Optical and X-Ray Studies of Compact X-ray binaries in NGC 5904

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OPTICAL AND X-RAY STUDIES OF COMPACT X-RAY BINARIES IN NGC 5904

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ABSTRACT

Globular clusters are the oldest objects in the Milky Way, serving as probes of early galactic evolution due to their chemically uncontaminated history. Compact binaries act as an internal energy source through their dynamical interactions, and measuring the types of X-ray binaries within a cluster provides an understanding of its stellar population and dynamics, as stellar collisional frequencies have been correlated to the number of X-ray sources detected in globular clusters. Compact binaries can be found by correlating X-ray positional data with optical imaging data. In this project, optical fluxes of sources from archival HST images of NGC 5904 have been measured using a DOLPHOT PSF photometry in the optical and Hydrogen-alpha (Hα). A data analysis pipeline has been developed to process of tens of thousands of objects using Awk, Python and DOLPHOT.

We identify potential optical counterparts of X-ray sources detected with the Chandra X-Ray Observatory based on their positions as outliers in color-color diagrams and color-magnitude diagrams. Seven out of nine Chandra X-ray sources within the field of view (FOV) of our HST images of NGC 5904 contain such outliers. Furthermore, X-ray fluxes of the sources in NGC 5904, along with DOLPHOT photometric fluxes are also used to determine the X-ray to optical flux ratio, which is used to identify the types of compact X-ray binaries in NGC 5904. We find four out of seven compact X-ray binaries to be Cataclysmic Variables, two to be Active Binaries, and one to be a Millisecond Pulsar. This provides details of the inner workings of NGC 5904, which has a high number of X-ray sources and a large collision rate. Support for this research from the Illinois Space Grant Consortium is gratefully acknowledged.
0.1 Introduction

Since antiquity, the study of observational astronomy has been centered around understanding stellar properties. It is now known that a clear understanding of stellar dynamics and evolution affects subfields ranging from planetary to extragalactic astronomy, and yet, as seemingly well-studied stellar systems are, there seems to be no dearth of new properties to uncover. Globular clusters are some of the oldest members of the universe, yet, despite their long histories of survival, they remain elusive in multiple ways. There is still not a clear understanding of what governs the different populations of compact X-ray binaries within galactic globular clusters, and how cluster properties affect the formation of certain types of compact X-ray binaries.

The purpose of this thesis is to use methods of PSF photometry and overlaying X-ray positional data onto HST images to identify the types of compact X-ray binary systems within NGC 5904. Measurements exist correlating the number of X-ray sources to the encounter/collisional frequency within the cluster (Pooley et al., 2003), and understanding the compact X-ray binary population of the cluster provides a richer understanding of the cluster’s stellar dynamics, and provides a space for comparisons between clusters of similar collisional frequency, for example to determine if they have similar compositional/dynamical properties. The astrometric data is supplied from measurements by the Chandra X-ray observatory, and the PSF photometry measurements of sources is achieved through operating the DOLPHOT photometry package on archival HST images of NGC 5904.

Chapter 1, on Compact X-ray binaries and Globular clusters, introduces both of these objects, and provides theoretical details on their mutual evolution and impact. It also provides a brief historical overview of globular cluster imaging and observations, highlighting the great advantages the advent of space telescopes brought
upon us. Chapter 2 outlines the theoretical background of the tools used in analyzing globular clusters, such as Color-Magnitude diagrams and PSF photometry, whereas Chapter 3 provides details into the observations made, including the significance of space-based observatories in this research. Subsequently, Chapter 4 describes all the steps needed to reduce the data, including DOLPHOT PSF photometry, filtering spurious objects out of the DOLPHOT output, combining HST and Chandra data to identify optical outliers of the Chandra X-ray sources, and characterizing the type of compact X-ray binary system responsible for producing the X-rays. Finally, Chapter 5 presents the results, while Chapter 6 draws conclusions and discusses implications for future work.

0.2 Acknowledgements

I start, awestruck by the magnitude of a single, persistent thought - a thought that my 5-year old self had of one day understanding the magic that happens in the skies above the sky. The journey I have embarked on since then would not be possible without the kindness and investment of the people who believed in me throughout.

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CHAPTER 1

Compact X-ray Binaries and Globular Clusters

This chapter places my project in historical context, elaborating on the reasons globular clusters are ideal environments to probe when looking to study compact X-ray binaries. §1.1 examines why globular clusters are interesting astrophysical environments and §§1.2.1 explores exotic stellar objects, such as compact X-ray binaries, that form in these clusters. Finally, §§1.2.2 describes the relation between compact X-ray binary systems and globular clusters, along with placing the study of compact X-ray binaries in NGC 5904 in historical context.

1.1 Globular Clusters

Globular clusters are tightly-bound, spherical collections of millions of stars and are unique astronomical tools due to their broad applications to many astronomical subfields. As they are the oldest objects observed in the Milky Way till date, they serve as witnesses of early galactic evolution, chemically uncontaminated through the passage of time. Furthermore, members of a globular cluster are very closely related, sharing a chemically homogeneous history due to their isolation from external sources, resulting in a stellar population ideal for using as a ‘stellar clock’, to test theories of stellar evolution (Murdin, 2001). The dense environment in a cluster also provides an opportunity to probe stellar dynamics, due to the large amounts of collisions and mergers that result in the formation of exotic objects such as X-ray emitting compact binaries, blue stragglers, etc.
1.2 Compact X-ray Binary Systems

Due to their high stellar densities and low stellar velocities, globular clusters present opportunities for stellar dynamics that would not be possible in the galactic disk. Both of these factors increase gravitational focusing, resulting in collision cross-sections thousands of times greater than geometric cross sections of stars (Gursky, 1973). Such conditions can result in the formation of binary (2-body) star systems. Compact binary systems refer to a binary system of stars where one or more objects are compact remnants of stellar evolution, such as a neutron star or a white dwarf. Due to their old age, mass segregation, and high central stellar density, up to $10^6 \, M_\odot \, pc^{-3}$ (Meylan & Pryor, 1993), globular clusters host a large population of compact objects and thus, such compact binary systems. Gravitational accretion onto the compact star, accretion through stellar winds and thermonuclear flashes result in the emission of X-rays from these compact binary systems. 10% of luminous X-ray sources in the galaxy are found in globular clusters, which implies, based on the number of galactic X-ray sources, the chance of finding a luminous X-ray source in a globular cluster is hundred to thousand times higher than in the rest of the galaxy (Gursky, 1973; Katz, 1975)

1.2.1 Types of Compact X-ray Binaries and methods of X-ray emission

There are multiple types of compact X-ray binaries throughout the galaxy. In general, X-ray binaries can be classified in terms of stellar masses: High Mass X-ray binaries (HMXBs) with companion stars $> 10 \, M_\odot$ and Low Mass X-ray binaries (LMXBs) with companion stars $\leq M_\odot$, as seen in Tauris & van den Heuvel (2006). However, due to the low density of young objects in globular clusters, HMXBs have not yet been found in globular clusters. Fig. 1.1 shows the various types of binary systems that have been detected in globular clusters to data (Verbunt & Lewin,
Sources with X-ray luminosities $\leq 10^{35}$ erg/s were first discovered in 1983 by the Einstein Observatory and set the course for the discovery of dimmer X-ray sources (Hertz & Grindlay, 1983a). ROSAT discovered more such sources, clarifying the diversity in dynamics underlying the X-ray emission (Verbunt, 2001), revealing that not just cataclysmic variables, or LMXBs were responsible for these emissions, and there exists a broad range of compact binary systems emitting X-rays. This range is outlined in Fig. 1.1.

Figure 1.1: Types of compact X-ray binaries found in globular clusters, where MS, WD and NS stand for main sequence star, white dwarf and neutron star. From top-to-bottom is an LMXB system, a cataclysmic variable, a millisecond pulsar with a white dwarf companion, and a magnetically-active binary star. Adapted from an illustration in Verbunt & Lewin (2006).
Most compact binary systems in globular clusters evolve from, or are a twist on a traditional LMXB system. In an LMXB system, the compact object, i.e. a neutron star accretes material gravitationally and this gravitational accretion generates X-rays. In the LMXB configuration, the neutron star accretes material when its companion star has evolved to the point where it has filled its Roche lobe, and the neutron star is more massive than its companion. Due to this, the neutron star gravitationally accretes mass that is transferred through the unstable Lagrange point, L1 of any LMXB/LMXB-type system.

The X-ray profiles of LMXBs are unique. Unlike the regular pulsations seen in the X-ray spectra of highly magnetized neutron stars in binary systems, the neutron star for LMXB systems have relatively weak magnetic fields ($10^9 - 10^{11}$ G), with rare pulsations. The weak magnetic fields in LMXBs is hypothesized to be due to accretion-induced field decay (Taam & Heuvel, 1986; Geppert & Urpin, 1994; Konar & Bhattacharya, 1997; Cumming, Zweibel & Bildsten, 2001). However, LMXB systems exhibit X-ray bursts very often, due to the thermonuclear fusion of the infalling accreting material on the neutron star surface. Neutron stars with strong magnetic fields can suppress these bursts (Lewin & Joss, 1983).

There are two types of LMXBs. One is a luminous LMXB, which refers to a LMXB system with an X-ray luminosity $\geq 10^{36}$ erg/s. X-ray measurements using the first X-ray satellite, Uhuru, showed a concentrated number of luminous ($\geq 10^{36}$ erg/s) X-ray sources in globular clusters versus the rest of the galaxy, and have been attributed to X-ray bursts in LMXB systems with neutron stars (Clark, 1975; Lewin et. al., 1993). The X-ray bursts in luminous LMXB systems are due to thermonuclear burning on the surface of a neutron star on which material has freshly been accreted. This freshly accreted material is compressed and heated to densities and temperatures suitable for thermonuclear fusion in a matter of days. The quick nature of this thermonuclear burning results in an uncontrolled process creating short and abrupt
increases in X-ray flux, that last from ten to hundred seconds, recurring with a frequency set by the rate of accretion. Conclusive proof of the compact nature of LMXBs was observed by the X-ray spectra generated during the bursts, which were consistent with thermonuclear burning on a neutron star (Kuukers et. al., 2003).

