Clues from stellar catastrophes

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1 Introduction

1.1 Overview

Much of astronomy plays out over timescales much longer than a human lifetime. From the gravitational dances of galaxies to the nuclear furnaces powering the stars within them, we typically see these processes as if frozen at a moment in time. Large ensembles of observations, along with the fortune of being able to view into the past with greater distances, are often needed to piece together a picture of the evolution of these phenomena. However, in certain cases, we are lucky enough to observe full astrophysical events unfolding before us—or, at least, study their consequences. These short-timescale processes, often involving high-energy astrophysics, form the basis of much of the work in this thesis. In particular, we focus on catastrophic events involving stars, and what these events can tell us about the environments in which they occur.

We begin by covering the main astrophysical phenomena examined here. The first topic is a common theme through most of the following chapters—and one of the most rapid events to occur in astronomy—the supernova explosion at the end of a massive star's life (Section 1.2.1). In the first two of the following chapters, we are interested in studying the consequences of supernovae near supermassive black holes like the one in the center of our Milky Way Galaxy. We aim to use this as a tool to infer properties of otherwise obscure galactic centres. We therefore focus briefly on our understanding of the environment of these black holes (Section 1.2.2). In the subsequent chapter, we shift focus to the effect of a supernova on an even more immediate surrounding, a stellar companion (Section 1.2.3). The final chapter considers interactions between two stars not during an explosion but during a collision. By looking at the end product of these collisions, observed as 'blue straggler' stars, we may be able to infer properties of the stars that collided and of the parent cluster. Therefore, for the final subject, we present a brief overview of blue stragglers (Section 1.2.4).

In order to investigate this variety of problems, we create or employ a number of different techniques. These methods are needed as the problems do not lend themselves to tractable analytic solutions. Therefore, after reviewing the astrophysical topics in this thesis, we continue this introduction by covering the main methods used (Section 1.3). We then provide an overview of the content of each of the following chapters, emphasizing the novel contributions of the thesis to these topics (Section 1.4). Finally, we conclude with an outlook, where we consider how future work, based on the results of this thesis, can continue to contribute to the problems we have addressed here (Section 1.5).

1.2 Astrophysical phenomena in this thesis

1.2.1 Supernovae and supernova remnants

Lying behind much of the work in this thesis are the predictions from a pillar of modern astronomy, the theory of stellar evolution. The changes in the structure of a star over its lifetime are now very well understood, and they are largely determined by a single parameter: its mass. Although the Sun is more massive than about 9 out of every 10 stars, its mass is still low enough that the end of its life will be a relatively gentle display, finally forming a planetary nebula containing a white dwarf remnant. For stars with initial masses greater than about 8 times the mass of the Sun ($8\ M_{\odot}$), the (electron degeneracy) pressure that supports a white dwarf is eventually exceeded in the core.

The pressure in the core of a massive star is overcome by the inward force of gravity once the series of fusing elements reaches iron, with catastrophic consequences. On the timescale of about a second, the core of the star collapses into either a neutron star or, with a sufficiently large amount of mass, a black hole. The collapse of the core ends abruptly (the equation of state of the proto-neutron star is very stiff, meaning that its surface has little 'give' against the remaining in-falling matter), and the resulting 'bounce' at core-collapse drives a very strong shock outward through the remaining layers of the star. The energy from the resulting supernova explosion synthesises a large number of new elements—a primary source of the elements heavier than iron in the universe—and drives out the rest of the stellar material as supernova ejecta. The supernova ejecta trail the shock that has broken out through the surface of the star and into the interstellar medium (ISM). The cinder left behind from the core of the star, whether a neutron star or black hole, is referred to as a stellar remnant; the expanding shell of ejecta, as well as the ISM swept up by the shock, is referred to as a supernova remnant (SNR).

SNRs can usually be distinguished from the ISM for $\gtrsim 10^6$ years (Padmanabhan 2001). The evolution of radius and velocity for an SNR in a typical ISM is shown in Figure 1.1 (note that higher densities of gas near SMBHs will generally shorten the characteristic scales compared to the 'canonical' ones shown here). The initial stage of the SNR is referred to as the ejecta-dominated or free-expansion stage, where little of the ISM has been swept up by the shock and the SNR expands at roughly the initial velocity, determined by the kinetic energy imparted to the mass of the ejecta (blue in Figure 1.1). Once the mass swept up from the ISM is roughly equal to the mass of the ejecta, by momentum conservation the deceleration of the SNR becomes appre-

