X-ray spectral analysis of non-equilibrium plasmas in supernova remnants

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Summary

Supernovae and their remnants

When looking up at the night sky, preferably while being at a nice dark place (for example a beach in Greece), you can see thousands of stars. There are bright and faint stars, blue, red and yellow in colour. Often there are planets visible, and if it’s dark enough you can see even the Milky Way. It is a fascinating and beautiful sight at which you can stare for hours without growing bored.

Staring at stars is therefore something that people have been doing for a very long time. Ancient sources have been found of Arabian, European and Chinese astronomers, which show that astronomers have been studying the night sky for millennia. When viewed with the naked eye, nothing much really happens in the sky. The moon changes phase, planets move and sometimes a falling star is visible. The old sources show, however, that every once in a while a new star, a nova, appeared in the sky. Depending on whether the observing astronomer wanted to make a promotion, or wanted to be beheaded, the newly appeared stars where interpreted as good or bad omens. The novae shone for times ranging from weeks to years, and were in very rare cases as bright as the full moon.

In the 1920s it became clear that these novae could be divided in two different events, based on their intrinsic brightness. Ordinary novae are, for a few days, about 20,000 brighter than our sun. So called supernovae, however, on which we will focus our attention, radiate for a short time about as much light as the entire galaxy they are in. They are caused by some of the most massive explosions known in the Universe, and due to their large brightness they can be seen even at very large distances. The high amount of energy released in the explosion allows for the fusion of lighter elements, such as silicon, into heavier elements such as iron and nickel.

* Until the year the tv was invented
Supernovae are subdivided into two main classes, depending on the type of object that explodes: core-collapse and thermonuclear supernovae. Core-collapse supernovae mark the end of a star with a mass about 5 times the mass of the sun. During the lifetime of a star, two forces are continuously in equilibrium. On the one hand there is gravity, which wants to collapse the star, and on the other hand there is the force of the light that is produced by the fusion of hydrogen to helium in the core of the star. Due to this fusion, the amount of hydrogen in the core of the star grows smaller, so that less energy can be produced to halt the gravitational collapse. The core shrinks, and as it shrinks it grows hotter which for a short time allows the core to gain energy from the fusion of heavier elements such as helium, oxygen and silicon. Inevitably, however, gravity wins, and the core collapses to a neutron star or a black hole. In this violent process, which lasts a few seconds, enormous amounts of energy are liberated which blow away the outer layers of the star: the supernova explosion.

The other type of supernovae, thermonuclear (also: type Ia) supernovae, are the result of a nuclear explosion in the center of a white dwarf that consists of oxygen and carbon. These white dwarfs can explode if their mass grows so large that the pressure and temperature in the center are high enough for the onset of nuclear fusion. Once nuclear fusion starts in the white dwarf, there is no stopping it and a chain reaction follows which burns up the whole star. This process releases such a large amount of energy that the white dwarf is blown apart in a supernova explosion. The white dwarf can only grow heavy enough to explode if mass is transferred to it from a companion star, or by merging with another white dwarf.

In both types of supernovae the material from which the star consists, hot gas containing different elements, is ejected with high velocities into space. An expanding ball of hot gas forms, which shocks and sweeps up the surrounding material. In these shocks the gas is heated up to millions of degrees celsius, after which it will keep glowing for thousands of years: a supernova remnant. Supernova remnants of a few hundred years old are already many lightyears in diameter, which allows us to study their structure in detail even at distance of thousands of lightyears. These expanding and glowing supernova remnants are the objects I have been studying for the past 4 years.

**X-ray radiation**

Supernova remnants radiate light in a large range of wavelengths, from low-energetic radio to high-energetic gamma-ray radiation. The hot gas they contain, however, is best studied by looking at the X-ray radiation it emits. Obviously we cannot observe X-ray radiation with the naked eye, and besides that it doesn't penetrate the atmosphere. Therefore we use satellites which are sensitive to it. X-ray astronomy has thrived for the past
Figure 6.13: RGB Image of the supernova remnant Cassopeia A. Red corresponds to emission coming from oxygen, iron, neon and magnesium, green with silicon and sulphur and blue with synchrotron radiation coming from highly-energetic electrons.

15 year, due to the launch of two great satellites: the European XMM-Newton and the American Chandra satellites. Fig 6.13 was created using the Chandra satellite, and shows how the young Galactic supernova remnant Cassopeia A looks in X-ray radiation. The different colours correspond to different wavelength areas of X-ray radiation. From theoretical work and laboratory experiments on earth we know that different wavelengths of X-ray radiation correspond to emission from different elements and radiation processes. The red color in the figure corresponds to emission from oxygen, iron, neon and magnesium, the green color with emission from silicon and sulphur, and the blue emission with synchrotron radiation coming from highly energetic electrons.
An important tool to understand the physical conditions present in a supernova remnant is the spectrum, of which one is shown in Fig. 6.14. In such a spectrum, the x-axis shows the wavelength or energy of the radiation we receive, while the y-axis shows the amount of radiation we receive at the particular wavelength. The black points in the figure are the data, obtained this time with XMM-Newton. As mentioned before, emission at different wavelengths corresponds to emission from different elements, but it also corresponds to emission from different ionization states of the same element. In the figure different emission lines are indicated. The label Fe XVIII for example, indicates that the emission is coming from iron atoms which have only 10 electrons, Fe XVIII indicates emission from iron with 9 electrons and O VII indicates emission from oxygen with two electrons. These kind of ionization states, in which atoms have only a few electrons, can only occur at very high temperatures.

