UNIVERSITY OF AMSTERDAM

Spectroscopy of the Environments of Long Gamma-ray Bursts and their Progenitors

O.E. Hartoog

Summary in English

Long duration[1] gamma-ray bursts (GRBs) are the most energetic explosions we know of in the universe, except for the Big Bang. They are believed to be associated with the deaths of particular kinds of massive stars. In these events, the core of a massive star collapses and material and energy is emitted with almost the speed of light in two confined cones, or jets. When we see a GRB, one of these jets is pointing in our direction. GRBs can be so bright, that we can essentially see them up to any distance, from anywhere in the universe as long as the light had time to reach us. Because the velocity of light is finite, 'far away' means 'long ago'. The most distant GRBs that have been observed actually happened when the universe was younger than only a few percent of its current age of 13.8 billion years. Studying GRBs and their environments offers the opportunity to see what the universe looked like at earlier cosmic times, how it evolved and how these enigmatic explosions come to be.

This thesis is about the cosmic environments of GRBs and about the massive stars that might become a GRB one day. In this summary I will introduce some basics about the phenomena and techniques that are presented in my thesis. At the end of the summary I will briefly describe the essence of the different Chapters in this book that represent my PhD research.

Stars and their evolution

A star is an opaque sphere made out of gas that radiates because of its temperature. The nature of starlight is in general not much different from that of a glowing wire in a light bulb or a white hot piece of iron: a thermal spectrum. The outermost layer of the star, the atmosphere, contains atoms and ions that absorb part of the light at very specific wavelengths, creating atmospheric absorption lines. These lines help us identify for example the composition, temperature and gravity of a star. The temperature of the star is maintained by nuclear fusion in the stellar core. In a nuclear fusion reaction, atomic nuclei merge into new, more massive ones, though just a bit lighter than the sum of the masses of the nuclei that fused. The missing mass is converted into energy following Einstein's famous formula $E = mc^2$, where energy E is equal to the mass m times the speed of light c squared. Because c^2 is a very large number, only a small amount of mass releases a lot of energy. In stars, this equilibrium of energy loss and generation is sustained for a very long time (millions to billions of year), but one can imagine that the core will run out of fuel at some point.

Stars that are as massive as the Sun live for about ten billion (10^{10}) years. These, and stars with a lower mass, which have even longer lifetimes, are very common. There are also stars that are more massive than the Sun when they are formed. From about eight times the

[1]There are two types of GRBs: short and long. This thesis is only about the long type, which is the one connected to the deaths of massive stars.

mass of the Sun and on we call these stars ‘massive stars’. Massive stars are a much rarer sight: if a giant cloud of gas has formed stars, there will always be many more light ones than heavy ones. But massive stars are also rare because they live shorter than lower-mass stars, despite the fact that they have more fuel available. If you would look at a stellar cluster of a few billion years old, all the massive stars are gone, while the lighter ones are still around. The mass of the star pushes on the core, making it very hot and dense. As a result of the strong temperature dependence of the nuclear reactions inside massive stars, the reaction rates are higher than in less massive stars, and they use up their fuel in a shorter time. A star with a mass twenty times the mass of the Sun only lives for ten million (10^7) years, a thousand times shorter than the Sun. The short life of a massive star is characterised by violent and energetic effects and events with which it has a strong influence on its surroundings. Despite their rarity, massive stars play a crucial role in the structure and evolution of the galaxies they live in.

The influence of massive stars

Galaxies are vast gravitationally bound structures consisting of gas, dust and stars. The gravitational potential of a galaxy is largely determined by the mysterious ‘dark matter’, an important but poorly understood component. The average distance between stars within a galaxy is a couple of light years[2], while the distance between galaxies within a group is thousands to millions of light years. The Milky Way, the galaxy in which our solar system lives, contains about a hundred billion stars and has a flat ‘pancake’ shape with a spiral structure when seen from above. On a dark night, we can see this pancake as a bright band across the sky, which explains its name. The Milky Way is part of the Local Group, together with the Andromeda Galaxy, another spiral and the largest galaxy in our neighbourhood, and several dwarf galaxies.