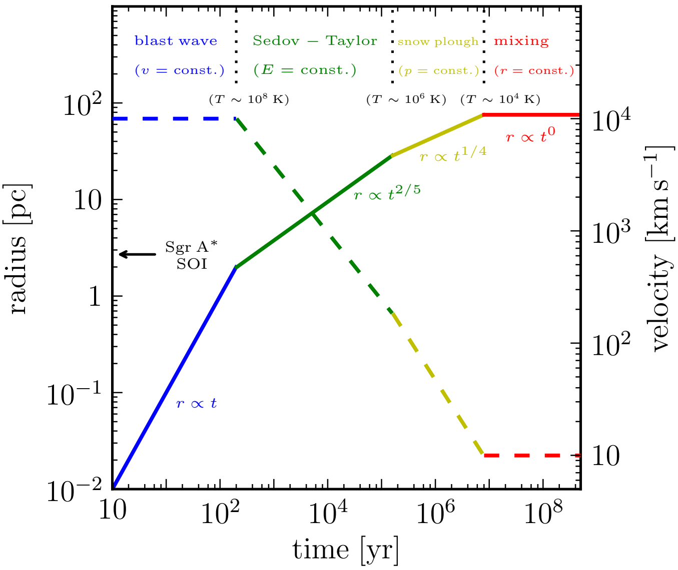

Figure 1.1: The stages of evolution of a supernova remnant for an energy of 10^{51} erg, an ejecta mass of $1\ M_\odot$ for a typical ISM ambient density of $n_{\rm H} \sim 1\ {\rm cm}^{-3}$. Temperatures, T, are given at each of the timescales of the transitions. The solid line shows the evolution of the radius, while the dashed line shows the evolution of the velocity. (More realistically, the evolution is 'intermediate-asymptotic', transitioning between these limiting functions.) The scale of the sphere of influence of the Milky Way supermassive black hole, Sgr A*, is indicated with an arrow. [After Padmanabhan, 2001, Figure 4.6]

ciable, and it has entered the next stage of adiabatic expansion (green in Figure 1.1). Particularly for a uniform ISM, where the expansion is spherically symmetric, this is also known as the Sedov–Taylor stage, and during this time the loss of energy interior to the SNR is minimal. Eventually the SNR decelerates to the point where the temperature behind the shock, which is proportional to the square of the shock velocity, is low enough for line emission to generate a more rapid loss of energy (yellow in Figure 1.1). The SNR has reached the radiative stage of evolution, and once the energy density behind the shock is sufficiently low, the expansion of the SNR is no longer pressure-driven but momentum-driven. Eventually the SNR slows to the sound speed of the ISM and mixes with the ambient medium (red in Figure 1.1).

For a strong shock originating from a point explosion in an ambient medium, it is possible to derive the velocity, and radius from the explosion, along the shock front as a function of time, during the adiabatic expansion of the SNR (the second, green, stage in Figure 1.1). This theory was first developed by Taylor (1950) and Sedov (1959) for investigations of (nuclear) explosions in a uniform ambient medium of gas. Soon after, Kompaneets (1960) developed a solution for shocks in the non-uniform (exponentially stratified) density of the Earth's atmosphere. Subsequent solutions were developed for other types of density profiles, such as for explosions offset from the center of power-law functions of radius (Korycansky 1992).

The theory elaborated by Kompaneets is generally applicable to different ambient density profiles, and is based upon a few assumptions. The first is that the post-shock pressure, P', inside the SNR volume, V, is uniform and equal to some fraction, λ, of the mean energy density: $P' = (\gamma - 1)\lambda E/V$, for a given adiabatic exponent, γ. The second assumption is that the direction of the shock velocity is normal to the curve defining the shock front at a given moment. The third is that the magnitude of the shock velocity, v_{s}, is found by equating P' to the ram pressure of the ambient medium, ρv_{s}^2. Like the Sedov–Taylor case, the solutions for the shock evolution in simple functions of density are self-similar, where the scaling depends on the energy of the explosion and the value of the ambient density.

We use the Kompaneets approximation to construct a numerical method of solving the decelerating shock front evolution in more general ambient media in the first of the following chapters. Instead, when studying supernovae in close binary systems, the initial free-expanding regime is the only relevant one, as the binary separation is much less than the radius at which the SNR reaches the stage of appreciable deceleration.

During the earliest evolution of the SNR (the first two stages of Figure 1.1), the temperature is high enough that much of the emission from the SNR is in the form of X-rays from bremsstrahlung ('breaking radiation' from the electromagnetic deflections of electrons). It is these early stages that are of particular interest in the first two chapters of this thesis, as we are interested in characterising the X-ray emission from SNRs for the time-scales that they survive near supermassive black holes.