The red line in the figure is a model which has been fitted to the data. In such a model, we calculate what kind of emission we expect from a gas at different temperatures, densities, ionisation states and of different chemical composition, and match the resulting expected emission with the data. If the model provides a good match to the data, as it does in this case, we know with high precision the physical conditions present in the supernova remnant. If you think about it, it is kind of impressive that we know what is going on in a supernova remnant thousands of lightyears away, just from looking at the X-ray radiation!

The study of supernova remnants is a very diverse field, which contains many different topics of physics and astronomy. Typical topics are shock physics, the acceleration of high energy cosmic rays, the nucleosynthesis of elements and the formation of dust.
Below I will briefly describe the contents of each scientific chapter in this thesis.

**Overionisation in a mature supernova remnant**

In chapter 2 we study the ‘mature’ supernova remnant SNR 0506-68, which is the result of a core-collapse explosion. The remnant is located in the Large Magellanic Cloud, at a distance of approximately 160,000 lightyears. In the spectrum of this source we find indications of the presence of overionisation, which indicates that the gas has cooled strongly in a short time. This is surprising, since overionisation is normally not found in these types of remnants. We therefore derive the physical conditions under which overionisation can occur, and it turns it that it may be more important in these kinds of supernova remnants than previously thought. We calculate that the age of the remnant is about 4000 years.

**A bullet of supernova ejecta**

Chapter 3 discusses the Galactic supernova remnant SN 1006, which was already observed by Chinese Astronomers in the year 1006. In this remnant of a type Ia supernova, a bullet of ejecta material is present, which is currently shooting out of the remnant at high velocity. This bullet emits very strongly in X-rays, which allows us to use a specific analysis tool with which we can determine the temperature of the oxygen atoms. We find that the temperature of these atoms is about 300 times higher than the free electrons in the gas, and this confirms that particles of the different mass gain different temperatures when shocked at high velocities.

In addition, we find slightly ahead of the ejecta bullet highly energetic synchrotron and so-called Hα emission. The particular morphology of this emission, where the synchrotron emission is located ahead of the Hα emission, has not been observed before. We therefore discuss different possibilities which would allow such a morphology to form.

**RCW 86, a type Ia supernova expanding in a low-density bubble**

In chapter 4 we investigate one of the largest unsolved questions in the current study of type Ia supernovae, namely which kind of progenitor system they have. Are they all
fusing white dwarfs or are they single white dwarfs accreting mass from a companion stars?

To gain further insight into this question we look at the Galactic type Ia supernova remnant RCW 86, which was again observed by Chinese astronomers in the year 185. This particular remnant is very large for its age, which indicates it has been expanding in a very low density bubble. In this chapter we first calculate the amount of iron the remnant contains, and the amount we find of about 1 solar mass confirms that it was indeed a type Ia explosion. Next, we investigate which type of progenitor system of the explosion can create such a cavity. It turns out that a single white dwarf accreting mass from a companion star is the best candidate for this. The low-density bubble has then been blown by the stellar wind of the companion star. This shows not only that these kind of systems indeed explode as a type Ia supernova, but that they can also actively modify their environment before the explosion.

A mixed-morphology remnant

In chapter 5 we look at Chandra data of the mixed-morphology remnant 3C 400.2. Remnants belong to the mixed-morphology class if their morphology in radio strongly differs from their X-ray morphology. How these remnants are formed exactly is still an unsolved question.

In our data analysis, we find that the remnant has properties typical for a mixed-morphology remnant: it shows overionized gas and a concentration of ejecta material such as iron and silicon in its center. Our data suggests that this particular remnant has most likely formed due to high density material surrounding the original explosion. The remnant then expands into this material, which allows the outer layers of the remnant to cool fast, while the inner parts of the remnant remain hot due to the low density present there.

Kepler, a type Ia explosion into a disk of material

The final chapter investigates the type Ia supernova remnant Kepler. The supernova explosion which formed this remnant was first observed in the year 1604. It is named after the famous astronomer Johannes Kepler, who wrote a whole book on the supernova.

Kepler is the archetype of a type Ia supernova remnant which shows a strong interaction with surrounding material. A large amount of surrounding material suggests that the origin of the supernova is a single white dwarf accreting from a companion star, which
Kepler, a type Ia explosion into a disk of material makes this source important to answer the type Ia progenitor question. In this chapter we use a statistical technique called principal component analysis to locate the parts of the remnants which show interaction with surrounding material. We find that such interaction takes place around the whole remnant, but is most strongly present in a band running from the northeast to the southwest of the remnant. This suggests that at time of explosion the white dwarf was surrounding by a band of high density material. We propose a morphology of Kepler that can explain the current emission properties of the remnant.