lines generally associated with quasars. We noted a plethora of such identifiers including the nonrestframe wavelengths of Hβ at 6148 Å, [OI] at 7965 Å, [NII] at 8320 Å, and [SII] at 8510 Å. This corroborated our conclusion that X-37 is a quasar.

Using the observed, narrow [OIII] lines at 6270.45 Å and 6330.94 Å, Micol Christopher measured a redshift of z=0.26. At the redshift to this quasar, X-37 would now have an X-ray luminosity of \( L_x = 1.4 \times 10^{43} \) ergs s\(^{-1}\). As I show in Table 6-1, this luminosity is typical of the X-ray luminosity for quasars at a similar distance (Schartel et al., 1996).

### 6.1.3 Photometry

To investigate how much of the continuum flux could be due to the quasar, I compared the photometric properties of this source to that of other quasars at X-37’s redshift of z=0.26. I chose \( U \) and \( V \)-band photometry from the \( HST \) images and \( K_s \)-band photometry from the WIRC images. This choice in filters covers the full wavelength range used in my studies of the Antennae (Chapter 5).

I performed aperture photometry in each of these bands following the procedures discussed in Chapters 2 and 5. Next, I converted these photometric measurements to reddening-corrected absolute magnitudes. At the redshift of X-37, the distance modulus is 40.1 mag. I derived reddening in \( V \), \( A_V = 1.3 \) mag, using the X-ray derived column density, \( N_H \), listed in Table 5 of Zezas et al. (2002a) and the relationship \( A_V = 5 \times 10^{-22} \) \( cm^{-2} \) \( N_H \). I used the \( N_H \) value provided by the power-law spectral fits of Zezas et al. (2002a). These authors computed \( N_H \) assuming the absorption is at zero redshift. This
should not be a problem for me since the broad absorption lines observed in the X-37 spectrum suggest there is little extinction along the line of sight to it.

To find reddening in other filters, I used the extinction law defined in Cardelli et al. (1989, CCM). I also computed separate redenings in each filter using the Rieke-Lebofsky (RL) Law (Rieke and Lebofsky, 1985). I then expressed errors in reddening, $\sigma_A$, as the difference in $A_U$, $A_V$, and $A_{K_s}$ derived from each law. Adding $\sigma_A$ and $\sigma_m$ in quadrature, I computed a total error in absolute magnitude.

In Table 5-1, I compare the absolute magnitudes, $M_U$, $M_V$, and $M_{K_s}$, of the X-37 counterpart to typical magnitudes for quasars at a similar distance. I obtained $M_U$ and $M_V$ from the Sloan Digital Sky Survey (SDSS) quasar catalog (Schneider et al., 2003) for 33 quasars at a redshift of 0.26. Using color transformations listed in Fukugita et al. (1996), I converted SDSS magnitudes to the Johnson photometric system. I used the catalog described in Barkhouse and Hall (2001) to derive $M_{K_s}$ for 17 quasars at a redshift of 0.26. Considering the absolute magnitude of X-37 in the $U$, $V$ and $K_s$ bands falls within the range of catalog quasar magnitudes, X-37 has the luminosity of a typical quasar.

6.2 Discussion

The identification of X-37 with a background quasar further demonstrates the importance of spectroscopic followup for the study of ULX sources. While the overabundance of such sources near galaxies clearly demonstrates that a physical connection does exist for many ULX sources as a population (e.g. Colbert and Ptak, 2002), the strong possibility of background quasar contamination makes such identification for any particular source perilous (see also Gutiérrez and López-Corredoira, 2005).

A specific example involving X-37 is the recent work of Miller et al. (2004). In their Figure 2, Miller et al. (2004) compare the black hole mass to inner disk temperature for both ULX sources and “standard” stellar-mass black holes, finding that the ULX sources have cooler disk temperatures. They use this to conclude that ULX are likely to
be powered by accretion onto Intermediate-Mass Black Holes (IMBH). While some of the sources in this diagram are almost certainly ULXs (i.e. NGC 1313 X-1 and NGC 1313 X-2), and thus possible IMBH, it is somewhat surprising to note that the “ULX” X-37 is grouped with these sources in the diagram—despite the fact that its actual black hole mass is at least 4 orders of magnitude higher than assumed by Miller et al. (2004). Thus, X-37 illustrates the importance of follow-up spectroscopic confirmation of ULXs, and sounds a cautionary note regarding conclusions based on observations without such confirmation.
Table 6-1: Absolute Magnitude Comparison to Quasars at $z \approx 0.26$

<table>
<thead>
<tr>
<th>Filter</th>
<th>Observed Magnitudes $^a$</th>
<th>Typical Catalog Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U$</td>
<td>-20.9±0.2</td>
<td>-23.9 to -20.8</td>
</tr>
<tr>
<td>$V$</td>
<td>-20.4±0.2</td>
<td>-23.4 to -21.0</td>
</tr>
<tr>
<td>$K_s$</td>
<td>-24.1±0.1</td>
<td>-25.6 to -23.8</td>
</tr>
<tr>
<td>$\log(L_x)$</td>
<td>43.1</td>
<td>43.7 to 44.1</td>
</tr>
</tbody>
</table>

