Forside

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Besvarelsesinformationer

Tro og love-erklæring: Ja

UNIVERSITY OF COPENHAGEN

A thesis presented to the Faculty of Sciences in partial fulfillment of the requirements for the degree

Bachelor of Science in Physics

Gamma Ray Bursts

Bachelor

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June 16th, 2021

Pages: 25

Nr. of characters: 53540

ABSTRACT

In this project we will analyse the spectral afterglow observations of Gamma-ray Bursts that have led to very high energy gamma radiation. In January 2019 and December 2020 there was detection of TeV photons from Gamma-ray Bursts. In both cases the afterglow was observed by the X-Shooter spectrograph, which is a part of the Very Large Telescope at the European Southern Observatory in Chile. In this project we will analyse these two afterglow spectra with the purpose of investigating, if there are properties of the two events, that can point to an explanation on why, those Gamma-ray Bursts gave rise to such extreme gamma-ray emission. Our approach to investigate this, is by writing scripts with the goal of comparing equivalent widths and velocity profiles of the two spectra, and compare it to the spectrum of a typical Gamma-ray Burst. We will also give a thought on what relation there might be behind the event, which we believe will need further observations to conclude on.

CONTENTS

PROBLEM STATEMENT

The phenomenon of Gamma-ray Bursts (GRBs) is one of the most extreme phenomena we know in astrophysics. The field revolutionized in 1997 when a GRB was first precisely localized and longer-lasting emission at longer wavelengths, the so-called afterglows, was first detected. Lately, there has been a new ”first” discovery in the GRB-field, namely the discovery of TeV photons from GRBs. The first detection was on January 14th 2019 (GRB 190114C). Recently, there was a second detection of TeV emission from a GRB, namely on December 16th 2020 (GRB 201216C). In the thesis we will try to explore the optical afterglows of these two TeV-bright GRBs and a third ”normal” GRB from the 4th of February 2021. Concretely, we will characterize the absorption lines in the three afterglow spectra to explore, if there is anything we can infer from the absorption lines, about why these particular two GRBs displayed TeV emission.

1

INTRODUCTION

1.1 A brief history of Gamma Ray Bursts

1.1.1 First observations

The first observation of a Gamma Ray Burst (GRB) was not intended. It was detected in 1967 by the American *Vela* satellites, sent to orbit around the earth to monitor gamma radiation from nuclear bombs[1]. The Vela mission was commenced following the Limited Test Ban Treaty of 1963 between the USA and the Soviet Union, which prohibited nuclear weapon tests in the atmosphere, outer space and under water[2]. On July 2nd 1967, one of the satellites detected several bursts of gamma rays, which lasted for only a few seconds[1]. The bursts seemed to have no preferred direction, indicating that they were not caused by humans or anything from the solar system. The following years, more satellites were launched in missions to detect and observe more GRBs. In 1991 NASA launched the *Burst And Transient Source Experiment* (BATSE) instrument, mounted on the *Compton Gamma-Ray Observatory* (CGRO), which would come to detect more than 2.700 GRBs in the following decade. The bursts showed an isotropic distribution on the sky, as seen on the skymap on figure 1, giving no reason to believe they came from the Milky Way or even a nearby galaxy. The long distances proposed by this observation, and the high level of observed fluence, meant that the GRBs must be extremely energetic to reach us with gamma-rays[1].

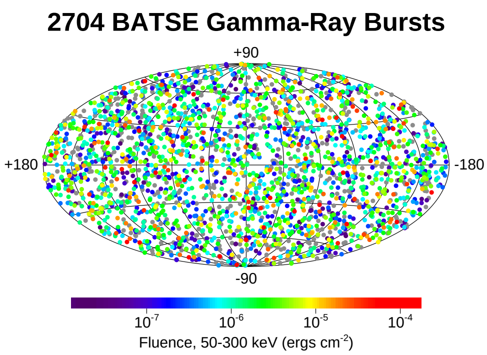

Figure 1: *Skymap of the locations of the 2704 Gamma-Ray Bursts recorded with the BATSE on board NASA's Compton Gamma-Ray Observatory. Fluence is flux integrated over the event. Source: https://gammaray.nsstc.nasa.gov/batse/grb/skymap/*

1.1.2 Afterglows

A new breakthrough came almost 30 years after the first GRB detection. On February 28th 1997 the Italian-Dutch satellite *BeppoSAX* turned its Narrow Field Instruments (NFIs) to the area of GRB970228, which had been localized within 8 hours by the Wide Field Camera (WFC) and the Gamma Ray Burst Monitor (GRBM) on-board[3]. A comparison between NFI measurements at 8 hours and 3 days after the burst showed a decrease in flux by a factor of 20, indicating that there was in fact a previously unknown X-ray source, and that it was fading. The proof, that these observations were due to the same event, came from the fact that the decrease in flux, measured by WFC and later the NFIs, followed the same power law[3].