1.2.2 Supermassive black hole environments

Black holes are found with masses spanning many orders of magnitude and in a wide range of environments. Following a supernova explosion in the most massive stars, the core of the star collapses into a stellar-mass black hole of several $M_{\odot}$. Their much larger cousins, supermassive black holes (SMBHs, which can be as massive as $10^{10}\ M_{\odot}$), are found in the centres of nearly all massive galaxies (Ferrarese and Ford 2005; Marleau et al. 2013). The origin and growth of supermassive black holes is an active and debated topic in astronomy. Instead, for this work, we are interested in the immediate environment of supermassive black holes like the one in the centre of the Milky Way, known as Sagittarius A* (abbreviated as Sgr A*). The 'central engine' of Sgr A*, like almost all SMBHs in the present-day (*i.e.* local) universe, is categorised as 'quiescent'; that is, the emission of radiation from the vicinity of the SMBH is very low compared with much more active galactic nuclei (AGN).

Light emitted from near the SMBH comes from the accretion flow, and the radiated energy is supplied by the gravitational potential energy liberated by this in-falling matter. The measure of luminosity of the SMBH is typically given in units of the Ed-

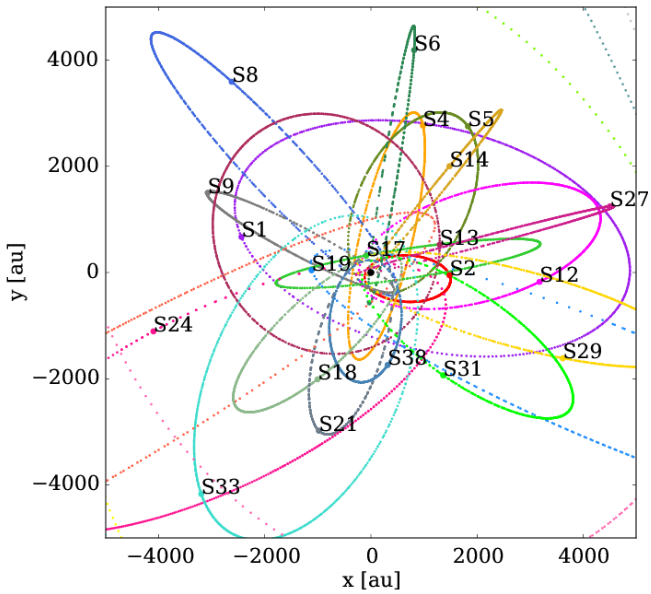

Figure 1.2: Orbits of the S-stars around the supermassive black hole (SMBH) Sgr A*. The orbits are integrated using `ph4` in the Astrophysical Multipurpose Software Environment (`AMUSE`), with observed orbital parameters from Gillessen et al. [2009]. The black point is the SMBH of Sgr A*. [From Lützgendorf et al., 2015]

dington luminosity, L_{Edd}, which is an upper limit at which the force on matter from the radiation pressure of the accretion flow equally opposes the central force of gravity. Due to the immense amount of potential energy released as radiation, accretion flows can be some of the most luminous objects in the universe. Quiescent SMBHs like Sgr A*, however, emit at many orders of magnitude less than the Eddington luminosity.

It is difficult to observe quiescent SMBHs, including Sgr A*, in bands such as the optical due to the large amount of obscuring matter—and, therefore, extinction—in the direction of the galactic nucleus. Instead, searches for these SMBHs have often employed instruments such as the *Chandra* X-ray telescope, as X-rays from the accretion flow penetrate the surrounding material more readily (Baganoff et al. 2003; Wang et al. 2013). A deeper understanding of these obscured environments can shed light on the evolutionary histories of these nuclei (such as the link between the AGN of the earlier Universe and their comparatively inactive present-day forms), as well as help to constrain or rule out different accretion flow models.

The low luminosity of quiescent SMBHs has been explained with radiatively-inefficient accretion flows (RIAFs), such as the 'standard' RIAF model, known as the advection-dominated accretion flow (ADAF; Narayan et al. 1995; Narayan and Yi 1995). In an ADAF, much of the energy is contained within the ions of the plasma in the accretion flow—whereas it is the electrons that emit most of the radiation. The exchange of energy between the ions and electrons is inefficient, and therefore much of the energy is carried (advected) into the SMBH before it can be radiated, explaining the very sub-Eddington luminosity. ADAFs are geometrically thick, and their properties can therefore be well approximated by power-law functions of radius