$^a$ Absolute magnitudes include uncertainties in each value. Catalog values were taken from separate sources: $U$ and $V$ from Schneider et al. (2003), $K_s$ from Barkhouse and Hall (2001), and $L_x$ from Schartel et al. (1996).
Figure 6-1. $U$ band image (left) and $K_s$ band image (right) showing a 1-arcsecond positional error circle centered on the X-ray source, X-37. Notice the bright source well within this circle.
Figure 6-2. X-37 spectrum. Red text denotes quasar lines, blue text denotes lines from the Antennae background emission.
NGC 1569 is a dwarf, starburst galaxy vastly different from the large, merging system of the Antennae. It contains two super star clusters (SSCs) (Arp and Sandage, 1985) and 16 X-ray sources, in the line of site, which range in luminosity from $L_X = \sim 5 \times 10^{33} - 3 \times 10^{36}$ ergs s$^{-1}$ (Martin et al., 2002). At a distance of 2.2 Mpc (Israel, 1988), it is closer than the Antennae at 19.3 Mpc (for $H_0=75$ km s$^{-1}$ Mpc$^{-1}$), allowing me to probe star cluster masses, down to $\sim 1000$ M$_\odot$.

My work presented in Chapter 4 defined the quantity, $\eta$, relating the observed number of XRBs per star cluster mass as a function of mass in the Antennae. I found that the functional form of $\eta$ remained constant, demonstrating that the number of observed XRBs simply scaled up linearly with cluster mass. In this chapter, I will compute $\eta$ for NGC 1569. The large contrast in galactic environments between the Antennae and NGC 1569 raises several fundamental questions regarding $\eta$. For instance, does the functional form of $\eta$ in NGC 1569 remain consistent with a single value, as it does for the Antennae? If so, how does this value compare between these two, disparate galaxies.

In this chapter, I extend my study of X-ray sources and their IR counterparts to NGC 1569. In §7.1, I discuss my IR, $J$ and $K_s$ observations and the subsequent data reduction. I identify IR counterparts to X-ray sources and analyze their photometric properties to characterize these sources in §7.2. I summarize results and give conclusions in §7.3.

### 7.1 Observations and Data Analysis

#### 7.1.1 Infrared Imaging

On January 17–19, 2005, I acquired IR observations of NGC 1569 using FLAMINGOS on the KPNO 4-meter telescope. FLAMINGOS has a field-of-view (FOV) of $10' \times 10'$ with a plate scale of 0.32″. The total exposure time of my final science image was $\sim 2$ hours in $J$ and $\sim 1$ hour in $K_s$. These composite science images consisted of many, randomly dithered exposures with minimum integration times of 60 seconds in $J$ and 15 seconds
in $K_s$. To correct for the high sky background in the IR, I imaged the sky using similar dithered exposures every 40 minutes in $J$ and every 30 minutes in $K_s$. The typical seeing throughout the observing was $\sim 1.2''$ in both filters.

I produced science quality images using the pipeline, the Florida Astronomy Tool Born Of Yearning for high scientific quality data (FATBOY). FATBOY was developed by C. Warner, A. H. Gonzalez, S.S. Eikenberry and other members of the FLAMINGOS-2 team. This software calibrates each image using flat fields and dark frames and corrects for cosmic rays, bad pixels and image distortion. This software produced final images for each dither run, which I drizzled together to produce master images in the $J$ and $K_s$ bands. In Figure 7-1, I show a $4 \times 4$-arcminute color image of NGC 1569.

7.1.2 Astrometric Frame Ties

Before performing a frame tie between Chandra coordinates and IR positions, I used the astrometry routine bundled with FATBOY to fit Two Micron All Sky Survey (2MASS) coordinates to the $J$ and $K_s$ master images. This routine cross-correlates sources between 2MASS and FLAMINGOS and then applies a 4th order polynomial fit to match 2MASS coordinates to the IR images. The fit produced an rms positional uncertainty of 0.1''.

As I demonstrated in Chapter 3, it is essential to produce a relative astrometric fit between the X-ray images and images at other wavelengths to search for counterparts to X-ray point sources. As I did in Chapter 3, I chose IR images as my initial link to X-ray source positions in NGC 1569. This choice of wavelengths offers many benefits. While extinction intrinsic to this dwarf galaxy is low, it is patchy, ranging from $A_V = 0.0$–0.8 (Relaño et al., 2006). Considering that the near-IR will reduce these values by a factor of 10, making extinction almost negligible, this wavelength regime facilitates counterpart identification. Furthermore, since my IR observations are less confused than HST observations of NGC 1569 (Anders et al., 2004) my chances of finding accurate
matches to X-ray sources are significantly improved. Finally, I note that IR and X-ray wavelengths penetrate dust in similar ways, making it easier to correlate sources.

My astrometric frame tie method follows the procedure described in detail in Chapter 3. In summary, I identified seven bright, isolated sources in common between the IR and X-ray images (Table 7-1). Applying a two-dimensional linear mapping function to the Chandra right ascension and declination coordinates of these sources (see Table 1 of Martin et al., 2002) and the corresponding $x$ and $y$ pixel centroids in the FLAMINGOS $K_s$ image, I produced a frame tie between the images in these two wavelengths. I achieved a fit with a rms positional uncertainty of 0.2″.