Unlike bright X-ray sources that are clearly identifiable as X-ray bursts in luminous LMXBs, the nature of low-luminosity X-ray sources with $L_x \leq 10^{35}\text{erg/s}$, was not as easy to determine. Decades of research showed that these low luminosity sources could be Cataclysmic Variables (Hertz & Grindlay, 1983b), quiescent LMXBs (Hertz & Grindlay, 1983a), Millisecond Pulsars (Saito, 1997) or magnetically active binaries (Bailyn et. al., 1990).

Thus, the second type of LMXB discovered is a low-luminosity LMXB. This is also an LMXB system, and gravitationally accretes material from its companion star after the companion’s Roche Lobe is filled to produce X-rays like the luminous LMXB, but has a lower X-ray luminosity of $\leq 10^{35}\text{erg/s}$. This is thought to be due to an LMXB being observed during a period of inactivity (quiescence) (Verbunt et. al., 1984).

Millisecond Pulsars (MSPs) are formed from LMXB systems in globular clusters. In a globular cluster, due to its high stellar densities, a compact binary is formed via stellar exchange interactions when a main sequence star in a binary is replaced by the neutron star. For MSPs, these neutron stars have magnetic fields. Once the compact binary is formed, the companion starts evolving to the red-giant phase, fills its Roche lobe, and transfers material to the neutron star, creating an LMXB-type system, although material is redirected to the neutron star’s magnetic poles. Angular momentum from the inner edges of the accretion disk is also transferred to the neutron star and causes it to rotate with a period of a few milliseconds. X-ray emission in a MSP is completely powered by accretion, and the X-ray emission is bright and periodically fluctuating (Tauris & van den Heuvel, 2006).
Cataclysmic variables (CVs) are another kind of low-luminosity, compact X-ray binary source. Similar to LMXBs, the companion star fills its Roche lobe and loses mass to the compact object, which is a white dwarf in the case of a CV. CVs can be thought of as white dwarf analogs to LMXBs that exhibit X-ray emission due to gravitational mass loss resulting in thermonuclear burning on the white dwarf surface.

Furthermore, some stars found on the lower main sequence can produce X-rays in their coronae, due to processes occurring in their convective zone. The motions of gas in the convection zone and the differential rotation creates electric currents and thus a magnetic field. In general, the X-ray luminosity of these single chromospherically active stars is determined by their rotation rate, so as they age and their rotation rate slows down, their X-ray production drops to inconsequential values. However, in globular clusters, chromospherically active stars can be found in a binary combinations, known as active binaries (ABs). They are tidally locked, and thus forced to continually rotate at high frequencies, unlike the single active stars that eventually rotate at slow speeds and generate little X-ray emission. ABs make up the majority of the faintest globular cluster X-ray sources, with X-ray luminosities $L_x \leq 10^{32}\text{erg/s}$ (Heinke, 2010).

In order to differentiate between MSPs, CVs and ABs, X-ray to Optical flux ratios are used (Tauris & van den Heuvel, 2006; Verbunt & Lewin, 2006). Active Binaries have the smallest $F_x/F_{opt}$ ratio, always much less than 1, whereas MSPs have an X-ray to Optical flux ratio $(F_x/F_{opt}) \geq 0.1$ and $\leq 0.5$. CVs have the highest $F_x/F_{opt}$ ratio, greater than 1. While qLMXBs have similar $F_x/F_{opt}$ ratios to CVs, their X-ray luminosity is generally higher and can be used to differentiate between these compact binaries.
1.2.2 Formation of compact binary systems and their effect on globular cluster evolution

Binaries in clusters evolve in conjunction with the cluster itself. As is true for all self-gravitating systems, globular clusters are under the threat of core-collapse without a source of internal energy. Binaries are essential to globular clusters for this reason: they act as an energy source through their dynamical interactions, postponing core-collapse. While there are other methods of internal energy generation in a cluster (Goodman & Hut, 1989), they will not be discussed here.

Binary dynamics and evolution in clusters mainly happen due to the processes of mass segregation, three-body or stellar exchange interactions, binary-binary interactions, and stellar/binary evolution (Hut et. al., 1992). Mass segregation occurs when binary systems, due to their larger masses, move towards the cluster’s core. This is the reason for dense globular cluster cores as seen in archival images in Ch. 4 and also explains why a large population of compact binaries are found in cluster cores.

It is also important to note that adding energy to a self-gravitating system cools it down, as it postpones core collapse (Fregeau, 2007). This is phenomenon occurs even as a proto-star collapses. If it is given external energy, its core does not get as compressed and it will not heat up as much as if it were under its own self-gravity. This is especially important when examining three-body/ stellar exchange interactions in the cluster’s heavily populated core. When a binary system of stars encounters a single star where the orbital speed within the binary is larger than the relative speed of the single star and binary, it transfers energy to the single star. Such a binary system is known as “hard”, as it has an orbital velocity exceeding the average velocity of the system, or in other words, a greater orbital speed than encounter speed. Since the hard binary system gave up energy when encountering the single star, it will become more tightly bound with a larger orbital speed and will continue becoming harder with a closer orbit as a result of dynamical interactions.
(Heggie, 1975). This population of hard binaries is a great source of internal energy generation in a cluster, as single stars come out of the scattering process with more energy than they initially had (Hut et. al., 1992). While hard binaries in cluster cores tend to become more and more closely bound, softer binaries (with great encounter speed than orbital speed) are quickly destroyed by three body/stellar exchange interactions in the cluster’s core (Heggie, 1975; Hut, 1983) as seen in Fig. 1.2. The violent encounters with harder binaries propel single stars to greater distances, counteracting the core collapse of the cluster.
Figure 1.2: Illustration of a three-body interaction resulting in a compact binary adapted from Seward & Charles (2010). A main-sequence binary encounters a neutron star, resulting in a LMXB. The inset shows how this looks at a distance.

Binary-binary interactions have more outcomes than three-body interactions and result in a larger variety of dynamics, however in all binary interactions, wide binaries are destroyed, and harder, more energetic binaries are formed (Mikkola, 1983). The single star products of such binary-binary interactions can either reach a velocity high enough to escape the cluster, or physically collide with another star.
Furthermore, Stellar evolution within binaries also has an impact on their eventual fate (Hut et. al., 1992).

Compact binaries are formed using a combination of processes. Mass segregation, coupled with three-body/binary-binary interactions is one method of formation. Apart from the cluster's old age, and large population of compact objects, such binaries are also formed due to the fact that the heaviest stars tend to be left in the final hard binary (Hut et. al., 1992). This is because of a tendency of systems to achieve a state in which the lightest star would have the highest velocity in the final state. To add to previous discussion on the formation of hard binaries, the increase in mass in the final binary also increase gravitational forces, making collisions more likely than before the dynamical interaction, and helps produce other compact binaries. This tendency for the final binaries to be heavier (thus having more compact objects) and harder illustrates the intertwined evolution of compact binaries and globular clusters.

Tidal capture is another method by which compact binary systems are formed. In this process, a sufficiently close encounter between two unbound stars loses enough energy in tidal oscillations that the pair of stars becomes bound. Forming a binary system requires a transfer of kinetic energy to potential energy, and since stars in the cluster core move at high velocities significant kinetic energy needs to be transformed. Tidal dissipation of energy is effective in slowing down stars although it is not one of the most effective method of binary formation in cluster cores, since stars must be relatively close to experience tidal forces. Tidal-capture binaries are expected to make up less than 1% of cluster binaries (Hut et. al., 1992).

Thus, compact X-ray binaries are formed through tidal capture, binary-binary interactions and three-body/stellar exchange interactions. All these processes have lasting influences on the evolution of a cluster. Optical and X-ray observations have been made (Pooley et. al., 2003) to explore the relationship between a cluster's
physical properties and its compact binary systems, as seen in Fig. 1.3, and show that the number of X-ray sources in a cluster increases as the stellar encounter frequency increases. This demonstrates that compact X-ray binaries seem to be formed in stellar encounters.

Figure 1.3: Graph relating the number of globular cluster X-ray sources, $N$, to the normalized encounter rate $\Gamma$ for globular clusters. NGC 5904 is one of the clusters included in this study. Graph taken from Pooley et. al. (2003).

The encounter rate $\Gamma$ effectively measures stellar densities in the cluster cores, while $N$ is the number of compact X-ray binary sources found. As seen from Fig. 1.3, high core densities result in more compact X-ray binaries, which in turn affect the cluster. The cluster NGC 5904 follows the trend.
1.3 Historical observations of globular cluster and their compact X-ray binaries

Globular clusters were first used by Kapetyn to investigate the structure of the Milky Way, which was then thought to be the extent of the universe, and our position in it. In 1830, John Herschel and in 1909, Karl Bohlin revised Kapetyn's model by observing the distribution of globular clusters. Harlow Shapley made a significant advance in this area using variable stars to measure distances to these globular clusters in 1918, creating a more accurate model of the Milky Way. In the 1940s, Walter Baade concluded that galactic globular clusters consist of older stars, and the value of clusters in understanding stellar evolution was discovered.