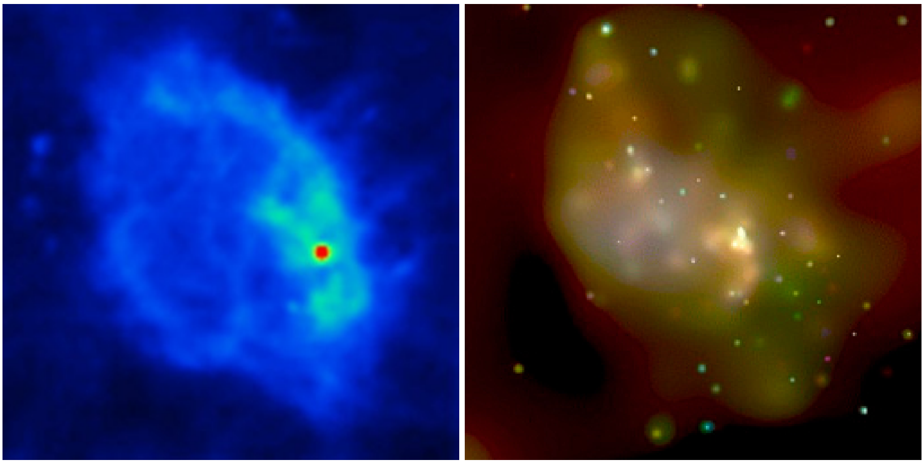

Figure 1.3: The Sgr A East supernova remnant at the centre of the Galaxy. Left: 20 centimetre continuum image from the Very Large Array (VLA); Sgr A* appears as a red point [University of Illinois/NCSA/R. Plante/K. Y. Lo/R. M. Crutcher]. Right: X-ray image from *Chandra*; Sgr A* is located near the bright white points. [ASA/MIT/F. Baganoff et al.]

from the SMBH. The exact form of the power-law dependences depend on the type of accretion model, and in this thesis we investigate a range of models and their effects on our predictions. We will use the radial properties of these models, in particular the density, as the background environment into which a supernova will explode.

Young, massive stars are often seen close to quiescent SMBHs, including Sgr A*, suggesting that ongoing star formation in such regions is common. The proximity of Sgr A* allows us to distinguish a group of massive stars as close as milliparsecs (thousands of au) from the black hole, known as the S-stars (Figure 1.2). Further out, to a distance of half a parsec, are hundreds of massive stars that appear to lie in a rough disc-like structure (Bartko et al. 2009). With this many massive stars, we expect that core-collapse supernovae near SMBHs like Sgr A* should be a frequent occurrence. Indeed, we do see evidence for at least one SNR near Sgr A*, known as Sgr A East (Maeda et al. 2002), which in fact seems to be engulfing the SMBH (Figure 1.3). The winds from the stars near the SMBH provide the material for the accretion flow for the black hole, which is the ambient medium into which any supernovae will explode.

1.2.3 Two tales of two stars: supernovae in binary systems

The majority of massive stars have a binary companion (Sana et al. 2012), and for core-collapse supernovae we therefore expect the presence of a companion star to be an important consideration. Core-collapse supernovae in giant stars typically produce supernovae classed as Type II (containing hydrogen lines). However, for closer binaries, much of the envelope of the exploding (primary) star can be stripped either by stellar winds or by interactions with the close binary companion. The loss of the hydrogen envelope from the primary means that these stripped core-collapse supernovae tend to show little or no hydrogen, and are therefore classed as Type Ib (containing helium lines) or Type Ic (containing no helium lines). The mass of the ejecta in these supernovae is small (and may be almost non-existent in the case of ultra-stripped Type Ic supernovae), and therefore so is the total mass of the exploding star.

If there is negligible effect of the supernova impact on the companion star, the binary system is unbound if the mass lost in the supernova ejecta is more than half of the total mass of the system (Hills 1983). However, the analysis is complicated if the impact of the supernova ejecta cannot be ignored, which is the case at small orbital separations. The impact of the shell on the companion strips material from the outer layers of the star; additional material is subsequently lost due to ablation from shock heating. The impact also imparts additional momentum to the companion star.

The combined effects of mass lost and momentum gain—in particular, the directions in which material is lost (for example, we see a clear burst of material out the far side of the star due to shock convergence)—determine the final velocity of the companion. These effects were treated analytically by Tauris and Takens (1998) using impact predictions from Wheeler et al. (1975) and early, lower resolution simulations of the impact by Fryxell and Arnett (1981). We approach this problem with higher resolution simulations beginning from shortly after core bounce in the supernova progenitor to study the effects of the supernova on the companion star. Of particular importance to the theory developed in Tauris and Takens (1998) is the total amount of mass stripped from the companion star and the additional velocity imparted to the companion by the impact, and so we investigate these effects in our simulations.

1.2.4 Two tales of two stars: stellar collisions and blue stragglers

Star clusters are broadly grouped into two types: ‘open’ clusters, which contain hundreds or thousands of stars and have recently formed in the galactic disc, and ‘globular’ clusters, which are much older, dense hives of tens of thousands (up to millions) of stars found in galactic halos. Observations of globular clusters indicate that the majority of the stars share a common origin at the formation of the cluster, where the clusters often are almost as old as the Universe itself.