### 7.1.3 Infrared Photometry

I restricted photometry to an elliptical region centered on NGC 1569 with a long axis of 2.4′ and short axis of 1.0′ (see Figure 7-3). This ellipse surrounds most of NGC 1569 and I was confident that most of the sources contained within it are star clusters. Due to the numerous stars surrounding this galaxy, I estimated the stellar density in the field outside of the ellipse encircling it and found there were $7 \times 10^{-3}$ stars per square arcsecond. Multiplying this density by the area of the ellipse, implies that 11% of the clusters in my sample are stars, assuming an isotropic distribution. In §7.2.2.2 below, I will examine what effect this will have on my results.

I then performed $J$- and $K_s$-band aperture photometry on 462 sources within this ellipsoidal region using a self-written IDL program previously developed for the Antennae (see Chapter 2 and Brandl et al., 2005, for additional details). I found a full width at half maximum (FWHM) of 3.5 pixels (1.1″) for both the $K_s$- and $J$-bands. I used a photometric aperture with a 4.4-pixel radius in each band, corresponding to $\sim 3\sigma$ of the Gaussian PSF.

I compensated for the crowded field in NGC 1569 by measuring sky background in two separate annuli, from $\sim 6-10\sigma$ of the Gaussian PSF. In addition, I divided the annuli into arcs for exceptionally crowded regions. Multiplying the mean and median sky
background in each annulus by the area of the central aperture and then subtracting this from the central aperture flux yielded four separate flux measurements for the source. I then averaged these four values to give me the source flux. When computing errors, I considered variations in the sky background, $\sigma_{\text{sky}}$, and Poisson noise, $\sigma_{\text{adu}}$. To calculate $\sigma_{\text{sky}}$ I found the standard deviation of the four flux values for each source. Dividing the mean source flux by the instrument gain and then taking the square root of these, I found $\sigma_{\text{adu}}$. The known gain for FLAMINGOS is $4.9 \ e^{-1} \ DN$ (Elston, 1998). Both $\sigma_{\text{sky}}$ and $\sigma_{\text{adu}}$ were added in quadrature to yield a total error in flux, $\sigma_{\text{flux}}$.

I then calibrated my photometry using the bright 2MASS star ‘2MASS 04305877+645163’ at $04^d30^m58.77^s$, $+64^d51^m56.33^s$ which is listed in the 2MASS database with $J = 16.197$, $\sigma_J = 0.09$ mag, and $K_s = 15.768$, $\sigma_{K_s} = 0.1$ mag. This star was in the FLAMINGOS FOV for the NGC 1569 observations.

### 7.2 Results and Discussion

#### 7.2.1 Identification of IR Counterparts to Chandra Sources

I restricted my analyzes to clusters with signal-to-noise (SNR) > 10 (see §7.2.2.1 below). I searched for IR counterparts to X-ray sources in NGC 1569 using the same technique developed for the Antennae and discussed in detail in Chapter 3. In summary, I used the 0.2″ rms positional uncertainty to define circles with 2$\sigma$ and 3$\sigma$ radii. Those IR sources lying within 0.4″ ($2\sigma$) of a Chandra X-ray source I defined as a “strong” match. If an IR source was between 0.4″ and 0.6″ ($2-3\sigma$) of an X-ray source position, I defined this as a “possible” match. Including all 45 X-ray sources listed in Table 1 of Martin et al. (2002), I found 19 “strong” matches and eight “possible” matches to IR sources. Restricting X-ray sources to the 16 within the ellipse defined in §7.1.3 above, I found three possible and four strong matches to IR star cluster counterparts in NGC 1569.

Following the method discussed in Chapter 3, I attempted to estimate the source contamination by measuring the source density in a 0.8″–1.2″ ($4-6\sigma$) annular region around the X-ray sources. Including all the X-ray sources in the 9.0′ × 9.0′ field, I expect
two with $1\sigma$ uncertainty\(^1\) of $+1.2/-0.7$ of the “strong” matches and two with a $1\sigma$ uncertainty\(^1\) of $+1.2/-0.4$ of the “possible” matches are chance alignments of unrelated objects. For those X-ray sources most likely associated with IR clusters in NGC 1569, I expect one with $1\sigma$ uncertainty\(^1\) of $+0.8/-0.3$ of the “strong” matches and two with a $1\sigma$ uncertainty\(^1\) of $+0.7/-0.3$ of the “possible” matches to be false associations.

These statistics indicate that most of the IR counterparts found in the field of NGC 1569 are real—of all 27 matches only four are chance alignments. But, the story is different for IR counterparts identified on the face of NGC 1569, where three of the seven IR matches to X-ray sources are most likely false identifications. This is not surprising, considering the high IR source density in this galaxy. Nevertheless, the majority of the matches are real and source contamination is not significant enough to prevent a meaningful photometric study of them.

Figures 7-2 and 7-3 show IR counterpart candidates in NGC 1569. Figure 7-2 is a 9.0′ × 9.0′ field around this galaxy showing all X-ray source positions identified by Martin et al. (2002). Figure 7-3 is a 4.0′ × 4.0′ field with the ellipse used to designate those IR sources that are most likely clusters associated with NGC 1569. In further analyzes, I only consider the IR counterparts to X-ray sources in this region. I display subimages for all IR counterparts to X-ray sources in Figures 7-4 and 7-5.

