Clues from stellar catastrophes

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Thesis summary

Stellar catastrophes

A star much more massive than our Sun ends its life in a spectacular fashion. Once its nuclear fuel is exhausted, the core of such a star can no longer support itself, and collapses into a compact object—either a neutron star or a black hole. Within seconds, the remaining outer layers of the star are violently expelled in a (core-collapse) *supernova* explosion.

An immense amount of energy is released in a supernova—about 100 times more than what the Sun will provide over its entire 10 billion year lifetime. Nearly all of this energy is quietly carried away by neutrinos, particles that are copiously produced during the supernova but are almost undetectable through their weak interaction with other matter. Only 0.01% of the energy is emitted as the light that so conspicuously signals the death of the star. Despite being such a small fraction of the total energy, in its earliest days the luminosity of a supernova is still enough to outshine a whole galaxy worth of stars. The remaining energy, about 1% of the total, goes into the motion of the gas that is shed from the star during the explosion. As this material, the *supernova ejecta*, expands into the surrounding medium, it sweeps up more gas, and evolves as a *supernova remnant* (Figure 5.8). Supernova remnants feature in most chapters of this thesis.

Most known supernova remnants are expanding into a relatively uniform interstellar medium that sits between the stars. However, in this thesis I investigate a more extreme medium—the environments found at the centres of massive galaxies. At the heart of nearly all large galaxies is at least one 'supermassive' black hole. In the case of our own Milky Way Galaxy, this black hole has about 4 million times the mass of the Sun. Despite being so massive, it is gravitationally dominant only over a region equivalent to a few times the distance between the Sun and the nearest known star.[5] Within this *sphere of influence*, 'winds' of particles emitted from nearby stars are captured by the the black hole, forming an *accretion flow*. Many young, massive stars (the type of star expected to undergo a supernova explosion) have been observed near

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[5] Proxima Centauri—about 1 parsec, or 4 light years from the Sun

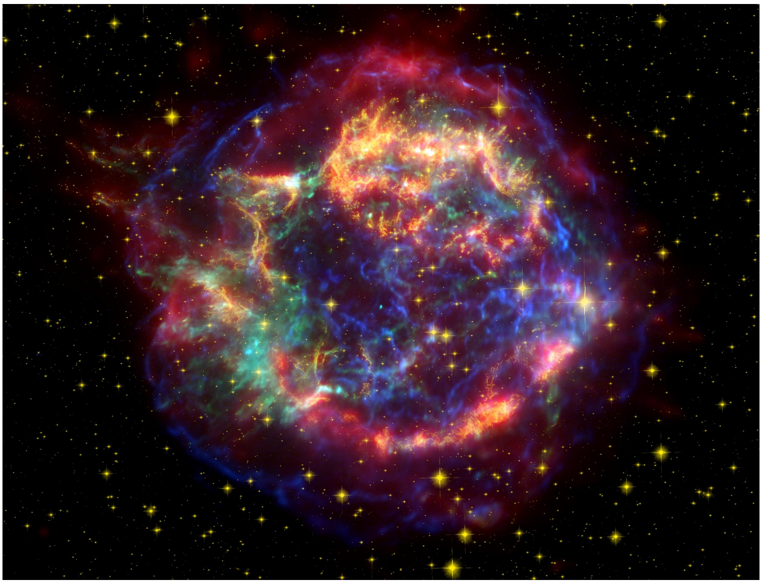

Figure 5.8: The core-collapse supernova remnant Cassiopeia A. Red represents infrared light from the *Spitzer Space Telescope*, orange is visible light seen by the *Hubble Space Telescope*, and blue and green are X-ray light from the *Chandra X-ray Observatory*. The compact object left behind from the explosion can be seen as the cyan point near the center of the shell. Credit: O. Krause, G. H. Rieke, E. Le Floc'h, K. D. Gordon, E. Egami, J. Bieging, E. Young, J. L. Hinz (Steward Observatory); S. M. Birkmann, S. P. Quanz (Max-Planck-Institut fur Astronomie); J. P. Hughes (Rutgers University); D. C. Hines (Space Science Institute).

supermassive black holes, which has been seen most clearly in the Milky Way.

Properties of the accretion flow of the black hole, such as the variation in gas density over distance, depend on how energy and matter is transported within it. A number of different mechanisms have been proposed, leading to different possible models of the accretion flow. When a supernova explodes in such an environment, its evolution is determined by the structure of this gas around the black hole.

Supernovae can have dramatic effects on much more immediate surroundings, such as a companion star that is paired to the exploding star in a *binary* system. If the companion is close enough, the impact from the explosion will substantially distort the star, removing material from its outer layers and giving it a kick in the direction of the expanding material. In some cases, the binary may be unbound by the supernova, so that the companion escapes as a *runaway* star. Knowledge of how the companion star is affected by the supernova, and how the supernova remnant is affected by the companion, can help to inform searches for these companions. An understanding of runaway stars from unbound binaries is also important to distinguish them from other sources of stars with high velocities.

