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X-Ray Diversity in Old Star Clusters

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Summary

The work presented in this thesis discusses the properties of low-luminosity X-ray sources in old star clusters using two very distinct stand-points – in Chapters 2 and 3, I discuss the properties of faint X-ray sources within old open clusters, and in Chapters 4 and 5 I discuss the cooling of accretion-heated neutron-star crusts in low-mass X-ray binary systems (LMXBs) in globular clusters. In the following paragraphs, I will elucidate the physics and methods I used to carry out my research, and the results I obtained.

Our Galaxy, the Milky Way, is one amongst billions of galaxies dotting the Universe, and is host to billions of stars, all with their unique sets of properties. Stars are born in ultra-dense regions that arise inside massive reservoirs of gas in interstellar space called molecular clouds. These "stellar nurseries" may lead to the formation of many stars, giving rise to groups of stars over time, which could be anything from loose associations of stars that dissipate over time, to dense, gravitationally-bound clusters of stars. A lot of these stars are formed in bound pairs called binaries, where these binaries may or may not get disrupted over the lifetime of the component stars. Individual stars inside clusters may also form pairs with other stars over time if there are stellar interactions within these clusters. Some of these binaries, called interacting binaries, are very close to each other, causing them to interact with one another. This interaction gives rise to a host of phenomena. Such systems have interesting properties that can help us understand both the properties of the stars making up the binary, as well as the cluster within which these binaries exist. In this thesis I am presenting the work I did on understanding and unraveling the nature and physical properties of interacting binary systems within these clusters. For this I studied the properties exhibited by binaries in their X-ray spectrum, at times in combination with their optical properties.

Star clusters may be found in our Galaxy in two different flavours – open clusters and globular clusters. Open clusters have fewer stars than globular clusters, and contain anywhere from a few tens to a few thousands of loosely bound stars, compared to several thousands to a few million gravitationally-bound stars found in globular clus-

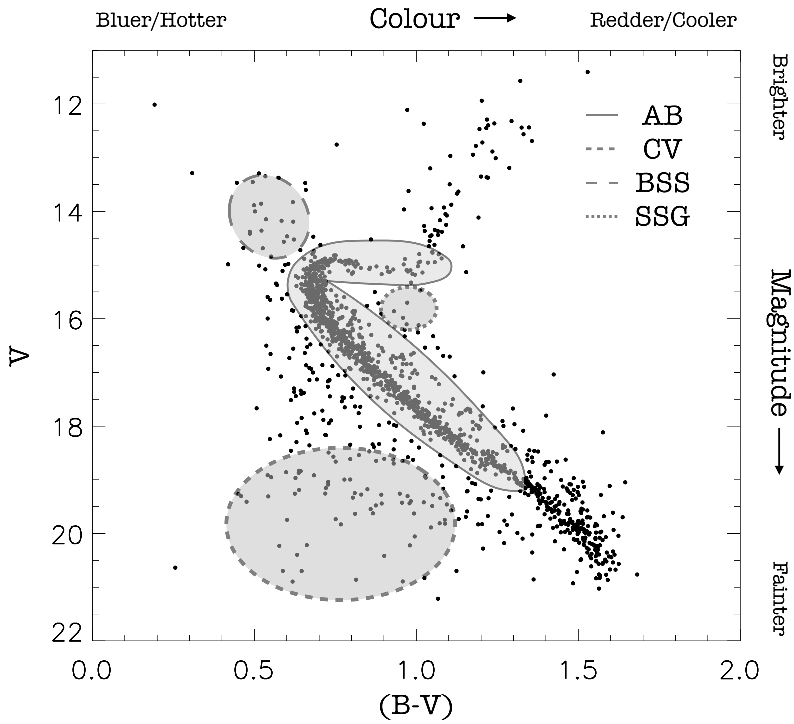

Figure A: Colour versus magnitude diagram (CMD) for the old open cluster NGC 188. Each point represents a star in the cluster. Magnitude is represented on the y-axis and is the brightness of a star in a given filter (here the V band). Colour is represented on the x-axis and is the difference of brightness of a star in two different filters (in this case B and V bands). The colour is a representation of the temperature of the stars. The locations of the optical counterparts to the observed X-ray sources in the CMD, give us an indication to the nature of those X-ray sources. Here, AB stands for active binaries, CV stands for cataclysmic variables, BSS stands for blue straggler stars, and SSG stands for sub-subgiants. For more information on these classes of sources, refer to Sect. 1.2 in Chapter 1. Copyright S. Vats.