Over time, mass segregation causes more massive stars to sink towards the centre of globular clusters. In principle, this process causes an instability during which the core undergoes a runaway increase in density known as ‘core collapse’,[1] were it not for the dynamical heating from binaries in the core, whose supply of energy can prevent the collapse from continuing. Some globular clusters show evidence of a ‘cusp’ in surface brightness towards the centre, suggesting core collapse has occurred, whereas

[1] Not to be confused with the same term referring to the process during a supernova

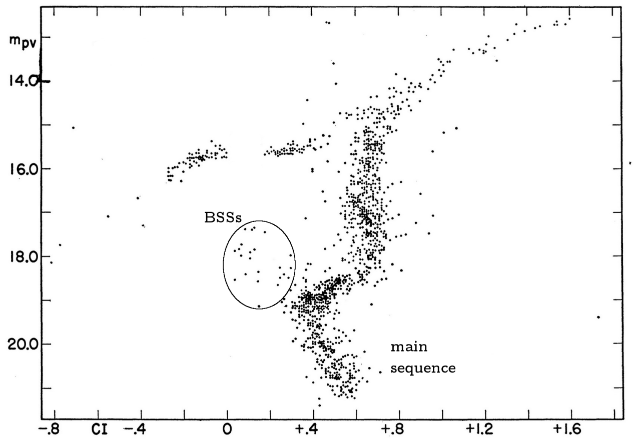

Figure 1.4: The first blue straggler stars (BSSs) discovered, found by Sandage in the globular cluster M3. [Adapted from Sandage, 1953]

others show a 'core' (flatter) distribution in brightness, suggesting they have not undergone core collapse.

Plotting the positions of the stars on a Hertzsprung-Russell (HR), or colour-magnitude, diagram shows that almost all the stars in globular clusters can be fit with an isochrone (a line of constant-age stellar models) through the ridge-line of the diagram. The position of the main-sequence turn-off of the isochrone gives an indication of the age of the cluster. However, a small number of globular cluster stars sit in the 'blue' region near the main sequence, above the turn-off (Figure 1.4).

Since they were found in M3 by Sandage (1953), these 'blue straggler' stars (BSSs) have posed a puzzle regarding their origin, and they have been discovered in other environments such as open clusters (Ahumada and Lapasset 2007) and the Milky Way bulge (Clarkson et al. 2011). Stars in these positions of the HR diagram should have left the main sequence and crossed the Hertzsprung gap had they formed at the same time as the rest of the stars in the cluster. BSSs therefore appear much younger than the rest of the cluster—yet these environments are nearly devoid of the gas required to build new stars. Instead, the two main channels proposed for the formation of BSSs are either the collision of two stars or the transfer of mass from one star to another in a binary system. The collision mechanism is expected to be more likely in the centre of globular clusters, where the stellar density is higher—particularly if the globular cluster has undergone core collapse.

Observations of globular clusters, such as the cluster Hodge 11 examined in this thesis, have placed the innermost BSSs and outermost BSSs at slightly offset positions on the HR diagram. This has been proposed as indicating different processes of BSS formation (for example, Li et al. 2013). Assuming a given BSS was formed from a collision, simulations of this process can be used to estimate a most likely collision time. Doing this for a sample of the BSSs in the cluster allows us to test for consistency with a burst of formation that peaks at the cluster core collapse time. If the BSSs are collisional products, it is in principle possible to use this method to constrain the core collapse time of the cluster.

1.3 Methods used in this thesis

This thesis employs a variety of techniques to solve problems that are otherwise very complex or infeasible to solve analytically. Chapters 2 and 3 use the theory of shock front evolution (the Kompaneets approximation) to construct a more versatile numerical technique for solving the shock problem. The following, final two chapters employ codes within the Astrophysical Multipurpose Software Environment (`AMUSE`). Chapter 4 uses a smoothed-particle hydrodynamics code to model the problem of a supernova in a binary star system. Chapter 5 uses a combination of codes running with `AMUSE` to construct BSS models along with a code that performs a Markov Chain Monte Carlo study. We provide more detail in this section on all of these numerical techniques.