The first detections of X-ray sources, albeit with a luminosity $\geq 10^{36}$ erg/s were made using UHURU and OSO-7 satellites in the 1970s, and it was found that 10% of the luminous galactic X-ray sources were in globular clusters (Katz, 1975). Although it was realized that globular clusters have some characteristics that make them efficient in X-ray production, it was not clear then that X-rays were emitted by binary systems (Lewin & Joss, 1983; Verbunt & Hut, 1987). Later, it was then suggested that binaries formed by capture of massive stellar remnants produced X-rays (Clark, 1975), and multiple mechanisms of forming compact X-ray binaries were discussed, such as tidal capture, star exchange interactions etc. (Fabian et. al., 1975). The efficiencies of tidal capture and exchange encounters for compact objects, like neutron stars and white dwarfs were compared, and it was shown that the distribution of X-ray sources in globular clusters with different central densities and core sizes matches what should be observed if compact X-ray binaries were formed by close encounters (Verbunt & Hut, 1987), and the effect of mass segregation was appreciated (Verbunt & Meylan, 1988). Luminous cluster sources were found to be neutron stars (Lewin et. al., 1993), and positional measurements of these sources were made. Greater sensitivity by Einstein then ROSAT and finally
Chandra and XMM-Newton telescopes allowed observations of less luminous sources (Hertz & Grindlay, 1983a) and the positional accuracy along with the HST-era led to optical observations of X-ray sources. It was then discovered that low-luminosity sources are of various types, such as CVs, LMXBs, MSPs, and ABs, and the optical observations and photometry of the sources enriched our understanding of their dynamical formation. Correlating optical and X-ray data has resulted in better characterization of cluster X-ray sources, and also enabled a correlation between the number of compact X-ray binaries and the collisional frequency in the core of the cluster, as seen in Fig. 1.3.
CHAPTER 2

Tools used to understand globular cluster evolution and composition

This chapter goes into details about the role of color-magnitude diagrams and PSF photometry techniques in reducing and interpreting observational HST ACS data.

2.1 The Role of Color-Magnitude Diagrams (CMDs) in understanding Globular Cluster Evolution

Color-magnitude diagrams, or CMDs, play a crucial role in understanding stellar evolution since they allow us to evaluate the stellar content of a globular cluster. As globular clusters are tightly-bound collections of stars, a color-magnitude diagram of a globular cluster represents the fundamental properties of its constituent stars, and thus provides insight into the cluster’s evolution.

2.1.1 Features of a Globular Cluster CMD

A key feature of a CMD is the stellar sequence, as seen in Fig. 2.1. This stellar sequence is a result of single stars evolving via fusion. Fusion starts when the central temperature in a proto-star increases due to its gravitational collapse and nuclear reactions in its core are stimulated. This results in the in-falling hydrogen gas forming helium, eventually reaching an hydrostatic equilibrium. In the state of hydrostatic equilibrium, the radiation pressure due to fusion in the star’s core is in equilibrium with its self-gravity. When this equilibrium is reached, a star reaches the main sequence, where it approximately spends 70% of its stellar lifetime, until there
is no more hydrogen left to fuse in its core. As the hydrogen in the core diminishes, a shell of helium forms and the star contracts due to decreased radiation pressure. This causes its outer layers to expand and cool down. This change takes place at the main-sequence turn-off point, which is the hottest and bluest point on the main-sequence. The location of the turn-off point depends on the age of a globular cluster as more massive stars deplete hydrogen faster. Thus, the turn-off point can be thought of as a stellar clock. While the turn-off point is luminous and blue/hot for younger stars, as the stars in a cluster grow older, the main-sequence turn-off point moves to a lower luminosity and cooler/redder location because older stars tend to be dimmer and redder than younger ones. Thus, the luminosity of the turn-off point can be used effectively to find the age of a globular cluster. An interesting note about the main-sequence for globular cluster CMDs is that they display a very sharp turn-off point and a narrow main-sequence, illustrating that the stars in the cluster formed around the same time, and have similar chemical compositions and thus similar colors.
On crossing the turn-off point, stars start fusing hydrogen around the newly created helium core. As the core contracts due to its self-gravity, the outer shells expand due to increased radiation pressure from fusion. This cools down the star, causing it to become a red-giant. This red-giant transition continues until the helium core is gravitationally compressed to commence fusion via the triple-alpha reaction. This helium burning creates carbon and oxygen, along with maintaining the hydrogen shell around the core. Following the creation of metals in the core, the hydrogen shells starts fusing and the star enters the asymptotic giant branch. At this stage
fusion to heavier metals and mass loss due to stellar winds result, until a white dwarf remains. In the CMD in Fig. 2.1, a class of objects called “blue stragglers” (Sandage, 1970) are also seen. Although they seem to be along the path of the main-sequence, they are at a higher mass than the turn-off, where they should have already evolved off the main sequence. Multiple methods of evolution of blue stragglers have been proposed and more than one are perhaps at play in a cluster (Bailyn & Pinsonneault, 1995; Sarajedini, 1993; Leonard, 1989). There is a suggestion that the collisional and mass-transfer interactions in clusters result in blue stragglers however this is not the only mechanism by which they are thought to evolve (Murdin, 2001; Ashman & Zepf, 1998).

2.1.2 Identifying binaries in globular clusters using a CMD

The evolution of a single star would follow the path outlined in the CMD above, however, this is not true for binaries. If a binary system is composed of two main-sequence stars with the same color and luminosity, the total luminosity of a binary star system would be twice that of a single main-sequence star with the same color, so these binaries are expected 0.75 mag above the main sequence. Furthermore, if one of the stars is an accreting compact object and has a lower luminosity compared to its main-sequence companion, it will be above but closer to the main-sequence, and bluer due to the energetic process of accretion. Given that compact X-ray binaries consist of a pair of stars, and in many cases accretion-powered evolution, they are expected in certain parts of the CMD. Details of where to expect CVs and ABs are seen in Fig. 2.2.
Figure 2.2: CMD showing expected positions of CVs and ABs. Data was taken for 47 Tuc in astronomical filters F300W and F555W, and adapted by J. E. Grindlay from Heinke (2010)
Since LMXBs, MSPs and CVs are accretion dominated, they are expected to be found in the bluer parts of the CMD, unlike ABs, which are composed of two main-sequence stars and are expected at the same color, just 0.75 mag above the main sequence. A combination of $F_x/F_{Opt}$ and CMD positions is used when identifying optical counterparts to X-ray sources. Thus we can apply this method of classifying and identifying optical counterparts to X-ray sources to the CMDs generated using DOLPHOT in §5. This will allow us to probe NGC 5904’s compact binary composition and thus better understand its evolution.

2.2 Point Spread Function (PSF) Photometry theory and advantages

Photometry needs to be performed on the optical images of NGC 5904 to measure the magnitudes needed to construct CMDs such as Fig. 2.2. There are two methods of measuring the brightness of point sources from CCD images - aperture photometry and PSF photometry. In aperture photometry, a circle enclosing the source is an aperture, and another ring outside the first circle contains the sky. Mean counts per pixel are measured when the sky aperture subtracted from counts of the source aperture. However, given the crowded field of NGC 5904, aperture photometry will not provide accurate results since it assumes a linearly-varying background in the aperture’s vicinity. Furthermore, since the background does not vary uniformly throughout the image, performing aperture photometry on NGC 5904 would require manually setting the aperture for each object. Even if one were to manually set apertures, it would provide inaccurate photometry due to the globular cluster background’s non-linearity and the fact that an aperture may contain contributions of multiple objects due to the high density of stars in the cluster images.

Thus, PSF photometry must be used. The PSF is determined by a Pixel Area Map (PAM) for the particular filter. Multiple overlapping stars can be fit simultaneously by using a PSF fitting algorithm, which identifies the stars and fits a model to their
intensity profiles. Furthermore, since the PSF is based on information obtained from the various PAMs in different filters, it accounts for the variations between different filters and can be fit to the centroid of each bright point source. Additionally, the height of the PSF curve corresponds to the brightness (Stetson, 1987). In all the photometry programs for crowded fields, such as DAOPHOT, HSTPhot and DOLPHOT, star brightness and position measurements are made using PSFs that best match the data (Dolphin, 2000).

Since the HST ACS camera is used for all images in this study, stellar PSF models corresponding to ACS are built into DOLPHOT and are used as initial PSF fits (Dolphin, 2000). These PSFs allow a detailed PSF model to fit the crowded field of NGC 5904 and measure magnitudes. The PSF determination is dependent on preprocessing steps prior to running DOLPHOT are described in §4, and one can calculate a sky image for the cluster. The sky image generated is subtracted from the data image, and the residual is scanned for peaks in various trials. At the location of a detected peak, an initial guess is made for the central position of the star using positional averages weighted by the pixel values. Through an iterative process, a photometry solution to measure the star’s brightness and improve its position is implemented, with a quality-of-fit parameter determined in every trial. The quality-of-fit parameter is maximized in DOLPHOT PSF photometry (Dolphin, 2000). Thus, PSF-fitting allows for photometry to be done in the crowded fields of globular clusters, like NGC 5904, and produce accurate CMDs as seen in §5.
CHAPTER 3

Observations and Instrumentation

This chapter discusses the reasoning behind using the Chandra X-ray Observatory and the Hubble Space Telescope for measuring compact X-ray binaries in NGC 5904 in §3.1, and provides details of the archival datasets used in §3.2.

3.1 Instruments

We used archival Hubble Space Telescope images of NGC 5904 for this study. We then overlaid positions from the Chandra Source Catalog and searched for optical counterparts near these source positions. These instruments are described in further detail in the following subsections.

3.1.1 Hubble Space Telescope

Given the large stellar densities that exist in globular clusters, ground-based telescopes, despite their state-of-the-art adaptive optics systems, are unable to resolve a cluster’s core to the high angular resolution of HST. However, HST is able to probe the regions with extremely high stellar densities at the center of the cluster. The advantage of using HST for observations of globular clusters is seen in Fig. 3.1, where the cluster 47 Tuc is imaged both from the ground using the Schmidt telescope as part of the Digitized Sky Survey (DSS), and HST ACS. A clear difference in resolving power is seen, which is a major advantage that HST brings to globular cluster imaging. A second advantage is the ability to obtain images in the UV, which is
not possible by ground-based telescopes due to atmospheric absorptions. High resolution images are extremely important when trying to identify optical counterparts within the Chandra positional error circle that corresponds to an X-ray source, and thus, HST data is used.