ters. Open clusters are typically also much younger than globular clusters, however, they show a large range of ages (from a few million to a few billion years). Globular clusters, on the other hand are host to some of the oldest stars in the Galaxy. The advantage of studying the properties of objects within a cluster is that properties like distances and ages of clusters can be more easily determined than those of individual stars floating in the Galaxy. Stars in clusters can be represented in the form of colour-magnitude diagrams (Figure A), where the only information required is observational information about the brightness of these stars. From this diagram we can get the classification of each star, as shown by the regions indicated in the colour-magnitude diagram in Figure A. In addition to this, one can also study the possible effects of dense cluster environments on objects like binary systems.

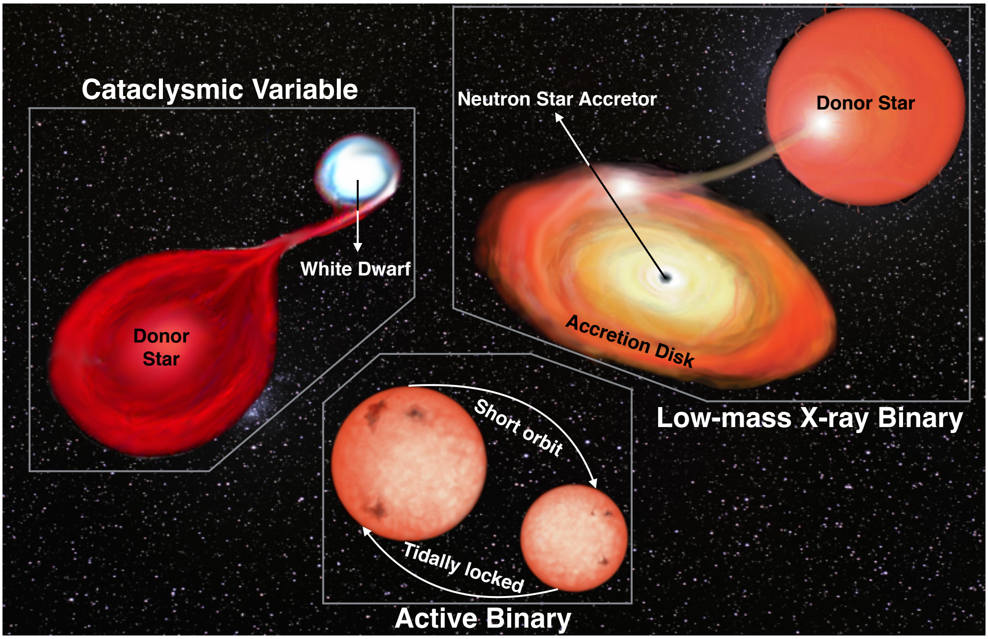

Figure B: Some of the binaries found in old star clusters – active binaries, cataclysmic variables and low-mass X-ray binaries (in this case the compact object is a neutron star, although a black hole is also possible). Adapted version of the figure (original credits: cataclysmic variable – *Chandra* X-ray Observatory/NASA; active binary – J. Pinfield; low-mass X-ray binary – NASA; background – ESO/S. Brunier)

Multi-wavelength studies are beneficial for efficiently and securely characterising the properties of stellar objects. For the objects that I studied in old open clusters (in Chapters 2 and 3) X-ray observations were, first and foremost, the key component for selecting the sources of interest, i.e. the binary population. Single stars can be luminous sources of X-ray radiation by virtue of rapid rotation. However, as they grow older and begin to spin slower, their X-ray luminosity drops to non-detectability when at large distances ($\sim$ a few kiloparsecs), such as those between their host clusters and our X-ray telescopes. The sources that are detected as X-ray sources in our observations are objects where some kind of binary interaction is taking place and causing emission of X-ray radiation (Figure B). Studying the underlying X-ray spectrum of these systems also gives us clues to the kind of binary interaction taking place. Combining the information gathered from studying these sources in different wavelengths strengthens source classification. The sources that I found in the two open clusters I studied in Chapters 2 and 3 were cataclysmic variables (CVs), magnetically active binaries (ABs), blue straggler stars (BSSs), sub-subgiants (SSGs), and yellow stragglers (all these classes except yellow stragglers are represented in Figure A).