The structure of a galaxy, and how it evolves is strongly influenced by the population of massive stars because of the following effects. Firstly, massive stars ionise and heat up the interstellar medium around them with their radiation. Massive stars are generally hotter and more luminous than less massive stars, resulting in higher emission rates of high-energy photons. Secondly, strong stellar winds fill the interstellar medium with new elements, momentum and energy. Every kind of star can have a stellar wind, but they are particularly strong in very massive (and thus luminous) stars, as the particles in the outer atmosphere of the star feel the outwardly directed radiation pressure. When a star swells up during its evolution, stellar winds get stronger because the gravity at the surface is lower. Especially heavier elements (‘metals’) with many possible electron transitions are sensitive to the radiation pressure, which is why the stellar wind strength is dependent on the concentration of metals in the stellar atmosphere (*metallicity*). Astronomers call every element heavier than helium a metal. The fraction of ‘metal’ atoms with respect to hydrogen and helium atoms is very small and we usually express metallicity as a fraction of he solar value. In a stellar wind, these metals drag along the rest of the gas, which is still predominantly hydrogen and helium. Lastly, massive stars usually end their life in a supernova, an event in which part of the products from nuclear fusion is given back to the interstellar medium, to be used as ingredients for new generations of stars, some with planets, and possible new life forms. During the explosion

[2] A light year is the distance traveled by light in a year; over 9 trillion (9×10^{12}) kilometres.

itself, heavier and more exotic elements are produced that cannot be created by fusion inside stars. The shock wave produced by a supernova can blow away gas and prevent further star formation in the neighbourhood, or it can trigger star formation elsewhere.

The deaths of massive stars

In the core of a star, hydrogen particles are fused into helium. After that, when the core contracts a bit, this helium can further fuse to heavier elements such as carbon, nitrogen and oxygen. In the most massive stars this can continue until the core consists of iron. Around the core, there will be shells made from earlier fusion reactions, like the layers in an onion. The outermost shell is contains predominantly hydrogen; it was never hot enough for fusion here and this is the primordial material of the star. Iron is the most stable element we know, and fusing iron nuclei would cost energy rather than producing it. So when the core is fully turned into iron, there is no energy source to prevent the core from collapsing under the weight of the star. During the gravitational collapse that follows, a lot of energy is released and the object becomes very bright for a couple of days to weeks. This is the phenomenon we already mentioned: a supernova.

A supernova explosion is believed to be close to spherically symmetric: it bursts out the same amount of material and light in all directions, and is equally bright from all sides. When for some reason a large part of the energy ends up in a confined space, this may lead to a highly asymmetric explosion where the outflow can reach velocities close to the speed of light (*relativistic*) and has the form of jets. This is what leads to a GRB. As confirmed by observations, it is possible that a stellar collapse produces a GRB and a supernova at the same time from one collapsing star; the fraction of the energy that ends up in the jet can differ strongly between events. This is how we found out in the first place that GRBs are associated with the deaths of massive stars.

It is uncertain what the exact physical process is that makes the GRB and powers the confined relativistic jets. There are two main models that are both plausible. In the first model, the stellar core collapses to a *black hole*. The surrounding material will, if it contains sufficient angular momentum, form an *accretion disc* which launches the jets. In the other model, the core collapses to a rapidly spinning *neutron star*, that powers the jet with its strong magnetic fields. Black holes and neutron stars are very compact, and the only objects extreme enough to power something as energetic as a GRB.