Figure 3.1: Comparison of HST ACS and ground-based DSS observations of globular cluster 47 Tuc [credit: NASA & ESA]. A comparison of the two images clearly shows the much higher spatial resolution of HST.

In particular, we used archival images of NGC 5904 taken with the Advanced Camera for Surveys (ACS) of the Hubble Space telescope. The archive also contains images of NGC 5904 taken with Wide Field Planetary Camera 2 (WFPC2) and Wide Field
Camera 3 (WFC3), but these were not used for this study. The Wide-Field (WF) channel of the HST ACS camera was used for data collection. The WFC instrument has two different CCD detector chips, WFC1 and WFC2, that produce 4096×2048 pixel images each, covering a total FOV of 202×202 arcsec. The detectors are manufactured by Scientific Imaging Technologies (SITe) and are thinned, backside illuminated, anti-reflection coated and multiphased pinned CCDs, with a spectral response ranging from 3500 Å to 11,000 Å and a peak efficiency (averaged for WFC1 and WFC2) at 7000 Å. Detectors are arranged to create a 4096×4096 pixel array, with a 50 pixel gap in between chips.

Multiple filters were also used to collect the data. For WFC imaging, the desired filter in one filter wheel is rotated into position and a CLEAR aperture in the other filter wheel is automatically selected since both filter wheels are attached and operate together. The wideband filters F435W and F625W were used in conjunction with the narrowband Hα filter 658N. F435W is part of the Johnson-Cousins BVI set and is on filter wheel 2, whereas F625W is part of the Sloan Digital Sky Survey griz filter set and on Filter wheel 1 along with F658N (Ryon, 2018).

### 3.1.2 Chandra X-ray Observatory

While luminous X-ray sources had been discovered by Uhuru and OSO-7 satellites, there were very little low-luminosity \( \left( L_x \lesssim 10^{35} \text{erg/s} \right) \) detections. The deployment of Einstein followed by ROSAT changed that, detecting multiple low-luminosity sources (Hertz & Grindlay, 1983a; Verbunt, 2001). However, the astrometric positions with Einstein and ROSAT were not precise enough to identify optical counterparts, as was necessary if one wanted to characterize the nature of low-luminosity X-ray sources (see §1.2 for a detailed discussion). Chandra’s high spatial resolution compared to previous satellites, as seen in Fig. 3.2 is crucial to identifying the kinds of compact X-ray binary systems and dynamics present in clusters. Fig. 3.2 shows
a collage of images taken with Einstein, ROSAT and Chandra that illustrate the improvement in spatial isolation (Pooley et. al., 2003).

Figure 3.2: Images of 47 Tuc created using 8 ks of Einstein data (left), 77 ks of ROSAT data (center), and 240 ks of Chandra data (right). The Chandra data has been color-coded so that 0.5 - 1.2 keV photons are in red, 1.2 - 2.5 keV photons are in green, and 2.5 - 8 keV photons are in blue. Image is taken from Pooley et. al. (2003).

Because the core of NGC 5904 is extremely crowded, it was important to use high-resolution Chandra data in order to limit the number of objects that have to be examined as potential optical counterparts. The Chandra Source Catalog (CSC) v1.1 was used to find X-ray sources corresponding to the measurement seen in Fig 1.3. The observation ID used to take the data used in Pooley et. al. (2003) was noted and used to search the CSC. The CSC contains the coordinates of each X-ray source along with positional uncertainties and X-ray fluxes. The RA and Dec of these sources were plotted on the HST drizzled image, and sources that fell within the FOV of the drizzled image were assumed to be the X-ray sources. Since we did not perform any astrometric transformations between Chandra ICRS and HST GCS1 coordinates, we increased the positional error circle radius by 0.5" (Schmidt & Green, 2003) to account for any sources that may not be visible due to lack of astrometric alignment.
3.2 Data

3.2.1 The globular cluster NGC 5904

The globular cluster NGC 5904 or Messier 5 was discovered by Gottfried Kirch in 1702, and first resolved into stars by William Herschel in 1791. It has an RA of 15h 18.6m and a Declination of +02° 05' and is 7.5 kpc away with an apparent visual magnitude of 5.6 and distance modulus of 14.46 (Harris, 1996). It is one of the largest galactic globular clusters, found in the constellation Serpens, with a diameter of 50 pc, and a half-mass radius of 4 pc. M5 is receding from us at 52 km/s and is thought to contain a large number of variable stars (Frommert & Kronberg, 2007; Bailey, 1899). Previous optical studies have been performed on NGC 5904, examining the proper motions of its compact objects (Friere, 2008), studying its blue straggler population (Lanzoni et. al., 2007), and performing photometry to obtain true distances (Layden et. al., 2005). However optical counterparts to its X-ray sources have never been examined before.

3.2.2 Details about the archival NGC 5904 data used

The archival HST NGC 5904 images used were taken by Scott F. Anderson, Lee Homer, Walter Lewin, Bruce H. Margon, David Pooley, Frank Verbunt and Cees Bassa on August 1, 2004. The proposal had the ID# is 10120 and title “The Formation Histories and Dynamical Roles of X-ray Binaries in Globular Clusters”. The study aimed to understand the optical nature of the various X-ray subpopulations in NGC 5904, NGC 6121, NGC 6266, NGC 6341, NGC 6541 and NGC288 in order to classify it into the various subtypes: CVs, qLMXBs, ABs and MSPs and build upon the previously measured relationship between the number of X-ray sources and the predicted stellar encounter frequency in globular cluster cores (Pooley et. al.,
2003). We chose this dataset for our study because it has images in three different filters taken in the same orbit. However, other images taken with ACS, WFPC2 and WFC3 are also available.

The X-ray sources of NGC 5904 were observed by Walter H. G. Lewin in September 2002. The proposal ID# 03300437, the Observation ID# is 2676. The proposal aimed to observe several of the clusters shown in Fig. 1.3. Given the HST FOV is only $202 \times 202$ arcsec$^2$ compared to the $8.3 \times 50.6$ arcmin$^2$ ACIS-S FOV, only nine sources were found in the FOV of the HST images, as seen in Fig. 4.15. The astrometric positions of these sources were computed by the Chandra X-ray Center (CXC) and made publicly available through the Chandra Source Catalog (CSC) version 1.1. In order to verify the astrometric positions, we accessed this astrometric data both through DS9’s catalog analysis tools that automatically identifies the positional range of the HST drizzled image and plotted X-ray sources, and compared it to a search by observation ID in CSCView, where the same sources were recovered.
CHAPTER 4

Analysis

This chapter provides a discussion of the analysis techniques used to obtain photometry from the HST images in §4.1 along with an interpretation of this photometric output in §4.2. The process used to combine Chandra astrometric data with HST photometric data is detailed in §4.3, in conjunction with how the compact X-ray binary systems are identified out of the multiple optical sources within the uncertainty of an X-ray astrometric position.

4.1 Performing Photometry

In order to accurately obtain the optical fluxes of all the objects in the crowded field of NGC 5904, it was necessary to perform PSF Photometry. Since the archival data was obtained using the HST ACS, it was most efficient to use a photometry software package that was calibrated to and had precomputed PSFs corresponding to HST ACS. DOLPHOT (Dolphin, 2000) is a software package developed to perform stellar photometry and has ACS-specific support. It is a more generalized adaptation of HSTPhot, which is a stellar photometry package designed for the former-generation WFPC2. DOLPHOT has camera-specific calibrations and PSFs not just for ACS but also WFC3.
4.1.1 Preprocessing steps prior to performing the photometry using DOLPHOT

Flat-fielded images for NGC 5904 are downloaded from the Mikulski Archive for Space Telescopes (MAST). They need to be corrected to eradicate bad pixels and to have image counts proportional to the number of electrons in the raw data. Pixel Area Maps (PAMs) provide the distribution of electron counts across the chips of the ACS in each filter and were available through the DOLPHOT package. Running the command `acsmask *fits` masks out all the pixels flagged as bad, and multiplies the flat-fielded images with the PAM in the corresponding filter.

When downloaded from MAST, the flat-fielded images were in a two-extension fits format, with fits images in both chips 1 & 2 of the ACS camera. DOLPHOT’s ACS module was used to separate the extensions and create two different fits files from each of the extensions in the original flat-fielded (.flt) file through the command `splitgroups *fits`. Creating separate fits files for each chip is important as sky values and stellar distribution is different between chips since each 2048pix × 1024pix chip looks at a different part of the sky.

After separating the fits files for each of the chips, the sky was calculated for each flat-fielded file using the command `calcsky <fits base> <inner annulus> <outer annulus> <step> <sigma_low> <sigma_high>` where parameters were set to values optimized for ACS. This was done for each fits file individually, and creates a sky image as seen in Fig. 4.1. The sky image is clearly non-uniform, with high sky brightness in the core region. Although they might seem like stars, the bright areas are purely the sky. This is due to the high core density of the stars in globular clusters, and clearly using aperture photometry with such a non-uniform sky and crowded field would create inaccuracies.
4.1.2 Using DOLPHOT to perform PSF photometry

PSF Photometry is performed in ACS module of DOLPHOT by providing a list of the flat-fielded fits files to be photometered and of parameters used for the photometry. A parameter file with the .par extension was used to input this information, via command-line scripting in bash using the command dolphot <base name of
output file> -p<base name of parameter file>. The parameter file fixes values of certain parameters to default ACS values prior to running DOLPHOT, as these parameter values control how the photometry is performed. The parameter file used in this study is shown in Appendix A.

In the parameter file, along with specifying the number of flat-fielded files to be photometered, and their base names, it is also essential to specify a reference image, which is used to ensure all the images are aligned. We used a drizzled .drz image available from the HST archives as a reference image. The flat-fielded files were then automatically aligned to the reference by the software. The particular drizzled image was chosen in the $B_{435}$ filter as it is the deepest image, especially when compared to the $H_{658}$ filter (see Figs. 4.2a, 4.2b and 4.2c).