Other than these sources, globular clusters are additionally host to LMXBs (Figure B). A LMXB is composed of a compact object (black hole or neutron star) that accretes matter from a companion star of mass less than or equal to the mass of our Sun. A LMXB can either continuously accrete matter from the companion or can have periods of outbursts, when it is accreting matter from the companion, and quiescence, when the accretion comes to a partial or complete halt. During an outburst, the system can be anywhere from a billion to a trillion times brighter than our Sun in X-rays. Therefore, X-ray observation are a very useful tool in studying LMXBs.

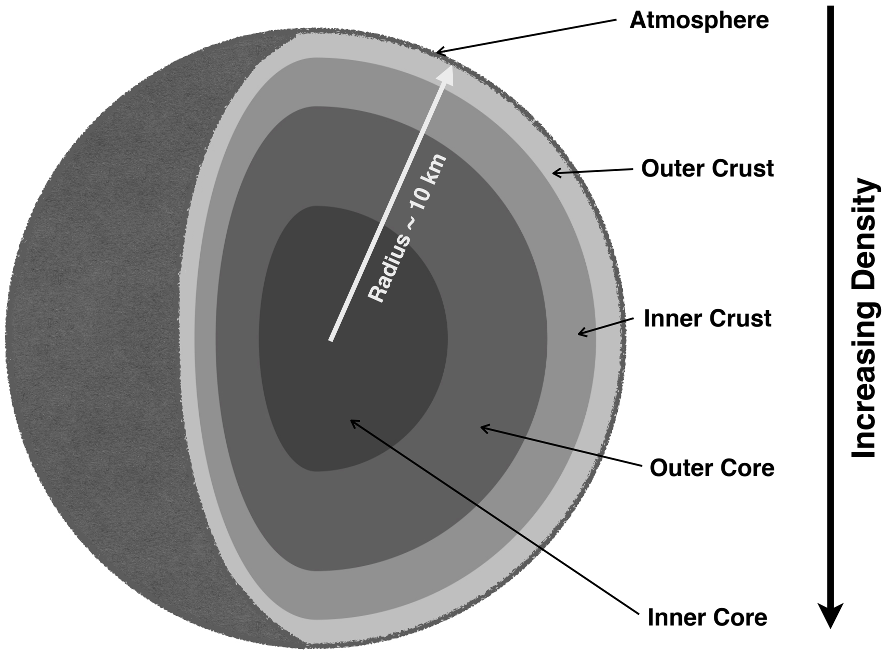

Figure C: Internal neutron-star structure. The density of the layers keeps increasing as we look deeper into the neutron star. Further explanation of the neutron-star structure can be found in Sect. 1.3.1 of Chapter 1. Copyright S. Vats.

In Chapters 4 and 5 I present the work I did on two such LMXBs, wherein the compact objects were neutron stars going through episodes of outbursts and quiescence (transient LMXBs). I studied the cooling of neutron-star crusts after accretion outbursts. A neutron star is formed when a massive star dies in an extremely energetic explosion called a supernova. The core of this star collapses to form a neutron star that has roughly the size of a city like Amsterdam, but a mass similar to the mass of the Sun. Neutron stars are very dense objects and are structured in layers (Figure C) of crust and core. Just before the onset of an outburst, the crust and the core of the neutron star are said to be in thermal equilibrium. However, during an outburst, the crust of the neutron star becomes considerably hotter due to compression induced exothermic nuclear reactions. The crust then dissipates heat both outwards to the surface and inwards to the core. X-ray observations from the LMXB during quiescence carry signatures of the temperature of the neutron star. Monitoring how the crust of the neutron star cools over time to attain thermal equilibrium with the core again, helps us probe the structure of the neutron star. The longer we monitor the neutron-star temperature, the deeper into its layers we probe, and improve our understanding of neutron-star structure and properties.

None of this work, however, would have been possible without the excellent X-ray and optical observing facilities currently in operation. For the work presented in this book, I made use of data obtained using different observatories. The optical data used in Chapter 2 were obtained from the Max Planck Group (MPG)/ESO 2.2 m telescope at La Silla, Chile, and the optical data used in Chapter 3 were obtained from the WIYN 3.5 m telescope which is part of the Kitt Peak National Observatory in Arizona, USA. For the X-ray analysis performed in both these chapters, I made use of data obtained from the *Chandra* X-ray telescope, which is a space-based observatory orbiting the Earth (X-ray emissions from outside our planet get blocked by our atmosphere, necessitating space-based missions). The X-ray data for Chapter 4 were obtained from the X-ray Multi-Mirror Mission or *XMM-Newton*, which is another space-based observatory. Data for Chapter 5 were obtained from *Chandra* yet again.