7.2.2 Photometric Properties of the IR Counterparts

7.2.2.1 Color magnitude diagrams

Using the 424 clusters with $J$ and $K_s$ photometry, I produced a $(J - K_s)$ versus $K_s$ color magnitude diagram (CMD; see Figure 7-6). Initially, I defined a magnitude cutoff using the method discussed in Chapter 3. Specifically, I found all sources with an error in magnitude, $\sigma_{mag} > 0.2$ mag. I found median $J$ and $K_s$ magnitudes for these

\(^1\) Found using confidence levels for small number statistics listed in Tables 1 and 2 of Gehrels (1986).
sources and used these cutoffs; discarding all fainter objects. Unfortunately, due the exceptional crowding and variable background flux of NGC 1569, $\sigma_{\text{mag}}$ was abnormally high for luminous sources. Thus when I took the median magnitude of sources with $\sigma_{\text{mag}} > 0.2$ mag, the cutoff was unrealistically bright. Applying this cutoff excluded many bright sources with high signal-to-noise. Therefore, I chose a different method to define a magnitude cutoff; I measured the SNR for each source and selected only those sources with SNR $>10$ to use in further analyzes.

The low Galactic latitude of NGC 1569 ($b = 11^\circ$; Cotton et al., 1999) meant that I could not ignore foreground extinction. Relaño et al. (2006) estimated an optical reddening of $A_V = 1.64$ mag. Using the extinction law defined in Cardelli et al. (1989) (hereafter CCM), I found that this value corresponds to an IR reddening of $A_{K_s} = 0.2$ mag in $K_s$ and $A_J = 0.4$ mag in $J$. Subtracting these values from cluster magnitudes, I corrected for foreground reddening (see Figure 7-7).

I measured “good” photometry for six of the seven clusters associated with X-ray sources. Here, as in Chapter 6, I defined “good” photometry as non-negative fluxes after performing background sky subtraction. Comparing these six clusters to the general population of clusters reveals a uniform spread in $K_s$ magnitude. This differs from the Antennae, in which I observed that X-ray associated clusters are brighter in $K_s$.

Furthermore, there does not appear to be a significant trend in cluster color. The mean $(J - K_s)$ color for all clusters is 0.81 mag with an uncertainty of $\sigma_{(J-K_s)} = 0.02$, while those clusters that are IR counterparts have a mean of $(J - K_s) = 0.74$ with $\sigma_{(J-K_s)} = 0.13$.

### 7.2.2.2 $K_s$ luminosity

I extended my analyzes of IR counterpart properties by computing $K_s$ luminosities, $M_{K_s}$, for all IR clusters. I corrected for extinction internal to NGC 1569 using the reddening estimates presented in Relaño et al. (2006). Using $\text{H}\alpha/\text{H}\beta$ emission line ratios to produce an extinction map of this galaxy, they found $A_V$ ranges from 0.0–0.8 mag.
Using the CCM reddening law, this implies a range in \( A_{K_s} \) of 0.0–0.1 mag, demonstrating that the reddening within NGC 1569 in the IR is almost negligible. Subtracting the mean intrinsic, \( A_{K_s} = 0.04 \) mag, and the distance modulus to NGC 1569, 26.7 mag, from the \( K_s \) magnitude for each cluster, I computed \( M_{K_s} \). Here the \( K_s \) magnitude has already been corrected for foreground reddening (see §7.2.2.1 above). I defined the error in internal reddening as \( \sigma_{A_{K_s}} = 0.05 \), which covers the range in \( A_{K_s} \) for this galaxy. Adding \( \sigma_{A_{K_s}} \) in quadrature with \( \sigma_{\text{mag}} \) for each source, I computed errors in \( M_{K_s} \).

In Figure 7-8 I plot a histogram of \( M_{K_s} \) for all clusters. This distribution has a mean \( M_{K_s} = -9.2 \) mag with an uncertainty of \( \sigma_{\overline{M_{K_s}}} = 0.1 \) mag, while the mean for those clusters associated with X-ray sources is \( M_{K_s} = -10.0 \) mag with \( \sigma_{\overline{M_{K_s}}} = 0.7 \) mag. Performing a K-S test between the distribution of X-ray associated clusters and all clusters in NGC 1569, I found a D-statistic of 0.32 and a probability of 0.50 that they are related distributions. This suggests that there is no distinction between these two groups.

As discussed in §7.1.3, 11% of identified “clusters” could be stars. I tested the possible repercussions of stellar contamination by randomly removing 11% of the sources in my sample. Then, I recalculated the mean \( M_{K_s} \) for two groups: all remaining clusters and for all remaining clusters associated with X-ray sources. Repeating this procedure 10000 times, I produced a simulated distribution of mean \( M_{K_s} \) for the two groups mentioned above. For the first group of all remaining clusters, I found a \( \overline{M_{K_s}} \) of -9.2 mag with an uncertainty of \( \sigma_{\overline{M_{K_s}}} = 0.1 \) mag, while for those remaining clusters associated with X-ray sources I found \( \overline{M_{K_s}} = -10.0 \) mag and \( \sigma_{\overline{M_{K_s}}} = 0.1 \) mag. These values are in close agreement with the observed value of \( M_{K_s} \) that I derived using all sources, demonstrating stellar contamination does not significantly affect these findings.