Finally, I focus on another type of catastrophic stellar event—this time, not an ex-

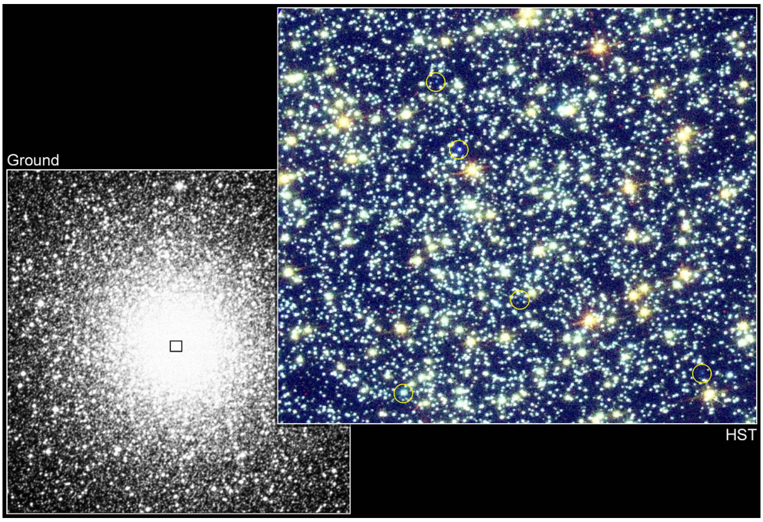

Figure 5.9: One of the most impressive globular clusters in the southern sky, 47 Tucanae. On the left is an image of the cluster from a ground-based telescope. On the right, the *Hubble Space Telescope* (HST) can resolve individual stars in the centre of the cluster, where blue straggler stars have been identified (circled). Credit: R. Saffer (Villanova University), D. Zurek (STScI) and NASA/ESA.

plosion of a star, but the collision of two stars. Although stars can collide in many possible environments, the occurrence is most commonly associated with stars deep within globular clusters (Figure 5.9). Globular clusters are ancient, dense objects whose stars formed around the same time. They are devoid of the gas required to form any more new stars. Yet, puzzlingly, short-lived blue stars have been found in all of these clusters that have been studied so far. At first blush, these stars should not be there; had they formed with the rest of the cluster, the lifetimes of these stars are too short for them to still exist. Two formation mechanisms are often considered for these *blue straggler* stars: the transfer of mass from one star to another in a binary system, or the collision between two stars. Stellar collisions, in particular, are more likely when the density of stars is very high, which is the case in the centres of globular clusters. The likelihood of a collision is further increased if the globular cluster has undergone a rapid increase in density known as *core collapse* (not to be confused with the type of supernova of the same name).

Clues from stellar catastrophes

The work presented here uses the catastrophic stellar events outlined above to investigate different aspects of their larger environment. The first part of this thesis examines what happens to supernova remnants in the innermost regions of galaxies like our own. In Chapter 2, I first develop a technique for predicting the evolution of supernova remnants in non-uniform density environments. This was created to investigate what happens to supernova remnants in the accretion flow near supermassive black holes, although the method is general enough to be applied to other types of environments. Different types of accretion flow will result in different shapes, sizes or lifetimes of supernova remnants. If we can predict how supernova remnants evolve in these environments, we can infer something about the medium into which they are expanding, and therefore about the surroundings of supermassive black holes.

Having established this method, in Chapter 3 I then make predictions of what could be observed from supernova remnants near supermassive black holes. Due to the vast distances to even the nearest massive galaxies, we cannot enjoy the same level of detail that can be resolved in the centre of our Milky Way Galaxy. Nevertheless, even if we are unable to observe the shape or size of supernova remnants directly, we can still measure their light, which is bright in X-rays when the supernova remnant is young. Therefore, in this chapter I estimate what contribution young supernova remnants can have to the X-ray emission from the centres of galaxies. I show that it can compete with other sources of X-rays, such as the emission from the accretion flow of the supermassive black hole itself. This is an important consideration in attempts to look for supermassive black holes in other galaxies, which in the present-day Universe tend to be relatively dormant, or *quiescent* (and are therefore more difficult to observe due to very little radiation being emitted).

In Chapter 4, I demonstrate what happens to a star that is a companion to a supernova explosion. I study a scenario that had not been well examined previously—a companion star very close to a star that has been stripped of much of its outer gas prior to its supernova explosion. These *stripped core-collapse supernovae*, categorised as Type Ib or Type Ic supernovae, have small amounts of ejecta that impact the companion star at high velocities. I use simulations with the Astrophysical Multipurpose Software Environment (`AMUSE`) to study the amount of mass removed from a companion star, as well as the kick in velocity it receives when it is hit by the expanding supernova ejecta. This information is helpful for predictions of the observable properties of runaway stars. Finally, I look at other effects such as the possible signature of the companion star in the expanding supernova remnant.

In Chapter 5, I use models of blue straggler stars (formed from stellar collisions) to learn about the globular cluster that contains them. I use simulations in `AMUSE` to evolve and collide stars at a given time to produce a blue straggler. Because the masses of the stars as well as the time at which they collide are varied, this produces a large number of possible models. The resulting models are compared with *Hubble Space Telescope* observations of blue straggler stars in a globular cluster, by determining what would be observed by this telescope for each of our model blue stragglers. By comparing the models with observations, we can estimate the formation times of the observed blue stragglers. In turn, it is possible to then make inferences about the history of the globular cluster, such as when it may have undergone core collapse.