Outline

Chapter 2 – *A* Chandra *study of the old open cluster Collinder 261*

Using X-ray observations performed with *Chandra*, in combination with deep optical observations obtained from the MPG/ESO 2.2 m telescope at La Silla, I studied Collinder 261 (Cr 261), which is one of the oldest open clusters known in our Galaxy. This was the first X-ray study of this cluster. Studying this cluster was quite challenging as it is a relatively less studied cluster and information about the member stars, mass, and radius is not very robust or not available at all. Nevertheless, I found 151 X-ray sources in the cluster, of which five were candidate CVs, 34 were candidate ABs, and 11 were unusual binary candidates like BSSs, SSGs, and yellow-stragglers. We do not know which stars in the field of Cr 261 are actually members of the cluster, hence these numbers are only upper limits. I also estimated the mass of this cluster by determining the number of contaminating background and foreground sources. I compared the X-ray luminosity per unit mass (X-ray emissivity) of Cr 261 with other old star clusters and found that Cr 261 is similar to old open clusters in terms of the total X-ray emissivity, and much brighter than globular clusters, as suggested in some earlier studies.

Chapter 3 – *X-ray census of the interacting binaries in NGC 188*

Since not many old open clusters have been studied in X-ray wavebands, I studied another old open cluster, NGC 188, to increase the sample of old open clusters studied in X-rays. Unlike Cr 261, NGC 188 is one of the best studied old open clusters in the optical and membership information is readily available. I detected 84 X-ray sources in the cluster, wherein 55 were detected for the first time. Of the 84 sources, 13 were matched with previously determined cluster members. Among these sources I found a mix of ABs and BSSs. I also discovered a very intriguing BSS in a highly eccentric orbit around its binary companion. X-ray emission is not expected for binaries with highly eccentric orbits, so I expect that this system has a third companion and that this system is actually a hierarchical triple system (a binary system with a third companion orbiting the pair), wherein the inner binary component is emitting the X-rays and the outer star is in an eccentric orbit around the inner binary.

The X-ray emissivity of NGC 188 is again in line with what has been previously found for old open clusters, strengthening the claim that old open clusters are indeed more luminous in X-rays compared to globular clusters and the local solar neighbourhood. This phenomenon could be explained in a few different ways – stellar encounters in globular clusters that aid both the formation and destruction of binaries, may have the net effect of destroying more binaries than creating them. Alternatively, this could be an effect of the typically higher metallicities of old open clusters (ages 3.5–10 billion years) compared to globular clusters.

Chapter 4 – *The quiescent state of GRS 1747–312*

In Chapter 4, I diverted my attention to the study of neutron-star low-mass X-ray binaries in globular clusters. In an old *XMM-Newton* observation of globular cluster Terzan 6, I found an X-ray source which has a spectrum that comprises of a soft and a hard component. I assume that the emitting source is GRS 1747-312, which is currently the only known transient LMXB in this cluster, and whose position determined by a *Chandra* observation in outburst matches that of the source in this observation well. The soft and the hard components in the X-ray spectrum contribute roughly equally to the observed X-ray luminosity. If this source is indeed GRS 1747-312, then this indicates that this cooling source may still be accreting at low-levels during quiescence, giving rise to both the soft component (expected from the neutron star atmosphere) and the hard component (attributed to accretion). However, a long *Chandra* observation of the cluster while GRS 1747-312 is in quiescence is required to confirm where the X-ray emission originates from in the cluster, and if there are other X-ray sources within the cluster that may be contaminating this emission.

Chapter 5 – *Continued neutron-star crust cooling in IGR J17480–2446*

In Chapter 5, I continued studying the quiescent behaviour of transient neutron-star LMXBs. The source in focus was IGR J17480–2446 in the globular cluster Terzan 5, which is currently in quiescence. Using some old but also several newly acquired *Chandra* observations, I studied the thermal evolution of the neutron-star crust starting from roughly two months after the end of the last outburst in August 2010, up to about 5.5 years after the end of that outburst. I saw that the neutron star has not yet attained the quiescent base-level temperature and continues to cool. I also found that the thermal conductivity of the neutron star near the junction of the inner and outer crust is lower than what is inferred from other cooling sources. The explanation to this may be hidden in the fact that IGR J17480–2446 harbours a relatively slow rotating neutron star with a higher than usual surface magnetic field. However, how exactly these factors affect the thermal conductivity in the junction of inner and outer crust is not fully understood.