![Figure 4.2: DOLPHOT PSF photometry output plotting the average photometric error versus magnitude for $B_{435}$, $R_{625}$ & $H_{658}$. Multiple sequences result from combining the photometry of flat fielded files with different exposure times, as seen in Table 4.1](image)

The two sequences seen in Figs. 4.2a and 4.2b are due to the fact that the photometry from various flat fielded images with different exposure times was combined. Dimmer objects were not visible in the flat fielded images with lower exposure times, thus providing some objects in the field with greater magnitude errors than others. Table 4.1 describes the filter and exposure time of each flat fielded file. Only the
$B_{435}$ images were used to generate the drizzled image.

Table 4.1: Flat fielded images in different filters with exposure times

<table>
<thead>
<tr>
<th>Image name</th>
<th>Exposure time (s)</th>
<th>Filter name</th>
</tr>
</thead>
<tbody>
<tr>
<td>j92101kjq</td>
<td>10</td>
<td>$R_{625}$</td>
</tr>
<tr>
<td>j92101kkq</td>
<td>170</td>
<td>$B_{435}$</td>
</tr>
<tr>
<td>j92101kmq</td>
<td>170</td>
<td>$B_{435}$</td>
</tr>
<tr>
<td>j92101koq</td>
<td>170</td>
<td>$H\alpha_{658}$</td>
</tr>
<tr>
<td>j92101kqq</td>
<td>170</td>
<td>$H\alpha_{658}$</td>
</tr>
<tr>
<td>j92101ktq</td>
<td>70</td>
<td>$R_{625}$</td>
</tr>
<tr>
<td>j92101kzq</td>
<td>110</td>
<td>$R_{625}$</td>
</tr>
<tr>
<td>j92101l1q</td>
<td>70</td>
<td>$B_{435}$</td>
</tr>
<tr>
<td>j92101l2q</td>
<td>270</td>
<td>$H\alpha_{658}$</td>
</tr>
<tr>
<td>j92101l4q</td>
<td>270</td>
<td>$H\alpha_{658}$</td>
</tr>
<tr>
<td>j92101l7q</td>
<td>110</td>
<td>$R_{625}$</td>
</tr>
</tbody>
</table>

The drizzled image stored in the archive is created using the DrizzlePac software package from the Space Telescope Science Institute (Gonzaga et. al., 2012), and is a composite image created by combining flat-fielded and cosmic-ray-rejected images using spatial transformations in the F435W filter. The drizzling process creates an image with higher spatial resolution and is deeper than the individual files as seen in Fig. 4.3. However, combining multiple flat-fielded images using the drizzling process distorts pixel values and makes it inaccurate for photometry. Thus, a drizzled image is best used as a positional reference image to shift all the dithered flat-fielded images to its positions, but photometry is performed on individual flat-fielded images.
(a) Drizzled image of NGC 5904 in the $B_{135}$ filter, obtained from the MAST archive. The distorted shape of the image is due to the titled position of the ACS WFC by 22° with respect to the focal plane (Ryon, 2018). During the drizzling process, this inherent spatial distortion in the flat-fielded files is removed, resulting in a distortion of the drizzled image shape.
Figure 4.3: When comparing the drizzled image with the individual flat-fielded images of NGC 5904 in the same ($B_{435}$) filter, it is seen that the drizzled image has higher spatial resolution and is deeper and thus better to use as a positional reference image.

Thus, along with the reference image, the base names of all the flat-fielded files in the $B_{435}$, $R_{625}$, and $H_{658}$ filters were specified in the parameter file so they would all be aligned to the drizzled image using DOLPHOT ACS’ built-in alignment utility. There were some other image-specific parameters that needed to be specified for each of the 22 images. In most cases, we decided to adopt the default values configured for HST ACS, as are listed in Appendix A.
4.1.3 Interpreting the DOLPHOT output

After DOLPHOT has been successfully run and measured photometry, \texttt{Awk} is used to extract the values of roundness, crowding and sharpness and magnitudes of $B_{435}$, $R_{625}$ and $H\alpha_{658}$ along with the magnitude errors. The roundness, crowding and sharpness values are used in §4.2 to filter out spurious objects, as roundness measures the degree of circularity of the object being photo-metered and can differentiate between stars and spiky objects like diffraction spikes. Similarly, sharpness uses the PSF fit to determine whether an object is a star or an extended object, such as a background galaxy. Finally, crowding measures, in magnitudes, how much brighter an object would be had the stars in its vicinity not be simultaneously fit (Dolphin, 2000). Along with the DOLPHOT input parameters, these output parameters can be used to eliminate spurious objects and background galaxies from the DOLPHOT output. Due to the millions of stars in the cluster, appropriate values for the output parameters were determined by looking at an arbitrarily chosen core region of NGC 5904 and an arbitrarily chosen region in the outskirts of NGC 5904, under the assumption that these sample regions were representative of all the core and outskirt regions of NGC 5904 respectively.
4.2 Creating Color-Magnitude Diagrams

Figure 4.4: Image shows a small portion of the cluster, where red circles represent all the “objects”, including spurious objects, on which PSF photometry was performed using DOLPHOT. These are all the “objects” to which a PSF was fit, and photometry was performed, however, they are clearly not all stars, or binary systems. As can be seen, multiple spurious objects are detected at the centers of saturated stars and along the diffraction spikes.

Color-Magnitude Diagrams (CMDs) are created using the PSF Photometry outputs from the ACS module of the DOLPHOT software package. Using the cumulative VEGAMAG magnitudes in the $B_{435}$, $R_{625}$ and $H_{658}$ band-passes, CMDs are generated. However, since DOLPHOT detects bright regions, it often erroneously fit diffraction spikes or made multiple detections within a saturated star. This made it necessary to filter out spurious objects.
A zoomed-in portion of the drizzled image, marked with red circles shows all the objects detected by DOLPHOT, including spurious objects, in Fig. 4.4. The CMD corresponding to this unfiltered DOLPHOT output is seen in Fig. 4.5.

Figure 4.5: \( B_{435} - R_{625} \) Color-Magnitude diagram for NGC 5904 using the unfiltered DOLPHOT output shows that there is a very large number of objects that do not fall on the main-sequence. Hence, examination of the data points that do not fall onto the stellar sequence shows that many of the data points seen in Fig.4.4 are in fact erroneous detections.

PSF photometry was performed on all the objects seen in Fig. 4.4, however, it is clear from a large number of stellar sequence outliers seen in Fig. 4.5 that there are too many spurious objects being detected along diffraction spikes, within saturated stars, and around stars that are responsible for this noise. In order to mitigate these
limitations of the software, the desired output can be filtered using some DOLPHOT output parameters that measure the goodness of fit, such as roundness, sharpness and crowding. These parameters are calculated as part of the DOLPHOT PSF photometry process and are discussed in §§ 4.1.3.

4.2.1 The role of DOLPHOT output parameters in creating the CMD

Multiple parameters were used for filtering objects detected by DOLPHOT. In order to avoid more spurious detections and generate a clean CMD, it was important to ignore saturated objects, to discard the objects at the edges of the drizzled image, and to filter out multiple objects along diffraction spikes (as seen in Fig. 4.4). DOLPHOT flags saturated objects in the output by giving them a magnitude value of 99, and this allowed us to filter out saturated objects. Objects at the edges of a chip that had zero counts were also filtered out.

Accounting for the objects along the diffraction spikes required more trial-and-error with multiple parameters. By observing the effects on the sample regions, we found the value of the sharpness parameter had minimal impact on filtering out spurious objects along the diffraction spikes of saturated stars, although it did filter out objects that were extended, such as background galaxies, and objects that were too sharp, such as cosmic rays. Fig. 4.6 shows some objects that were filtered out using this parameter.
Figure 4.6: Objects eliminated using sharpness parameters close to zero, as zero refers to a perfectly-fit star. Objects eliminated are either too broad or too sharp.

Another parameter that had to be tuned to detect all the stars in the crowded field was the crowding parameter, which describes how much brighter a star would be had its adjacent stars not been fit. Fig. 4.7 show all the objects with a crowding parameter exactly equal to 0 mags. In the uncrowded field, all objects should have a crowding equal to zero. However, given the high density of objects in a globular cluster, one cannot consider it an uncrowded field, and Figs. 4.7 and 4.8 illustrate why setting crowding equal to zero is not a good filter for a globular cluster, as it eliminates too many objects. Thus, after similar trial-and-error using the sample regions, the crowding was set to $< 1.2$ magnitudes.
Figure 4.7: This figure illustrates the effect of setting the crowding parameter to zero. Boxes trace objects with a crowding equal to zero. Clearly, many stars in the cluster have been ignored, including non-isolated stars in (a) and the cluster’s entire core in (b)! This shows that even though it leads to very clean photometry (see Fig. 4.8), a crowding value of 0 filters out many good cluster stars, as objects with higher crowding need to be considered in a crowded field.

The CMD corresponding to a crowding parameter of zero is seen in Fig. 4.8. Clearly,
very few stars are used, providing a CMD with an extremely narrow stellar sequence and very few outliers.

Figure 4.8: $B_{435} - R_{625}$ Color-Magnitude diagram corresponding to Figs. 4.7, when the crowding parameter is set to zero, considering only well-isolated, non-overlapping objects. There are almost no outliers, and the stellar sequence is very sparse.

Another parameter used was object type, which determines whether or not an object is a good enough star for PSF determination. There were only a few stars that were too faint for PSF determination, and they were filtered out, by setting object type to less than 2. Additionally, a major parameter in eliminating many of the spurious objects seen in Fig. 4.4 was the roundness, which can discriminate between stars
and extended objects. This parameter required the most trial-and-error, and it was concluded that a roundness less than 0.5 yielded the best results. Figs. 4.9 shows the objects chosen in a zoomed-in portion of the cluster when the roundness is set to less than 0.15, and Fig. 4.10 shows the corresponding CMD.