### 7.2.3 XRB-to-Cluster Mass Fraction

Using the function, \( \eta(M_c) \), presented in Chapter 4, I explored the relationship between XRBs and cluster mass in NGC 1569. As a reminder, this function relates the number of X-ray source detections per unit mass as a function of cluster mass (see Eq.
As I did with the Antennae, I first computed $\eta(M_c)$ using cluster $K_s$-band flux, $F_{K_s}$, to approximate cluster mass. In Figure 7-9, I show the distribution of $\eta(F_{K_s})$, where the bin size is $F_{K_s} = 1.5 \times 10^4$ data numbers (DN). This bin size is small enough to show a trend in $\eta(F_{K_s})$, but large enough to contain at least two clusters with X-ray sources, allowing me to compute errors in each bin. The error bars plotted on the graph are the measurement uncertainties in the three values of $\eta(F_{K_s})$ added in quadrature with the Poisson uncertainty of the mean $\eta(F_{K_s})$ for each bin. Notice each value of $\eta(F_{K_s})$ is roughly consistent with a mean $\eta(F_{K_s}) = 2.4 \times 10^{-6}$ DN$^{-1}$, with an uncertainty, $\sigma_\eta = 1.0 \times 10^{-6}$ DN$^{-1}$.

Next, I converted $\eta(M_C)$ into the physical units of solar mass, $M_\odot$. As demonstrated in Chapter 4, this conversion requires an assumption about cluster ages. Unlike the Antennae, I could not make the simplified assumption that all clusters have similar ages as there is a wide range ages in NGC 1569, from 4 Myr to 10 Gyr (Anders et al., 2004). Furthermore, Waller (1991) suggest this galaxy underwent six starbursts in its history. Clearly, assigning a single age to all clusters is not an accurate representation of the cluster environment in NGC 1569. Instead, I tried finding matches between my IR clusters and optical clusters discussed in Anders et al. (2004). Due to the complex structure of NGC 1569 and the difference in resolution between HST and FLAMINGOS, I was only able to find matches to 28 sources. Therefore, I adopted a different approach to estimate cluster ages in this dwarf galaxy to derive $\eta(M_\odot)$.

Following the procedure developed for the Antennae (see Chapter 4), I selected ages at random from a uniform distribution between 1 Myr and 10 Gyr, and assigned an age to each cluster in my sample. Applying the BC models, I computed each cluster’s mass based on the assigned age, produced a mass distribution, and then calculated a mean $\eta$. Performing a Monte Carlo (MC) simulation, I recreated cluster mass distributions 10,000 times, producing a large sample of $\eta$’s with a mean of $\eta = 3.274 \times 10^{-6} M_\odot^{-1}$ and $\sigma_\eta = 1.2 \times 10^{-8} M_\odot^{-1}$ (Figure 7-10).
7.2.4 Comparison with Models

As I did with the Antennae, I used the models presented in Sepinsky et al. (2005) to calculate what these authors would predict for $\eta(M_\odot)$ in NGC 1569. As a reminder, these authors used StarTrack (Belczynski et al., 2002) to investigate the rate of XRB formation and ejection from young, massive clusters. As discussed above, the cluster ages in NGC 1569 are not well defined and span a wide range. Therefore, I picked the maximum number of XRBs predicted by the models for a given age and thus computed upper limits for $\eta(M_\odot)$. Given a cluster mass of $5 \times 10^6 \, M_\odot$, the models predict the cluster will yield 6 XRBs, while a $5 \times 10^4 \, M_\odot$ cluster will only produce 0.05 XRBs. Recall an XRB is associated with a cluster if it is within $6''$, which is equivalent to 6.4 pc at the distance to NGC 1569. Since these models use a limiting X-ray luminosity of $5.0 \times 10^{35} \, \text{ergs s}^{-1}$ and the actual limiting $L_X$ for NGC 1569 is $5.5 \times 10^{33} \, \text{ergs s}^{-1}$, I used the cumulative XLF power law slope of $\alpha = -0.5$ (Martin et al., 2002) to estimate the number of observed XRBs predicted by these models for this galaxy. Therefore, the models predict 29 XRBs should be observed in a $5 \times 10^4 \, M_\odot$ cluster, while 38 should be observed in a $5 \times 10^6 \, M_\odot$ cluster. Expressing these model results as a fraction of XRB-to-cluster mass, Sepinsky et al. (2005) predict $\eta(M_\odot)$ ranges from $9.6$–$11.4 \times 10^{-6} \, M_\odot^{-1}$. These values are only within a factor of two of my measured value of $\eta$ in NGC 1569. Interestingly, if I place the Antennae at the distance to NGC 1569 and scale its measured value of $\eta$, I find $\eta(M_\odot) = 2.5 \times 10^{-6} \, M_\odot^{-1}$, which is well in agreement with my measured value for NGC 1569.

7.3 Conclusions

In this chapter I extended my study of XRB environments to the dwarf, starburst galaxy, NGC 1569. I produced a frame tie between Chandra X-ray coordinates and FLAMINGOS pixel positions with an rms positional uncertainty of $0.2''$. With the frame tie in place, I found seven of the 16 X-ray sources associated with NGC 1569 had IR cluster counterpart candidates. Of these seven matches, four were “strong” matches ($< 0.4''$ separation) and three were “possible” matches ($0.4''$–$0.6''$ separation). After
performing a photometric study of these IR cluster counterparts, I reached the following conclusions:

1. After estimating the IR cluster density around each X-ray source, I predicted one of the “strong” counterparts and two of the “possible” counterparts are chance alignments of unrelated objects. While this is a high number of false matches considering the small sample size of IR counterparts, most are real and therefore did not hamper a photometric study of these X-ray-associated clusters.

2. A $K_s$ vs. $(J - K_s)$ CMD revealed no trend in clusters with X-ray sources compared to the general population of clusters. They occupied a wide range in $K_s$ magnitude, with no obvious trend in color.