However, it seems that in order to get a GRB in any of these theoretical scenarios, the core of the progenitor needs to be rapidly rotating at the end its life. It might be that this can only be accomplished if the star was (originally) in a close binary stellar system: two or more stars that are so close to each other that there can be material transferred from one star to another. A single single star can easily spin down because of its strong stellar wind, but in a binary system, it might be possible that the star is ‘spun up’ again by the companion star. It could even be that the stars completely merge. From observations we know that massive stars are very often in close binary systems, so this idea might be plausible. What kind of star and what kind of process leads to a GRB is an important open question in the field of GRBs.

Regardless of the exact central engine and progenitor model, the physics of a GRB and its afterglow can well be explained by a ball of hot and ionised material that is moving towards us with a velocity close to the speed of light. The material is emitted in chunks, but due to the high velocities these will from ‘shells’. Collisions between shells of different velocities, known as internal shocks, produce a powerful flash of high-energy gamma-ray emission: the GRB itself. When the relativistic outflow (the jet) runs into the ambient medium and ploughs through it, it sweeps up electrons that will start to radiate. This is believed to produce the afterglow.

The afterglow is something else than the supernova we earlier mentioned. Both the GRB and the afterglow are primarily pointing in our direction[3] due to the outflowing jet, therefore the afterglow can be much brighter than a supernova, which is emits light in all directions. Studying the afterglows of GRBs gives much more information than the gamma-flash alone.

Optical afterglow spectroscopy

A GRB afterglow can be observed over a broad range of wavelengths: from X-rays, ultraviolet to optical, infrared and radio waves. All of this radiation is light; only the energy per photon (or equivalently wavelength, or frequency) is different. While the initial gamma-rays are observed from space with dedicated satellites that continuously scan the sky for transient gamma-ray sources, the optical afterglow can be observed with ground-based telescopes. GRBs and their afterglows fade very rapidly in time: after a day, the brightness has dropped by about a factor hundred compared to half an hour after the initial trigger. In order to obtain good-quality data, or sometimes to be able to observe the optical counterpart at all, it is crucial to follow up on a gamma-ray trigger very rapidly. Currently there are world-wide networks and collaborations in order to make this as efficient as possible. It depends on the time of the day and celestial coordinates from where on Earth the new source is visible on the sky.

It is particularly interesting to record a spectrum of an afterglow, for which we require the largest optical telescopes. With spectroscopy, the photons are sorted into wavelength bins, and we count how many we have of each wavelength. The result is the brightness of the source as a function of wavelength: a spectrum. A smaller bin size results in a better spectral resolution, but we need increasingly more light for this to be able to produce a useful spectrum.

A typical optical afterglow spectrum is smooth and featureless, but as the light shines through the gas in the dying star’s galaxy, it is absorbed at very specific wavelengths leaving a ‘fingerprint’ of absorption lines, similar to what happens in a stellar atmosphere. From the lab we know exactly where these absorption lines should be located in their own reference velocity frame: their position is directly related to a discrete energy change in an atom or ion. However, GRBs can be very far away from us. So far even, that we see the effect of the expansion of the universe: the more distant a source, the faster it is moving away from us. Due to the Doppler effect on the emitted light, the full spectrum, including the absorption lines, is shifted towards longer (redder) wavelengths. This effect is called *redshift*. In everyday life, we encounter this effect in the sound of a passing ambulance: we hear the pitch of the siren lower when it is moving away from us. The sound wave is stretched out when it is emitted (lower frequency: lower pitch), and the same happens to a light wave that comes from a distant GRB

[3]There should be of course many GRBs that are *not* pointing in our direction, about 99% of them. From these we see neither the GRB itself nor the afterglow, but we might see the supernova effect, which is spherical. These phenomena are probably hard to distinguish from the supernovae that did not have a GRB at all.

(lower frequency: redder). Since more distant sources are moving faster away from us, the redshift is a measure for the distance, and also for the cosmic time at which the light was emitted, because even light needs time to reach us.