Figure 4.9: Green circles trace the objects with a roundness less than 0.15. Although the objects along the diffraction spikes have been completely eliminated, many of the relevant objects are not being detected, and this illustrates that a larger values of roundness need to be accepted to account for all the objects.
Thus from Figs. 4.9 & 4.10 it is clear that a roundness of less than 0.15 is not good enough, as it eliminates too many cluster stars. Thus, after a few trials, it was observed that setting roundness to less than 0.5 was the best compromise between not eliminating too many good cluster stars and eliminating most spurious objects along diffraction spikes.
Figure 4.11: Green circles trace the objects with a roundness less than 0.5. Although there are more spurious objects detected along the diffraction spikes compared to Fig. 4.9, there are also fewer good cluster stars eliminated.

This is seen in Figs. 4.11 and 4.12. To check that the best possible value for roundness had been chosen, I filtered the data with roundness greater than equal to 0.5, and the objects that are being filtered out are seen in Fig. 4.13.
Figure 4.12: Green circles trace the objects with a roundness less than 0.5. Although notice the difference in objects detected in Figs. 4.13 & 4.4. While there is a compromise being made in detecting as many good cluster stars as possible, by comparison, it is seen that all relevant objects being detected, with the fewest spurious detections as possible.

The CMD corresponding to these objects that have been ignored is seen in Fig. 4.14, and one can clearly see from this CMD that there is no stellar sequence visible, and thus the objects being eliminated most likely do not include actual cluster stars with good photometry.
Figure 4.13: Blue circles trace the objects with a roundness greater than equal to 0.5, which are being eliminated when I set the roundness to less than 0.5
Figure 4.14: $B_{435} - R_{625}$ Color-Magnitude diagram when the roundness parameter is set to greater than equal to 0.5, as seen in Fig. 4.13, and the crowding parameter is set to greater than equal to 1.2mag. This CMD has no visible stellar sequence, and thus no good objects are being eliminated.

Thus, Awk was used to filter out the spurious objects, after which matplotlib and numpy packages in Python were used to plot the CMDs in various band-passes. Figs. 4.15 & 4.17 show the CMDs plotted in the $B_{435}$, $R_{625}$ and Hα$_{658}$ bands.
Figure 4.15: $B_{435} - R_{625}$ Color Magnitude diagram for NGC 5904. If compared to Fig. 4.10, one can see that more objects are being used to generate this CMD.

As it can be seen, these are much cleaner than Fig. 4.5, however not as clean as Fig. 4.8. This is on purpose, as a CMD as clean as Fig. 4.8 (where we required the crowding parameter to be 0) eliminated objects with good photometry. A balance between keeping objects with good photometry and those with bad photometry is needed in order to correctly identify the optical counterparts to X-ray emission. Thus the CMDs in Figs. 4.15 and 4.17 are created with roundness, crowding and sharpness values that minimize objects with bad photometry while considering all the cluster stars with good photometry.
Figure 4.16: $R_{625} - H\alpha_{658}$ Color Magnitude diagram for NGC 5904

Figure 4.17: Color Magnitude diagrams for NGC 5904, using appropriate DOLPHOT input and output parameters to filter all the objects from NGC 5904 on which PSF photometry was performed.

4.3 Identifying optical counterparts to X-ray sources from Chandra

4.3.1 Plotting Chandra positional coordinates on HST drizzled image

Once the CMDs were appropriately filtered, it was necessary to plot the X-ray sources on the drizzled image so as to identify the optical counterparts responsible for the X-ray emission. It is important to note that no astrometric corrections were
performed to align Chandra and HST coordinate systems, so the outliers identified are prospective candidates identified by increasing the error circle radius by 0.5", the estimated shift between the Chandra ICRS coordinates and HST GSC1 coordinates (Schmidt & Green, 2003). Table 4.2 provides the details of the X-ray sources within the HST FOV, obtained through CSC v1.1. The names are sorted by R.A., with CX0 having the lowest R.A. and CX8 having the highest. Cols. 2 and 3 provide the R.A. and Declination in ICRS coordinates, with an epoch of J2000. Col. 4 of Table 4.2 is the radius of the original error circle without the 0.5" correction, in arcseconds, and had an astrometric correction been performed between Chandra and HST coordinates, it would encompass all the possible optical candidates for the X-ray source. The broad-band (0.5-7 keV) flux is seen in Col. 5, along with the hard X-ray (2-7 keV) flux and soft X-ray (0.5-1.2) flux in Cols. 6 and 7.

Table 4.2: X-ray sources within NGC 5904 HST FOV

<table>
<thead>
<tr>
<th>X-ray source</th>
<th>R.A. ICRS</th>
<th>Decl. ICRS</th>
<th>$r_{err}$</th>
<th>$F_x$ (0.5-7 keV)</th>
<th>Hard X-ray (2-7 keV) flux (ergs s$^{-1}$ cm$^{-2}$)</th>
<th>Soft X-ray (0.5-1.2 keV) flux (ergs s$^{-1}$ cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CX0</td>
<td>15:18:28.728</td>
<td>+2:05:15.000</td>
<td>1.155</td>
<td>1.44753E-15</td>
<td>5.692E-16</td>
<td>5.647E-16</td>
</tr>
<tr>
<td>CX1</td>
<td>15:18:30.408</td>
<td>+2:04:59.520</td>
<td>0.977</td>
<td>8.65933E-16</td>
<td>7.367E-16</td>
<td>7.903E-16</td>
</tr>
<tr>
<td>CX5</td>
<td>15:18:34.296</td>
<td>+2:05:01.680</td>
<td>1.006</td>
<td>6.86120E-16</td>
<td>0</td>
<td>6.425E-16</td>
</tr>
<tr>
<td>CX6</td>
<td>15:18:34.440</td>
<td>+2:05:06.720</td>
<td>0.495</td>
<td>2.02165E-14</td>
<td>1.565E-14</td>
<td>1.721E-15</td>
</tr>
<tr>
<td>CX7</td>
<td>15:18:35.160</td>
<td>+2:04:36.120</td>
<td>0.654</td>
<td>4.92982E-15</td>
<td>3.376E-15</td>
<td>1.158E-15</td>
</tr>
</tbody>
</table>

Furthermore, Fig. 4.18 shows the location of the X-ray sources within error circles in the HST drizzled image. The gray scale is inverted and colormap is adjusted for better clarity in this drizzled image on which X-ray sources were plotted. The HST ACS drizzled image is in the F435W filter. The X-ray error circles are plotted using the Regions toolkit within DS9, with each source having different $r_{err}$ as seen in Table 4.2. The HST drizzled image coordinates could be converted to an
International Celestial Reference System World Coordinate System (ICRS WCS) using a bore sight correction, but due to time constraints, we did not complete this step in the data analysis. However, in order to ensure accurate alignment between the optical and X-ray data, it is best to perform a bore sight correction by matching bright stars in the image to an optical catalog in ICRS, such as USNO-A2.0. Thus, while the lack of a bore sight correction makes the alignment between Chandra and HST positions imperfect, adding 0.5" to the positional error of each source should allow consideration of any optical counterparts corresponding to the X-ray source (Schmidt & Green, 2003). Fig. 4.18 shows the location of all the X-ray sources within the FOV of the drizzled image. These sources are described in Table 4.2.
Figure 4.18: X-ray positions overlaid on grayscale-inverted HST image of NGC 5904. X-ray positions were found using the Chandra Source Catalog v1.1, and only 9 of the measured sources fell within the $202 \times 202$ arcsec$^2$ FOV of HST. The HST image colormap was adjusted, and the grayscale was inverted, to maximize contrast and minimize blurring.

After the 0.5"-adjusted X-ray error circles are plotted on the drizzled image, optical
sources within the error circle are identified and labeled with green crosses. Fig. 4.19 shows the original error circle (without the 0.5" addition) in yellow, and the revised error circle (to account for the estimated 0.5" offset between HST and Chandra coordinates) in red. Clearly, more objects are considered with the 0.5" addition. As is noticeable in Fig. 4.19, not all objects within the error circle are considered, and only objects with the appropriate parameters, as discussed in §§ 4.1.3, are selected.
Figure 4.19: All optical sources within CX5’s X-ray error circle, where sources are labeled with green crosses, the yellow circle corresponds to the original $r_{err}$ and the red circle corresponds to the revised $r_{err}$ with 0.5" addition. It is important to note that these are not all the sources measured from the DOLPHOT output, but rather are the sources remaining after appropriate filtering. Three objects do not have photometry are labeled with white arrows - the two dim objects are extended and have sharpness values beyond the acceptable range, while there is one saturated object. Since the saturated object does not have a DOLPHOT-measured magnitude, it may have been the optical counterpart to the X-ray source. Flat fielded images with shorter exposures could be used to perform photometry on it to determine this in the future.
4.3.2 Using CMDs, color-color diagrams and X-ray positions to identify optical counterparts

Outliers from the CMDs discussed earlier are important in identifying the optical counterparts to the X-ray sources, as compact X-ray binaries have colors and magnitudes that make them fall outside the stellar sequence. Figs. 4.20 and 4.21 show a zoomed in portion of the CMDs for various color and magnitude combinations. These are zoomed in CMDs from Figs. 4.15 & 4.17, where the gray boxes denote objects within all the nine X-ray error circles described in Table 4.2.

![Figure 4.20: Zoomed in $B_{435} - R_{625}$ CMD from Fig. 4.14 with optical counterparts for X-ray sources. The gray boxes refer to all the filtered objects on which photometry was performed (indicated by green crosses in Fig. 4.19 but for all nine X-ray regions).](image-url)
Figure 4.21: Zoomed in $R_{625}$ - Hα$_{658}$ CMD from Fig. 4.14 with optical counterparts for X-ray sources. The gray boxes refer to all the filtered objects on which photometry was performed (indicated by green crosses in Fig. 4.19 but for all nine X-ray regions).