3. I found those clusters with X-ray sources are not significantly more luminous than the general population of clusters. This result was substantiated by a K-S test, which revealed a relatively high probability of 0.5 that the distribution of clusters with X-ray sources are related to all clusters. This differs from the Antennae where I found a preference for more luminous clusters to harbor X-ray sources.

4. I estimated a constant value for $\eta = 3.274 \times 10^{-6} \ M_\odot^{-1}$ with $\sigma_\eta = 1.2 \times 10^{-8} \ M_\odot^{-1}$. If I placed the Antennae at the distance to NGC 1569 and scale its measured value of $\eta$, I found $\eta = 2.5 \times 10^{-6} \ M_\odot^{-1}$, which is consistent with the derived value for NGC 1569. This demonstrates $\eta$ is similar for two, very different galactic systems. A larger galactic sample is necessary to confirm the universality of $\eta$ for all environments.

5. Lastly, the models of Sepinsky et al. (2005) predict $\eta$ is only a factor of two higher than my measured value for $\eta$. Considering I chose the maximum number of XRBs predicted by the models, the model-predicted $\eta$ is an upper limit, suggesting the models produced in Sepinsky et al. (2005) roughly agree with my results.
Table 7-1: Common Sources Used for the *Chandra*/FLAMINGOS Astrometric Frame Tie

<table>
<thead>
<tr>
<th><em>Chandra</em> Source ID</th>
<th>RA (Chandra)</th>
<th>Dec (Chandra)</th>
<th>$J^b$</th>
<th>$K_s^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 ...........</td>
<td>04 30 30.91</td>
<td>+64 52 05.30</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>9 ...........</td>
<td>04 30 39.03</td>
<td>+64 50 12.80</td>
<td>13.59(0.01)</td>
<td>12.90(0.01)</td>
</tr>
<tr>
<td>12 ............</td>
<td>04 30 44.21</td>
<td>+64 49 24.90</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>20 ............</td>
<td>04 30 48.93</td>
<td>+64 49 40.10</td>
<td>12.71(0.01)</td>
<td>12.40(0.01)</td>
</tr>
<tr>
<td>31 ...........</td>
<td>04 30 58.37</td>
<td>+64 48 52.30</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>37 ...........</td>
<td>04 31 14.02</td>
<td>+64 51 07.90</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>39 ...........</td>
<td>04 31 16.85</td>
<td>+64 49 50.00</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

*a* ID numbers follow the naming convention of Martin et al. (2002).

*b* Units are magnitudes, from WIRC photometry. Values in parentheses indicate uncertainties.
Table 7-2: Potential IR Counterparts to Chandra X-Ray Sources

<table>
<thead>
<tr>
<th>Chandra Src ID</th>
<th>RA</th>
<th>Dec</th>
<th>$\Delta\alpha$</th>
<th>$\Delta\delta$</th>
<th>$J$</th>
<th>$K_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(arcsec)</td>
<td>(arcsec)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Strong”</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>04 30 39.59</td>
<td>+64 51 08.5</td>
<td>0.21</td>
<td>0.20</td>
<td>19.88(0.19)</td>
<td>18.60(0.08)</td>
</tr>
<tr>
<td>19</td>
<td>04 30 48.61</td>
<td>+64 50 58.5</td>
<td>0.04</td>
<td>0.36</td>
<td>14.87(0.16)</td>
<td>14.06(0.11)</td>
</tr>
<tr>
<td>26</td>
<td>04 30 52.34</td>
<td>+64 50 42.3</td>
<td>0.06</td>
<td>0.39</td>
<td>17.09(0.09)</td>
<td>16.32(0.25)</td>
</tr>
<tr>
<td>“Possible”</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>04 30 48.57</td>
<td>+64 50 49.6</td>
<td>0.42</td>
<td>0.04</td>
<td>17.20(0.63)</td>
<td>15.89(0.91)</td>
</tr>
<tr>
<td>22</td>
<td>04 30 49.85</td>
<td>+64 50 55.4</td>
<td>0.45</td>
<td>0.18</td>
<td>18.42(0.19)</td>
<td>17.82(0.45)</td>
</tr>
<tr>
<td>29</td>
<td>04 30 57.41</td>
<td>+64 50 48.6</td>
<td>0.03</td>
<td>0.55</td>
<td>19.17(0.11)</td>
<td>17.93(0.09)</td>
</tr>
<tr>
<td>23</td>
<td>04 30 50.23</td>
<td>+64 50 56.2</td>
<td>0.56</td>
<td>0.17</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

I was unable to measure good photometry for the IR counterpart to Chandra source 23 and therefore exclude magnitudes for it.

$^a$ ID numbers follow the naming convention of Martin et al. (2002).

$^b$ Chandra coordinates with an uncertainty of 0.5$''$ (Martin et al., 2002).

$^c$ Positional offsets in units of seconds of arc from the Chandra coordinates to the FLAMINGOS coordinates of the proposed counterpart.

$^d$ Units are magnitudes, from FLAMINGOS photometry. Values in parentheses indicate uncertainties in the final listed digit.
Table 7-3: Summary of Potential IR Counterpart Properties.