The afterglows are observed all across the electromagnetic spectrum, ranging from radio-waves to X-rays. This is believed to be due to the dissipation of kinetic energy in the GRB environment[4]. The GRB afterglows contains substantial amounts of information about the GRB and the system surrounding it. Analysing the afterglow can give an insight in which elements are present, and how these behave in terms of their velocities and excitation levels.

1.1.3 New observations

With photon energies reaching GeV ($10^9 eV$), the Gamma-ray Bursts were among the most bright known events in the Universe. On January 14th 2019, an even more energetic GRB was detected. The GRB showed immense energy output, exceeding all previous observations. The energy of the emitted gamma-ray photons exceeded 1 TeV ($1TeV = 10^3 GeV = 10^6 MeV = 10^9 keV$). Again on December 16th 2020, the second and most recent TeV GRB was observed. This means we now have two TeV-GRB observations and that the first event might not be a stand alone event. This has given rise to speculations, and an interest of knowing, what might be the event behind these bright GRBs.

1.2 Present GRB theory

Gamma-ray bursts are associated with the violent death that occur when a star with enough mass become supernovae[6]. After the collapse, the remains of the star, a neutron star or a black hole, will be spinning extremely fast because of the conservation of angular momentum. This induces new, or strengthens existing, extraordinarily strong magnetic fields along the remnant's rotational axis. If particles, namely electrons, happen to be caught in the strong field, they may accelerate to super relativistic speeds along the field lines. This results in electrons, with speeds remarkably close to the speed of light, getting ejected in jets along the axis of rotation. In order for us to observe the GRB and its afterglow, these jets have to be pointing in our direction. When they do, we will observe them as some of the most energetic events ever observed[6].

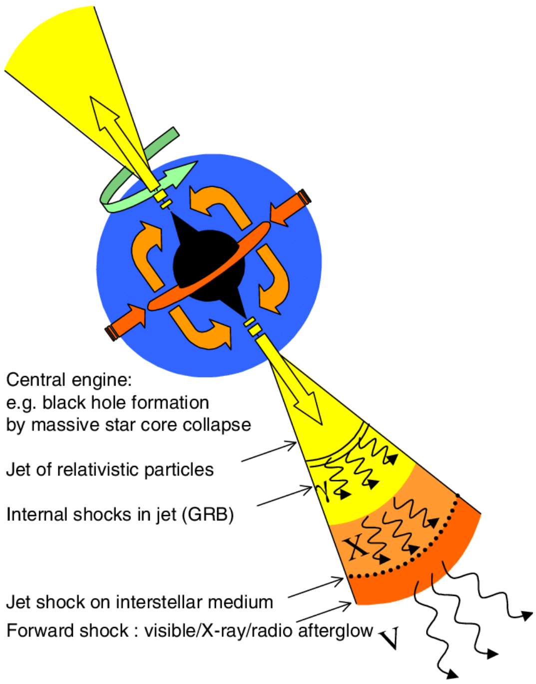

Figure 2: *A model of a massive object collapsing and exhaust gamma ray bursts. Internal shocks produce the initial gamma-ray prompt emission. The jets then reach the interstellar medium and external shocks occur, producing the afterglow emission. Figure adapted from S. Schanne et al. 2006[5].*

In the proposed fireball model, where the initial explosion expands as a relativistic fireball, the initial GRB emission, called the prompt emission, occurs because of *internal* shocks[4]. Several successive shells of outflow could have large relative velocities, allowing them to collide and produce shocks. The shocks heat up the electrons and the surrounding matter, generating new, or amplifying existing magnetic fields further. The electrons spiral around these magnetic field lines with great velocity. When electrons are accelerated perpendicular to their velocity, as they will be in a spiralling motion, they emit photons. This effect is called synchrotron radiation and is believed to be the main cause of the prompt emission of GRBs[4].

At some point the jets reaches the interstellar medium (ISM), where its high velocity results in several *external* shocks[4]. Some shocks may occur, as the outer layers of the jets are slowed by the ISM, allowing the inner layers to catch up. When the relativistic electrons in the jets interact with the surrounding matter, they are believed to transfer some of their energy through inverse Compton scattering. This scattering happens when the electrons hit photons of lower energy, transferring some of the energy to the photons. This chaotic system releases light in nearly the whole electromagnetic spectrum and is what we call the afterglow, which lasts from minutes to months[7].