However, despite the filtering using the parameters discussed in §§4.2, there is still a large number of normal cluster stars that do not fall onto the stellar sequence due to photometric errors, and not because they have unusual colors. On implementing some additional parameters, such as the photometry quality flag, and chi value, it was noticed that most objects with bad photometry disappeared under stricter filters, however, the objects in the gray boxes remained. The photometry quality flag indicates the quality of the photometry performed, and the chi value provides the mean chi-squared value of the fitted PSF profile. The potential optical counterparts
are plotted with error bars in Figs. 5.1 and 5.2 in §5, and in accordance with Figs. 4.2a and 4.2b, it was decided that a $B_{435}$ value $\geq 24$mag and a $R_{625}$ value $\geq 24$mag had errors too large to consider. The filtered CMDs corresponding to the ones below are seen in Figs. 5.1 and 5.2.
CHAPTER 5

Results

This chapter highlights the final results produced after performing the analysis. We present final CMDs, color-color diagrams, images displaying the optical counterparts of the compact X-ray binaries found and an identification of the type of compact X-ray binaries found.

5.1 Producing the final CMDs

Awk was used to filter out objects with roundness <$0.5$, crowding $>1.2$, object type $<2$, sharpness $<0.3$, but also photometry quality flag $<5$ and chi $<6$ parameters, to filter out as many objects with bad photometry. After filtering the data, matplotlib.pyplot and numpy packages in Python were used to plot the CMDs in various band-passes. Figs. 5.1 and 5.2 show the CMDs plotted in the $B_{435}$, $R_{625}$ and $H_{658}$ bands, along with the labeled optical counterparts. When compared to Figs. 4.20 and 4.21, it can be seen that Figs. 5.1 and 5.2 eliminate many spurious objects due to additional filtering by the photometry quality and chi parameters. The objects labeled by green crosses in Fig. 5.4 refer to all the objects within the nine X-ray error circles for which photometry was performed and which met the filtering criteria, and these are the same ones denoted by gray boxes in the CMDs in Figs. 4.20 and 4.21. Error bars are plotted in magenta for each optical counterpart in the CMD, and each optical counterpart is labeled according to its respective X-ray source. X-ray positions, optical/ H$\alpha$ magnitudes and the object type of each optical counterpart are listed in Table 5.1.
Figure 5.1: Final $B_{435} - R_{625}$ CMD with optical counterparts for X-ray sources. We have only shown the error bars for the outliers that were eventually concluded to be good candidates for optical counterparts to the X-ray source, and we have labelled all the optical counterparts, including those that may fall on the main sequence for this CMD, as they are outliers either in the color-color diagram or in the CMD for the other filters.
5.2 Identifying the optical counterparts to X-ray positional data

As is noticeable from the CMDs in the previous section, not all the outliers lie in the same space. Table 5.1 provides the color and magnitude for each identified candidate optical counterpart in various filters. Cols. 2 & 3 describe the positional offset, in arc seconds, between the center of the X-ray error circle and the location of the potential
counterpart. As is seen, the offset is never greater than the adjusted radius of the error circle (Col. 4), neither is it ever zero. This further clarifies the necessity of utilizing both X-ray and optical data in conjunction: Chandra positional data alone is not sufficient to pinpoint the location of the X-ray producing object, just as HST photometry cannot determine X-ray emission. Thus, a multi-wavelength study of the cluster permits a deeper understanding of its compact binaries.

Figure 5.3: Color-color diagram of \((B_{435} - R_{625})\) vs. \((H\alpha_{658} - R_{625})\). Outliers correspond to the optical counterparts to the X-ray sources they are labeled as. Error bars of outliers are in magenta.

As seen in Fig. 5.3, most stars appear to be on a stellar sequence (Lugger et. al., 2017). However, the outliers of the sequence have colors that are unlike those of
the sequence, and due to this, they refer to the potential optical counterparts of the X-ray sources. Given the multiple outliers in Fig. 5.3, outliers that do not have large error bars (i.e. error bars that could place them on the sequence) are selected. Thus, it is not enough to just use one CMD to identify the outliers, multiple CMDs and color-color diagrams must be used so that a thorough knowledge of the outliers is gained. Some CMDs for one color may not have the same outliers as CMDs for another color, because compact X-ray binaries have varying brightnesses in different filters. By using multiple CMDs and color-color diagrams, it is possible to identify outliers more reliably.

The optical counterparts corresponding to each X-ray source are labeled in Fig. 5.4. The red circle is the adjusted error circle for each X-ray source, as described in Table 5.1. The error circles each have different radii, as is apparent in the image, as each block showcasing the source is in a 4” × 4” FOV. The green crosses represent all the optical sources measured via PSF photometry in the circles, while the outlier corresponding to the X-ray emission, as deduced from the CMD and color-color diagrams, is circled in magenta. When this outlier is visible in the image, a white arrow points to it. The image contrast, stretch and grayscale are varied for each image to enhance the visibility of candidates. As seen, optical counterparts for X-ray sources come in a wide variety of ranges: from bright to dim, towards the edge, or towards the center of the error circle.

The ranges of $B_{435}$ magnitudes are expected for the particular cluster. The distance modulus (m-M) of NGC 5904 is 14.46 in the visual band (Harris, 1996) and the magnitude ranges calculated for CVs, MSPs, LMXBs and ABs, using Edmonds et. al. (2003), matches our expectations.
Figure 5.4: Objects measured and filtered using DOLPHOT (green crosses) overlaid within the Chandra astrometric error circle (red). All of these optical sources are possible candidates for the X-ray emission in the circle. Pictured above are 4” × 4” finding charts using HST archival data in the B(435W) filter. As can be seen, the radius of the error circle for the Chandra source positions are all different, generally reflecting the X-ray brightness (see Table 4.2). The optical counterparts to the X-ray emission are circled in magenta and have white arrows pointing to them.

A plot of broadband X-ray flux against X-ray to Optical flux ratios for the optical counterparts of X-ray sources is known to be effective at identifying the kind of compact X-ray binary system the outlier corresponds to (Pooley et. al., 2003; Lugger et. al., 2017), and thus, using Table 5.1 to obtain the DOLPHOT-computed magnitudes of the outliers in Fig. 5.4, optical fluxes were calculated and used to generate Fig. 5.5.

For CX0, no outliers are identified, as all possible objects that could be outliers had photometric errors and were very dim. It is likely the optical counterpart may be too dim for reliable photometry in the $B_{435}$ filter, and in the future, other filters could be examined. For CX1, one outlier is seen and given its optical brightness
Table 5.1: Optical counterparts to X-ray sources are described, with their position inside the error circles from Fig. 5.4, and their colors and magnitudes. The magnitudes were used to compute the flux in 435W, the filter used in the drizzled image, and the ratio of the broadband X-ray flux and the 435W-flux, along with Fig. 5.5 was used to categorize the type of compact X-ray binary.

<table>
<thead>
<tr>
<th>Optical counterpart</th>
<th>R.A. offset (&quot;)</th>
<th>Decl. offset (&quot;)</th>
<th>( r_{err} + 0.5&quot; )</th>
<th>( B_{435} )</th>
<th>( B_{435} - R_{625} )</th>
<th>( R_{625} )</th>
<th>( R_{625} - H\alpha_{658} )</th>
<th>Object type</th>
</tr>
</thead>
<tbody>
<tr>
<td>CX1</td>
<td>0.29</td>
<td>0.51</td>
<td>1.477</td>
<td>17.23</td>
<td>1.00</td>
<td>16.22</td>
<td>0.35</td>
<td>AB</td>
</tr>
<tr>
<td>CX2</td>
<td>0.43</td>
<td>0.26</td>
<td>1.199</td>
<td>20.53</td>
<td>0.68</td>
<td>19.85</td>
<td>0.20</td>
<td>CV</td>
</tr>
<tr>
<td>CX3</td>
<td>0.16</td>
<td>1.04</td>
<td>1.102</td>
<td>18.16</td>
<td>0.80</td>
<td>17.37</td>
<td>0.11</td>
<td>CV</td>
</tr>
<tr>
<td>CX4</td>
<td>0.08</td>
<td>0.46</td>
<td>1.383</td>
<td>20.42</td>
<td>0.35</td>
<td>20.07</td>
<td>0.30</td>
<td>CV</td>
</tr>
<tr>
<td>CX5</td>
<td>0.93</td>
<td>0.57</td>
<td>1.506</td>
<td>23.83</td>
<td>1.96</td>
<td>21.87</td>
<td>0.52</td>
<td>AB</td>
</tr>
<tr>
<td>CX6</td>
<td>0.32</td>
<td>0.12</td>
<td>0.995</td>
<td>21.12</td>
<td>0.67</td>
<td>20.45</td>
<td>0.77</td>
<td>MSP</td>
</tr>
<tr>
<td>CX7</td>
<td>0.36</td>
<td>0.51</td>
<td>1.154</td>
<td>23.44</td>
<td>0.66</td>
<td>22.79</td>
<td>0.53</td>
<td>CV</td>
</tr>
</tbody>
</table>

can be the source. If this object were an active binary, one could hypothesize that its low X-ray flux is due to a lower spin rate. However to accurately classify CX1 as an active binary, much more information including optical and X-ray variability and spectral data is needed.