<table>
<thead>
<tr>
<th>Category</th>
<th>$\bar{K}$</th>
<th>$\sigma_K$ a</th>
<th>$(J - K)$</th>
<th>$\sigma_{(J-K)}$ a</th>
<th>$M_{K_s}$</th>
<th>$\sigma_{M_K}$ a</th>
</tr>
</thead>
<tbody>
<tr>
<td>all clusters</td>
<td>17.34</td>
<td>0.07</td>
<td>0.81</td>
<td>0.02</td>
<td>-9.23</td>
<td>0.07</td>
</tr>
<tr>
<td>X-ray sources</td>
<td>16.59</td>
<td>0.69</td>
<td>0.74</td>
<td>0.13</td>
<td>-9.98</td>
<td>0.69</td>
</tr>
</tbody>
</table>

a Uncertainties in each value.
Figure 7-1. False color image of NGC 1569. Red is $K_s$ and green and blue are $J$. Notice redder clusters reside on the edge of the galaxy and bluer clusters are in the center. The field-of-view of this image is $4.0' \times 4.0'$. 
Figure 7-2. Large, 10.0′×10.0′, $K_s$ image of NGC 1569, highlighting IR counterparts to X-ray sources. Red circles are “strong” counterparts and “yellow” circles are possible counterparts.
Figure 7-3. Same as Figure 7-2, but smaller, 4.0′ × 4.0′ FOV centered on the galaxy. Ellipse encompasses those sources that are most likely clusters in NGC 1569 and that were selected for the photometric study of IR counterparts.
Figure 7-4. Subimages of IR counterparts to X-ray sources in the field around NGC 1569. Red circles are “strong” counterparts and “yellow” circles are possible counterparts.
Figure 7-5. Subimages of IR counterparts to X-ray sources in the line of sight to NGC 1569. Red circles are “strong” counterparts and “yellow” circles are possible counterparts.
Figure 7-6. CMDs for sources in the complete, 4.0′×4.0′ image of NGC 1569 (left) and those within the ellipse centered on the galaxy (right; see Figure 3). Dotted line shows cutoff defined using mean $J$ and $K_s$ magnitude for clusters with $\sigma_{mag} < 0.2$. “Pluses” signify sources with SNR < 10.
Figure 7-7. $(J-K_s)$ vs $K_s$ CMD for all clusters within the large ellipse around NGC 1569 and with SNR > 10. (left) I designate those clusters with X-ray counterparts. (right) These X-ray counterparts are labeled by their classification as listed in Table 1 of Martin et al. (2002).
Figure 7-8. $M_K$, histogram for all clusters. Binned by 0.2 magnitudes.
Figure 7-9. This figure displays $\eta(1/F_{K_s})$ plotted versus $M_{K_s}$. The bins are $F_{K_s} = 1.5 \times 10^4$ in size and designated by the histogram. Error bars are the uncertainties in the mean value of $\eta$ added in quadrature with the Poisson uncertainty in each bin.
Figure 7-10. Histogram of 10,000 realizations of $\eta$, assuming a uniform distribution in ages. The bin size in $\eta$ is $1 \times 10^{-7}$. 
CHAPTER 8
CONCLUSIONS

In my dissertation I presented a multiwavelength study of XRB environments in two galactic systems—the Antennae, a large interacting galaxy pair, and NGC 1569, a dwarf, starburst galaxy. I demonstrated a powerful method for this investigation using IR wavelengths to initially look for counterparts to X-ray sources. This exploited the similar dust penetrating properties of these wavelengths and facilitated a strong frame-tie between them. The majority of my thesis focused on the Antennae and developing the methodology for this investigation.

Chapter 2 presented the IR, $J$ and $K_s$ observations of the Antennae acquired with the WIRC camera on Palomar. Here I discussed the method for identifying clusters and how I measured photometry of them.

In Chapter 3, I produced a frame tie between Chandra, X-ray coordinates and WIRC, pixel positions with a positional uncertainty of 0.2″. With this frame-tie in place, I found 19 IR counterpart candidates to X-ray sources and only expect seven are chance alignments of unrelated objects. Performing a photometric study of the 15 IR counterparts that are star clusters, I found these are more luminous and more massive than the general population of clusters.

Chapter 4 formalized the relationship between XRBs and cluster mass by defining a function, $\eta$, relating the observed number of X-ray sources to cluster mass as a function of mass in the Antennae. I found this function remained constant, consistent with a single value of $\eta = 6 \times 10^{-8} \frac{M_\odot}{M}$. This demonstrated that the observed number of XRBs scaled simply with cluster mass. Comparing XRB formation models to this result, I found the models discussed in Sepinsky et al. (2005) are consistent with my findings.

I extend my study to optical wavelengths in Chapter 5. Using the IR as an intermediary, I produced a frame tie between Chandra, X-ray and HST, optical images with a positional uncertainty of less than 0.6″. I found the optical equivalents to all IR counterparts to X-ray sources. Fitting BC spectral evolutionary models, I found these
clusters are $10^5$–$10^7$ M$_\odot$ in mass, $\sim 10^6$–$10^8$ years in age, with metallicities of $z \approx 0.05$. Due to the complexity of the HST field I did not find reliable, strictly optical counterparts to X-ray sources.

In Chapter 6, I exemplified the power of my multiwavelength technique by using it to make an important discovering with respect to the unusual X-ray source, X-37. Using my frame tie procedure, I found both a strong IR and optical counterpart to this source. Examining an IR/optical spectrum of this counterpart revealed that X-37 was a background quasar. Previously thought to be a ULX escaping from its parent cluster (Zezas et al., 2002b), this discovery demonstrated the importance of finding accurate counterparts to ULXs and then taking spectra of these counterparts to rule out those ULXs that are background quasars.