1.3.1 A new numerical shock solver

As we are interested in problems with density profiles that are no longer described by simple functions, analytic solutions to the differential equations for shock evolution using the Kompaneets approximation quickly become intractable. We therefore use this theoretical basis (outlined in Section 1.2.1) to develop a code that numerically solves for the evolution of shock fronts in any axisymmetric configuration of densities. The code uses the assumptions in the Kompaneets approximation by breaking the shock down into individual elements that are evolved along 'flowlines' in the gas, normal to the shock front. In particular, we will apply this code to explosions offset from a varying power-law gradient (and also with discontinuity resembling a torus with different density), all of which preserve the axisymmetry of the problem. Maintaining axisymmetry means the problem can be solved in two dimensions, as the properties of the shock (such as its total volume) can be found by rotation about the symmetry axis. This in turn entails rapid solutions for the shock evolution, allowing us to investigate a large sample of the parameter space of interest.

1.3.2 AMUSE

For the remaining problems investigated in this thesis, we employ a number of codes developed by the astrophysics community. Unifying these codes is the framework of `AMUSE` which is under active development in Leiden by a team lead by Simon Portegies Zwart. `AMUSE` provides an interface to codes covering a range of domains such as stellar evolution, hydrodynamics, gravitational (N-body) dynamics and radiative transfer (often with multiple choices of codes for each domain). This enables complex astrophysical problems to be tackled by coupling codes across multiple domains, and allows ease of use of the codes with a unified `python` interface, which naturally handles units and physical constants. With `AMUSE` the final two chapters employ several codes, which we now turn to in more detail.

1.3.3 Smoothed-particle hydrodynamics

Distinct from grid-based hydrodynamics codes, which are typically Eulerian in construction (tracing a fluid by spatial coordinates), smoothed-particle hydrodynamics (SPH) codes are a particle-based Lagrangian formulation (tracing a fluid by mass). The fluid in SPH is broken down into (usually equal-mass) mass elements, each of which is assigned a 'smoothing length', h (where h is often determined by fixing the number of neighbour particles within h from a given particle). This gives the characteristic scale of the smoothing kernel.[2]

The smoothing kernel is used to calculate properties of the fluid, such as the density, pressure and pressure gradient, weighted across neighbouring particles by the kernel. The compact support of the kernel means that calculations are only performed on the $N_{\rm nb}$ neighbours within its support (an $\mathcal{O}(N_{\rm nb}N) \sim \mathcal{O}(N)$ calculation) and not the whole particle set (which would be an $\mathcal{O}(N^2)$ calculation). Including self-gravity of the gas with direct N-body calculations would worsen the computation to $\mathcal{O}(N^2)$; instead, codes such as `GADGET-2` (Springel 2005b) use a tree-based gravity calculation, which is dependent on the opening angle of the tree, but can improve the computational time to $\mathcal{O}(N \log N)$.

We use smoothed-particle hydrodynamics to investigate the effects of supernova on a close binary companion. As our problem involves the advection of gas in a vacuum (the stars in an orbit) as well as expansion of gas over a large range of radii (the supernova shell), this is naturally handled by the Lagrangian nature of SPH, without the restriction of bounding boxes common to grid codes.

1.3.4 Stellar structure and merger modelling

The coupled, non-linear differential equations of stellar structure do not have analytic solutions. As they must be solved numerically, a large number of stellar structure solvers have been developed over the past half-century. For our work, we use the stellar structure and evolution code `MESA` (Paxton et al. 2011). This solves the stellar structure equations under the conditions of local hydrostatic equilibrium using the Henyey method (Henyey et al. 1964), which assigns a one-dimensional Lagrangian mesh to

[2] In codes such as `GADGET-2`, which is used in this work, the kernels are cubic splines, although some recent codes have employed other kernels whose Fourier transforms do not go negative, which fixes a relatively benign 'pairing instability' seen with kernels like the cubic spline (Dehnen and Aly 2012).

the stellar interior. As opposed to finding structure solutions by iteratively performing explicit integrations from (for example) the stellar surface to the interior, the Henyey method performs iterative implicit integrations of the structure equations together with the equations of energy transport. The time evolution of the star is determined by nuclear reaction networks that change, at each time step, the composition (as well as, crucially, the opacity of the stellar material) and therefore the structure of the star. Stellar evolution models from `MESA` are used in the penultimate and final chapters of this thesis.

Stellar interactions can complicate the evolutionary picture considerably, and one of the most extreme interactions possible is the collision between two stars. One can simulate this process fully using hydrodynamical models of the stars, for example using the SPH technique described in the previous subsection. However, this process is computationally very expensive if many types of collisions need to be investigated. A general technique to calculate the structure of two merging stars has been developed by Gaburov et al. (2008) based on a technique first applied to low-mass stars by Lombardi et al. (1996). This implementation, in the form of the code Make-Me-A-Massive-Star (`MMAMS`), is motivated by Archimedes' principle for the buoyancy of fluid elements during a merger. The buoyancy of an element can be calculated from the entropy and composition of the fluid. The algorithm therefore uses a 'buoyancy' variable derived from the local specific entropy (which is conserved in adiabatic processes) to sort the fluid elements for the final stellar structure. This method has been validated against high-resolution hydrodynamic (SPH) simulations, and is much faster (converging in minutes) than the equivalent hydrodynamic simulations (which may take days to complete). We use both `MESA` and `MMAMS` in the current work to investigate the possible collisional origin of BSSs in a globular cluster in the final chapter.