However, fitting well with the afterglow observations, this model has only been able to explain the prompt emission energy curve for some of the observed GRBs. The energy curves generally follow a ”Band function” fit, best described as a ’broken power law’ (fig. 3). Therefore, other ideas have been suggested, most notably a hybrid model of a thermal and a non-thermal burst component, suggested by Felix Ryde [8].

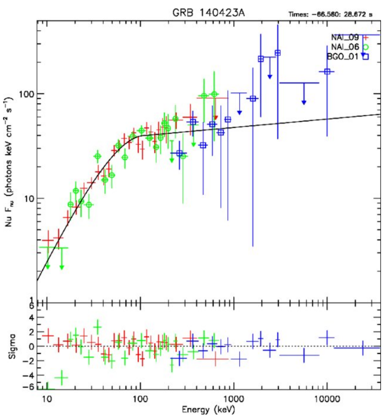

Figure 3: *The spectral fit for the prompt emission of GRB 140423A with a Band function (Band et al. 1993). Source: L. Li et al. 2020[9]*

This model suggests that the fireball explosion contains an optically thick photosphere, where photons within the sphere are thermalized before they are able to escape[10]. These photons would originate from the initial explosion or by any dissipation of kinetic energy within the photosphere. In addition to this thermal component, a non-thermal component should arise from the energy dissipation above the photosphere[10]. This two-part component model seems to fit well with observations and is therefore subject to extensive on-going research. There is not yet a fulfilling GRB emission theory, that is in agreement with the increasingly large amount of GRB data, collected by various teams around the globe. This factor of the unknown certainly makes the study of GRBs an inspiring subject.

1.3 Introduction to this work

The newer observations of Gamma Ray Bursts (GRBs) of higher than usual energies (TeV) have sparked the interest for this project. With the prominent question of what leads to the extreme event of the TeV GRBs, we want to look for differences in the spectroscopic afterglow data of both types of GRBs. A presentation of the specific cases will be made in section 2.1. In this section we will elaborate on why analysing the afterglow spectrum is useful and what information we can gather from such analysis. Furthermore, we will cover the observational challenge of an expanding Universe and how it affects the light we observe.

Looking at the spectroscopic afterglow data, we will be searching for peaks and troughs, which represents emission and absorption lines. These lines indicate that there is a higher or lower amount of flux with respect to the mean, at certain wavelengths.

1.3.1 *Why peaks and troughs are interesting*

The reasoning behind looking at the spectral lines is the fact, that we can figure out which atoms are present in the line of sight between us and the GRB. We know from labs that different elements absorb and emit photons in various, but specific, wavelengths. When an electron transits to a lower orbital, a photon is emitted. The wavelength of the photon is corresponding to the energy difference in binding energy of the corresponding orbitals. Each particular element has several energy orbitals and the transitions inwards can come from any outer orbital. This means that we can see several lines from one element, at different wavelengths. Since the energy levels are different for distinct elements, the photons emitted has very specific wavelengths, and can therefore be seen and used as fingerprints for the elements emitting them.

If an electron is situated in any of the lower orbitals and receives the specific energy needed, it can excite to a higher energy level. This energy comes from photons of specific wavelengths that match a transition, and therefore we see absorption lines, where some or all of the light at a given wavelength has been absorbed by electrons. If a cloud of gas gets heated up, some of the electrons belonging to certain elements in the cloud will get excited. The cloud gets rid of the energy again by emitting light. This light, along with the absence of light, can be observed here on earth. The observations contains information of which elements are present in the cloud, and this information comes as spectral lines in a continuous spectrum.

The continuous spectrum is due to the emission of light in a large continuous range of wavelengths. As covered in section 1.2, the source of a continuous spectrum comes from the chaotic jets, with shocks and strong magnetic fields, leading to synchrotron and inverse Compton emission. This emission functions as the background spectrum for spectral analysis. The above mentioned emission and absorption of the light, from the surrounding atoms, is added to this spectrum, resulting in deviations in flux at the corresponding wavelengths, as illustrated in figure 4.

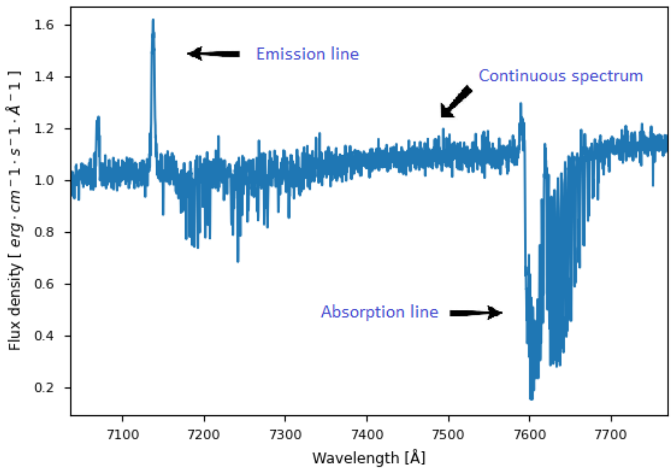

Figure 4: *Example of an emission and an absorption line in a continuous spectrum. In this example, the absorption line is from the atmosphere of the Earth, known as telluric absorption.*