Next, in Chapter 7, I extended my multiwavelength study to the dwarf, starburst galaxy, NGC 1569, using IR $J$ and $K_s$ observations acquired with FLAMINGOS on the KPNO 4-meter telescope. I produced a tighter frame tie between the IR and X-ray images than the Antennae, with a rms positional uncertainty of 0.2′′. With this frame tie in place, I identified seven cluster counterparts with in 0.6′′ of an X-ray source and expect three of these matches are chance alignments of unrelated objects.

Performing a photometric study, I did not find a trend in color or luminosity for those clusters associated with X-ray sources. Calculating $\eta$ for this galaxy, I found a value of $3.274 \times 10^{-6}$ M$_\odot^{-1}$ with $\sigma_\eta = 1.2 \times 10^{-8}$ M$_\odot^{-1}$. Interestingly, if I placed the Antennae at the distance to NGC 1569 and scale its measured value of $\eta$, I found $\eta = 2.5 \times 10^{-6}$ M$_\odot^{-1}$, which is consistent with the derived value for NGC 1569. Comparing the XRB formation models of Sepinsky et al. (2005) to my results for this dwarf galaxy, these authors predict $\eta$ ranges from $9.6$–$11.4 \times 10^{-6}$ M$_\odot^{-1}$, which is within a factor of two from my findings.

In the future, I plan to extend my multi-wavelength project beyond the Antennae and NGC 1569, to include additional galaxies, beginning with NGC 5253, NGC 3310, NGC 1313, NGC 4559, and M 51. All are nearby ($\lesssim 13$ Mpc) star-forming galaxies that,
like the Antennae, have substantial HST optical and Chandra X-ray observations. During observing runs on the KPNO 4-m using FLAMINGOS and the CTIO 4-m using ISPI, I acquired $J$ and $K_s$ observations for each of these targets.

With a larger sample of galaxies, I can test whether $\eta$ remains constant for a range in different environments. If this quantity varies as function of mass, it could indicate an over abundance of X-ray sources in more massive clusters, possibly suggesting a top-heavy mass function as seen in some pseudo-super star clusters in the Milky Way (e.g. Stolte et al., 2005). Regardless of the functional form of $\eta$, this quantity is important for understanding a galaxy’s star formation history.

For each galaxy, I also plan to extend my project to optical wavelengths, utilizing the substantial HST archival data. As I demonstrated, precise fits between Chandra coordinates and HST positions requires using the IR/X-ray frame tie as an intermediary. The resolution and high sensitivity of HST will facilitate identification of additional cluster counterparts to X-ray sources. I can then fit spectral evolutionary models to cluster photometry to estimate mass, age and metallicity. These parameters will further characterize the birth places of XRBs.

While photometry is important, spectroscopy is essential to understanding the X-ray-associated clusters. For instance, equivalent width measurements will break the age/reddening degeneracy inherent when using spectral evolutionary model fits (Whitmore and Zhang, 2002) and greatly improve age estimates. In addition, I can derive chemical abundances, key factors for deciphering the environs of clusters and X-ray sources. Also, high-resolution spectra will allow me to directly obtain cluster mass using velocity dispersion measurements. I will then refine the relationship between XRB formation rate and cluster mass, possibly finding a correlation with X-ray luminosity. Lastly, as I demonstrated in Chapter 6, spectra of counterparts to ULXs is essential to rule-out background quasars.
Future work will also incorporate spectroscopy. Using equivalent width measurements I can break the age/reddening degeneracy inherent when fitting spectral evolutionary models to cluster photometry (Whitmore and Zhang, 2002) and greatly improve age estimates. In addition, I can derive chemical abundances, key factors for deciphering the environs of clusters and X-ray sources. Also, high-resolution spectra will allow me to directly obtain cluster mass using velocity dispersion measurements. I can then refine the relationship between XRB formation rate and cluster mass, possibly finding a correlation with X-ray luminosity. Lastly, as I demonstrated in Chapter 6, spectra of counterparts to ULXs is essential to rule-out background quasars.

My multiwavelength study will not stop here. I will continue to search for additional star-forming galaxies to add to my repertoire. As larger ground-based telescopes come on-line, I can extend by project to include more distant galaxies and possibly explore the effects of galaxy evolution on XRB environments.
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BIOGRAPHICAL SKETCH

I was born and raised in Palo Alto, California. After attending Palo Alto High School, I went to Colby College for my undergraduate studies, where I majored in physics. Much of my independent study at Colby focused on astronomy. For my senior thesis I worked with Dr. Murray Campbell on ultra-compact HII regions. I also pursued astronomy in the summer, in between semesters. During summer of 1999 I attend the research education for undergraduates program at the University of Wyoming where I worked with Dr. Warren Skidmore on cataclysmic variables.

After Colby, I attended the master’s and doctoral astronomy program at the University of Florida. During my first two years at Florida I worked with Dr. Ata Sarajedini on the three-dimensional structure of the Large Magellanic Cloud using star cluster red clumps as distance indicators. In the summer of 2003 I presented this research to my department and received an MS in astronomy. Following this work, I switched projects entirely to work with Dr. Stephen Eikenberry on the environments of X-ray sources in extra-galactic systems for my PhD.