1.3.5 Monte Carlo and MCMC methods

For calculations that are too difficult or complex for derivation from first principles, or to even fully simulate numerically, the Monte Carlo (MC) approach often offers a solution. Particularly useful for problems requiring statistical estimates, the MC method involves random sampling of input parameters to make estimates of the distribution of output parameters. One of the first MC computations to be performed was on an analogue computer designed by Enrico Fermi (the FERMIAC) to model neutron transport as a random process (Figure 1.5; Metropolis 1987).

Extending Monte Carlo techniques is the concept of a Markov Chain. This is a set of random variables that, at any given moment, has a transition probability to a future state that is independent of the past state of the chain—in a simplified sense, a Markov Chain is 'memoryless'. Markov Chain Monte Carlo (MCMC) methods are useful in sampling multidimensional distributions via random walks, which enable an estimation of (in a Bayesian picture) the posterior probability distribution. Over time, the density of the chain in the parameter space obtained by applying an MCMC

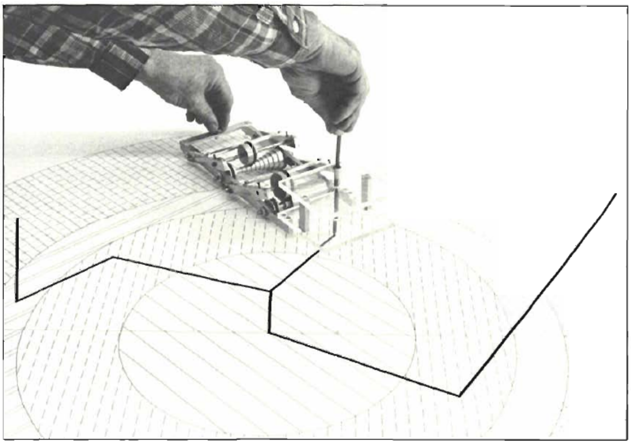

Figure 1.5: The FERMIAC analogue computer (the 'Monte Carlo trolley') in action. The paths of neutrons through a material were drawn on paper representations of different materials, where the drums on the trolley were set based on Monte Carlo choices of direction and distance traversed by fast or slow neutrons. [From Metropolis, 1987]

algorithm will represent the density of the posterior distribution.

One of the most common and intuitive MCMC algorithms, Metropolis–Hastings (Metropolis et al. 1953; Hastings 1970), evolves the chain from a given state by proposing a set of new values for the variables, and determining the resulting new posterior probability. If the new posterior is higher, the chain accepts the proposed values and transitions to the new state. If it is lower, the probability of the chain transitioning to the proposed position is proportional to the ratio of the new posterior to the current one (if the proposed step results in a low value, the chain is more likely to stay in its current position). In the code used in the last chapter, `emcee` (Foreman-Mackey et al. 2013), the Goodman–Weare algorithm (Goodman and Weare 2010) uses an ensemble of walkers in parameter space to construct the chain, where proposed values are made from linear extensions of the line connecting a given walker to another randomly selected walker.

For low-dimensional problems, MCMC methods can be compared with results from other optimisation methods such as χ^2 minimisation. We do such a comparison, with results from a grid of initial conditions, in the final chapter.

1.4 Content of this thesis

Much of the work in this thesis uses high-energy stellar phenomena as a tool to understand the nature, origin or evolution of their environments. The questions addressed inform the theory of supernova evolution, the nature of the environments near supermassive black holes and thus their influence on the galactic environment, as well as the dynamical history of globular clusters. In addition to addressing these theoretical matters, much of this work is also devoted to making predictions and interpretations of data from current and next-generation observatories. Outlined below is the content of each of the following chapters.

In **Chapter 2**, we use the theory of the Kompaneets approximation for strong shocks in non-uniform media to create a novel code that solves the evolution of a shock in arbitrary axisymmetric density profiles. This shock solver was developed in particular to investigate SNR shock evolution near quiescent supermassive black holes, but the technique is general enough to be useful for a variety of astrophysical problems. In this chapter, we outline the the theory behind this code, and provide examples of its use in predicting the lifetime of SNRs near quiescent supermassive black holes as well as the morphology of these SNRs over time.