The optical counterpart of CX2 is a bright source, and is clearly visible on the finding chart, and seen as an outlier in the \((B_{435} - R_{625})\) CMD. From the location on the CMDs we tentatively classify CX2 as a CV. For CX3, the outlier candidate is a bright object near the edge of the circle, with a bright \(B_{435}\) component of 18.16 mag. CX3 is an outlier in both CMDs. Given the X-ray flux and the location on the CMD, it is hypothesized that the outliers are CVs.
Figure 5.5: X-ray to Optical flux ratio VS. Broadband X-ray flux for the optical counterparts outlined in Table 5.1. The B (435W) flux obtained from DOLPHOT PSF photometry, along with the Broadband X-ray flux from the CSC [see Table 1] was used to compute the ratio. The red squares represent ABs, blue triangles represent CVs, and the green circles are MSPs.

For CX4, there is an outlier, that is bright, with a $B_{435}$ magnitude of 20.42, and persistent as an outlier in both CMDs and the color-color diagram. It has small error bars and is the bluest outlier in the $(B_{435} - R_{625})$ CMD. Given that it is an outlier in the color-color diagram as well as in the $(H_{658} - R_{625})$ CMD, it is a strong candidate, and its position on the CMD suggests it is a CV. However, it is also possible that light from its neighboring bright star may contaminate its photometry and make it seem like an outlier in the CMDs even though it might not be. For CX5, there is
also an outlier observed, however, it is faint ($B_{435} = 23.83$) and barely visible in the finding chart. It seems to only be a weak outlier from its positions on the CMDs, as it is close to the stellar sequence. Thus, we cannot exclude the possibility that it appears as an outlier due to contamination of its photometry by nearby bright stars. We do not have photometry for the saturated object in the error circle of CX5, and two of the fainter objects were filtered out because they appear extended. We cannot eliminate the possibility that one of these objects is the optical counterpart. In the future, however, flat fielded files with lower exposure times could be looked at to ensure this is not the optical counterpart. Given the identified optical counterpart’s position on the CMD and relatively high $B_{435}$ magnitude, its low X-ray to optical ratio can only be explained by low levels of X-ray emission, providing evidence for its classification as an AB. However, variability and spectroscopic studies would need to be performed to verify this.

For CX6, there is a single, optically-bright, isolated object that is measured to be the optical counterpart corresponding to the X-ray emission. This is the most reliable optical counterpart candidate in our study, with short error bars, and a great distance away from the CMD main sequences and color-color fit sequence. It is the outlier with the highest X-ray flux, and this fact, combined with its moderate X-ray to optical ratio, result in it being classified as an MSP. For CX7, it is a strong outlier in the ($B_{435} - R_{625}$) CMD and color-color plot, although is quite dim. As seen in the finding chart, it does not have a strong optical component, and it may also be affected by its neighbor - perhaps its optically bright neighbor is releasing the X-rays. The current X-ray to optical ratio for CX7 along with its position on the CMD are strong indicators of it being a CV, however, only variability studies and photometry in the UV can verify this. For CX8, there are no outliers. Any potential outliers in question are barely visible in the finding chart, with very dim brightnesses in both filters, and high photometric errors. Similar to CX0, it is likely the optical counterpart may be too dim for reliable photometry in the $B_{435}$ filter.
and other filters can be examined in the future.

Thus, as seen in Fig. 5.5, two out of seven optical counterparts were ABs, four were CVs, and one was an MSP. When the CMDs positions of the compact object types are observed, they fall on the areas expected. Thus, seven compact X-ray binary sources were measured in NGC 5904, the majority of which are CVs.
This chapter summarizes the results and presents the conclusions that can be drawn from HST and Chandra observations of NGC 5904, along with providing prospects for future work.

6.1 Conclusion

Thus, a clear picture of compact X-ray binaries in NGC 5904 emerges. From Chapter 1, that describes the theory of compact X-ray binaries in globular clusters, and their role in cluster evolution, we move to Chapter 5, that provides results about the compact X-ray binary systems of NGC 5904 and expands upon the knowledge of dynamical formation within NGC 5904. The tools and instruments used in this analysis were discussed in detail in Chapters 2 and 3, with the scientific methods of processing discussed in Chapter 4. PSF photometry was performed in DOLPHOT using HST ACS archival data. The photometric DOLPHOT output was filtered to minimize spurious objects (using Python and Awk) and used in conjunction with Chandra positional data (from CSCv1.1) to construct CMDs and color-color diagrams. These diagrams were used to identify the optical counterpart responsible for the X-ray emission, allowing for the discovery of the different types of compact X-ray binary within NGC 5904.

Out of the 9 X-ray sources within NGC 5904, only 7 were discovered to have optical counterparts. The finding charts showing these results can be seen in Fig. 5.4. Out of the seven compact X-ray binaries discovered, over half (four) have CMD
positions and X-ray to optical flux ratios indicative of CVs, two are indicative of ABs and one is indicative of an MSP. CV populations have been directly correlated with the encounter rate in globular clusters and the seemingly large population of CVs supports the high encounter rate of NGC 5904 seen in Fig. 1.3 (Pooley et. al., 2003; Ivanova et. al., 2006). The large number of CVs hypothesized to be present in NGC 5904 provides insights into the kinds of dynamical interactions occurring in the cluster. While the dynamical formation of CVs is difficult to classify in absolute terms across all globular clusters (Ivanova et. al., 2006), CVs are expected to be formed dynamically in globular clusters, via three-body exchange interactions or collisions (Davies, 1997; Di Stefano & Rappaport, 1994). Therefore, the collision frequency in a cluster directly impacts its CV population, and given NGC 5904’s moderately high encounter frequency of 69 (Pooley et. al., 2003), it is not surprising that more than half of its compact X-ray binaries are CVs.

### 6.2 Future Prospects

While this is a preliminary analysis of compact X-ray binaries in NGC 5904, a more in-depth analysis could uncover greater details. A single HST ACS dataset was used, containing only $\approx 15$ min of total HST exposures for each filter. A larger dataset, with more images or longer exposures could provide more detailed photometry, identifying objects that are too dim to currently uncover. There are already HST images of NGC 5904 in $B_{435}$ taken by S.F. Anderson, that can be used to probe the $B_{435}$ variability of compact binaries in NGC 5904 and create light curves. NGC 5904 data using different HST cameras could also be used. Furthermore, matching the Chandra and HST frames to sub-arcsecond precision using bore sight corrections could significantly improve the astrometric position of the counterpart identified, and if combined with higher quality HST data, may even be able to differentiate between dimmer objects in the vicinity of saturated ones.
Additionally, a deeper analysis of CVs within NGC 5904 can be performed, using spectroscopic X-ray analysis to measure variability in thermonuclear dwarf novae outbursts, or using bluer HST filters to observe UV excesses. Having longer HST exposure times would also allow for better photometry and more efficient filtering, eliminating spurious remnants and improving the number of isolated outliers at lower magnitudes. Thus, there are sufficient ways to build upon this project, as this only provides a starting point on a deeper analysis of compact X-ray binaries within NGC 5904.
Appendices
DOLPHOT Parameter File

Nimg = 22

where Nimg refers the integer number of images to be photometered, and the img_() assign the archival HST images to variables. The drizzled image is assigned to img0, and acts as the reference image to which all the flat fielded images are shifted.

img0_file = j92101011_drz.chip1
img1_file = j92101kjq_flt.chip1
:
img22_file = j9210117q_flt.chip2

Since DOLPHOT performs image alignment through the WCS specified in the header files, initial guesses of x and y shifts as 0 are appropriate. However, for the reference image, img_0, the shift must be zero as other images are shifted to match its positions. The img#_apsky variables describe the inner and outer annulus used for the particular images, and the values below are optimized for HST ACS.

img0_shift = 0 0
img1_shift = 0 0
:
img22_shift = 0 0
img0_apsky = 15 25
img0_xform = 1 0 0
img1_apsky = 15 25
img1_xform = 1 0 0
:
img22_apsky = 15 25
img22_xform = 1 0 0
The parameters described below are discussed in Ch. 4 in detail, along with the ACS DOLPHOT manual (Dolphin, 2000). Most of these parameters are predetermined for PSF Photometry with HST ACS, however, some parameters were necessary to tweak, as discussed previously. The #’s refer to comments within my code, describing each parameter, and int is shorthand for integer, while (flt) refers to parameters applied to the flt images while processing.

RAper = 4 #photometry aperture size (flt)
PSFPhot = 1 #photometry type (int 0=aper,1=psf,2=wtd-psf)
FitSky = 2 #fit sky? (int 0=no,1=yes,2=small,3=with-phot)
RSky0 = 15 #inner sky radius (flt>=RAper+0.5)
Rsky1 = 35 #outer sky radius (flt>=RSky0+1)
SkipSky = 2 #spacing for sky measurement (int>0)
SkySig = 2.25 #sigma clipping for sky (flt>=1)
SecondPass = 1 #second pass finding stars (int 0=no,1=yes)
SigFind = 3.0 #sigma detection threshold (flt)
SigFindMult = 0.85 #Multiple for quick-and-dirty photometry (flt>0)
SigFinal = 3.5 #sigma output threshold (flt)
MaxIT = 25 #maximum iterations (int>0)
NoiseMult = 0.10 #noise multiple in imgadd (flt)
FSat = 0.999 #fraction of saturate limit (flt)
ApCor = 1 #find/make aperture corrections? (int 0=no,1=yes)
Force1 = 1 #force type 1/2 (stars)? (int 0=no,1=yes)
Align = 2 #align images? (int 0=no,1=const,2=lin,3=cube)
Rotate = 1 #allow cross terms in alignment? (int 0=no, 1=yes)
RCentroid = 1 #centroid box size (int>0)
PosStep = 0.1 #search step for position iterations (flt)
dPosMax = 2.5 #maximum single-step in position iterations (flt)
RCombine = 1.0 #minimum separation for two stars for cleaning (flt)
RPSF = 10 #PSF size (int>0)
SigPSF = 3.0 #min S/N for psf parameter fits (flt)
PSFres = 1 #make PSF residual image? (int 0=no,1=yes)
psfoff = 0.0 #coordinate offset (PSF system - dolphot system)
UseWCS = 1 #ACS PSF library
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