Measuring the shift of spectral lines in an optical afterglow spectrum is the most reliable and accurate way to obtain the redshift (and thus the distance) of a GRB. This can be done with low-resolution spectroscopy, suitable for weak afterglows of if you can not observe with a very big telescope. With a good quality spectrum (a higher resolution, a strong signal and low noise), however, there is much more we can learn. The strength of an absorption line that arises from a certain element is proportional to the abundance of this element in the gas that we see in absorption. In this way we can determine the fraction of metals in the gas compared to hydrogen: the metallicity. We have already mentioned that this parameter is very important in stellar winds, which is a key effect in the evolution of massive stars and also in models that describe how to make a GRB. Furthermore, metallicity plays a big role in interstellar dust and how stars and their planets form. The shape and width of absorption lines contains information about the structure and dynamics of the absorbing gas and thus of the far-away galaxy in which the GRB went off.

All this information in the spectrum reveals properties of home-galaxy of the star that became a GRB. We do not know the nature of these stars yet, and which environmental circumstances should be in place in order to make a GRB, therefore this galaxy is an interesting one to study. Astronomers can also study galaxies by their own emitted light, but such observations will always be limited to the brighter ones. Looking at galaxies in absorption with help of a bright light, such as a bright GRB afterglow, that shines through it can be done for a galaxy of any brightness. This way we learn about the full galaxy population, also at earlier times, and not only the close by and/or bright ones.

This thesis

In this thesis I take you along the lifetime of massive stars towards their death, through observational highlights. After a more in-depth introduction in Chapter 1 (recommended for those who want to learn more after reading this summary), we take off in Chapter 2 with the observation of a ‘candidate’ massive star in a galaxy not so far from our own, but already at the limit of where we can take spectra of individual stars. We find, however, that our source is not single at all, but there should be at least a very hot and evolved massive star among a group of less massive, slightly colder stars. The data set that is used for this study is one of the first that is taken with the X-shooter spectrograph on the Very Large Telescope in Chile. This instrument comes back in most of the Chapters, because it is very well suited for observing both massive stars and GRB afterglows. The Netherlands have contributed to the development of X-shooter, for which we have been granted ‘guaranteed observation time’ for both topics.

In Chapter 3 we investigate the nature and the environment of a Wolf-Rayet star, which is a more evolved type of massive star, and a possible candidate for a GRB death. This study is mainly carried out by Frank Tramper, but I took care of the analysis of the surrounding region that is ionised by this extremely hot star.

What then follows in Chapter 4 is the study of galaxies in absorption towards bright background quasars. Quasars, being accreting supermassive black holes in the centres of distant galaxies, are interesting objects in itself, but here they are just used as bright background lights to identify galaxies that lie in front of them. In this Chapter we searched for the emission of three galaxies of which the presence was only known by the absorption they cause in spectra of quasars, and for one of these galaxies we actually found it. This Chapter looks a bit out of line, but it forms the prelude to the techniques used in the Chapters that follow.

In Chapter 5 we encounter the first GRB. We were able to obtain optical afterglow spectra at four moments in time, spread over a week. We find that the strength of some of the absorption lines was changing in time due to the radiation of the GRB afterglow. From this we derived on the distance between the GRB and the absorbing gas, and thus learned about internal structure of the host galaxy.

In Chapters 6 and 7 we present the spectroscopic observations of two other GRBs, but these were much more distant. Both these GRBs went off more than twelve billion years ago. These spectra are the most detailed that currently exist of high-redshift GRBs. Especially for a PhD candidate, it is a real privilege to work on these magnificent data sets. We have been able to determine the metallicities of the host galaxies of the two GRBs in these Chapters, and put constraints on their dust content. The burst described in Chapter 7 exploded so long ago that we start to see properties of the very young universe in its spectrum.

As a final Chapter, I present the outline of an idea that proposes to use the results of the newest cosmological simulations to interpret the picture we see arising for the metallicity of very distant GRBs, including those in Chapters 6 and 7. Cross-field research of this kind could be a key for further understanding of the formation of GRBs and their suitability as probes for the distant universe.