We apply the above code in more detail to models of quiescent galactic nuclei in **Chapter 3**, where we outline 'autarkic' or self-similar dependences of properties of the gas and stellar population on the SMBH mass. We additionally add a dense molecular torus, as observed in our own galaxy, to the density profiles to investigate the effect of its presence. We estimate the total number of core-collapse SNRs surviving around SMBHs based on the lifetimes found from our code, for supernovae exploding in the sphere of influence of a large range of SMBH masses. We predict the temperature evolution, as well as the total emission in hard and soft X-ray bands, from core-collapse supernovae that exploded in the sphere of influence of such SMBHs. We compare with other sources of X-ray emission and estimate the detectability of this contribution and potential for contamination in searches of quiescent SMBHs. We also comment on the implications for inferring the star-formation rate from the X-ray emission of the SNR component.

In **Chapter 4**, we model for the first time the explosion of a stripped core-collapse supernova from the moments after core bounce using stellar structure models of the progenitor and companion stars. The simulations are performed in `AMUSE` using the smoothed-particle hydrodynamics code `GADGET-2`. We use our simulations to estimate the amount of mass stripped from the companion star and the velocity imparted to the companion by the ejecta impact. These results can be used to calibrate theoretical predictions of the final binary parameters—or the runaway velocities of stars that originate from binaries disrupted by the supernova. These predictions are also important in understanding the potential for binary-disrupted runaway stars to contaminate the low-velocity population of hypervelocity stars (stars unbound from the galaxy).

The work in **Chapter 5** employs the codes `MESA` and `MMAMS` in `AMUSE` to produce BSSs formed from the collision of two stars born at the formation of the globular cluster Hodge 11. We generate a grid of these models over the two initial masses and collision time, and convert the final BSS model to magnitudes in the *Hubble Space Telescope* (HST) bands used to observe Hodge 11 by integrating the best-fit synthetic spectra from the BaSeL database. We additionally use the MCMC code `emcee` with our stellar modelling to estimate the initial conditions, starting from the observed HST magnitudes. We show general agreement between the two approaches, and comment on the implications of the collision times found for the BSSs. This correspondence of the MCMC code with the grid approach also suggests it can be used for higher-dimensional parameter searches for similar problems. By predicting the collision time of BSS progenitors, we can use the method developed here to predict the core-collapse time of the globular cluster, and therefore shed light on the evolutionary history of globular clusters.

1.5 Outlook

The ideas and tools presented here can be extended in a number of ways to continue addressing the questions outlined in Section 1.4.

In Chapter 2, we develop a numerical solver for shock fronts in order to predict the fate of SNRs from supernovae that explode near quiescent SMBHs. Although created to answer this specific question, this code was constructed in a manner to allow it to be as generally applicable as possible, and can therefore be used with any axisymmetric density profile. This lends itself to use for other problems involving shocks in the ISM. A natural development would be to extend the code to three dimensions; although this would be more computationally expensive, it would remove any constraints on the form of the ambient medium.

In Chapter 3, we make predictions of the X-ray emission from young core-collapse SNRs near quiescent SMBHs. These predictions suggest this emission is right at the cusp of detectability in many cases given current instruments. However, it is clear that this X-ray component should be considered as a possible contaminant in future X-ray searches for quiescent SMBHs. Next-generation X-ray telescopes such as ATHENA, with higher sensitivity, will help to constrain these predictions, and our work can then be used to infer in more detail the nature of SMBH environments. We show that, if SNRs can be observed near other quiescent SMBHs, their presence can also be used to give an indirect measurement of the local star-formation rate. Furthermore, in the Milky Way, a clear application of our code would be a more comprehensive investigation of the possible origins and age of the Sgr A East SNR.

In Chapter 4, we predict the effects on a companion star to a Type Ibc supernova. The flexibility of `AMUSE` allows us to easily modify this code to answer a number of other questions. Most immediately, different types of progenitors (such as ultra-stripped primaries) or companions (sub-solar or giants) are readily added with different stellar evolution models. It is also possible to easily incorporate other components to this model to study the effects of a supernova on them, such as circumbinary planets. The predictions from this work can be used to better determine the properties of runaway stars from supernova-disrupted binaries that may appear in searches for hypervelocity stars, such as with the recently launched *Gaia* mission.

In Chapter 5, we propose a method for estimating the collision time of stars that form BSSs in globular clusters, and apply this to observations of Hodge 11 in the

Large Magellanic Cloud. Our work shows that this method can be a powerful tool in inferring the dynamical history of clusters, such as the core-collapse time. This method may also be applied to other environments where BSSs are observed, such as in the galactic centre, to shed light on the formation history of the stellar component. The confirmation of effectiveness of the MCMC approach indicates it can be used for similar questions involving a larger number of free parameters, such as the merger of stars with different metallicities or birth ages, or multiple stellar collisions.