1.3.2 *Determining the redshift*

When light from distant objects reach the Earth, it does not have the same wavelength as when it was emitted. It is therefore not as easy to identify the elements it is coming from. The wavelength of the light is getting shifted on its path from the GRB system to our telescopes. There are two ways the light can be shifted. It can either be shifted due to the Doppler effect, as a result of relative velocities in the line of sight, or shifted due to the cosmological expansion of our Universe. The shift in wavelength is called redshift if the light gets “stretched”, corresponding to an increase in the wavelength, where the decrease in wavelength is called blueshift. The Doppler shift is due to the relative motion between an object and an observer. If the object is moving towards the observer, the time between each wave crest is decreased. This appears to the observer, as if the wavelength is shorter and the color of the light more blue, than if there was no relative velocity between the object and observer. The opposite effect, when an object is moving away from the observer, will cause the light to appear more red. The cosmological redshift however, is due to the fact, that the Universe is expanding and the light gets stretched over long distances while moving through space. The total shift in wavelength is noted as z, and is described by eq. 1.

$$z = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}} = \frac{\lambda_{obs}}{\lambda_{emit}} - 1 \tag{1}$$

The fact that the cosmological redshift changes the wavelength of light over vast distances, creates a challenge in determining elements that are present near the light-emitting GRB. The challenge is, that a single peak wavelength could correspond to different elements, depending on the value of the redshift. Say we observe a peak in the flux at a wavelength of 6564.610 Å, which is the emission wavelength of H-α in vacuum, when an electron of the Hydrogen atom jumps from the 3rd to the 2nd orbital. We can observe this wavelength in the lab and be quite certain, that it is in fact H-α emission. Now say we observe this peak from a system of which we know the distance to correspond to a redshift of $z = 0.35$. By using equation 1, we can calculate the wavelength the observed light would have when it was emitted, given we know the redshift. This resulting emitted wavelength, as seen in eq. 2, is actually the emission wavelength of H-β.

$$\lambda_{emit} = \frac{\lambda_{obs}}{1+z} = \frac{6564.610[\mathring{A}]}{1+0.35} = 4862.674[\mathring{A}] \tag{2}$$

To solve this challenge, we either have to know how far away the observed system is (how much the light gets redshifted), or be able to recognize specific lines in the spectrum. Measuring the distance to distant objects in the universe is very hard and we will therefore rely on the second method in this project. By recognising patterns of absorption or emission lines, we expect to be able to determine specific elements and use the known spectral wavelengths to determine the redshift of the GRB systems. With this information we can then calculate the emitted wavelengths of the observed spectral lines and determine other possible elements around the GRB system.

1.3.3 Further methods of comparison

To make further comparisons, we want to define the strengths and relative velocity of the lines, since this could indicate how much of a given element there is and how it is behaving in its environment. The total flux of the GRB afterglows depend on various things, especially distance. Therefore we want to use a method of defining the relative strength of the lines that takes into account the differences in the mean flux output. One of such measure is called the equivalent width (EW), which we will describe further in section 2.2.1. The section will also explain the method of producing velocity profiles. These profiles will indicate the relative velocities of elements, within the line of sight from the GRB, which is useful information to the understanding of the GRB and its surroundings.

2

METHODOLOGY & DATA

2.1 Introducing data

Our work is based on observations of the afterglow of GRB190114C (GRB19), GRB201216C (GRB20) and GRB210204A (GRB21). GRB19 and GRB20 has been confirmed as extremely energetic TeV-bursts [11][12] and our goal is to compare their afterglows to that of GRB21; a burst of lower and more common energy output ranging from keV to GeV.

2.1.1 GRB observers

All three burst were first detected by either the Burst Alert Telescope (BAT) on-board the Swift telescope or the Gamma-ray Burst Monitor (GBM) on-board the Fermi Gamma-ray Space Telescope (FGST)[13]. The telescopes observe a large field of view and uses algorithms to continuously look for excess light, compared to an expected background. The imaging energy range is 15-150 keV and 10 keV to 25 MeV for BAT and GBM respectively [14][15].

Shortly after detection and confirmation of a GRB, both telescopes distribute the burst coordinates through the Gamma-ray Burst Coordinates Network (GCN). This allows other telescopes, as well as amateur astronomers, to quickly point to the area on the sky, where the GRB might still be glowing. Since the average GRB lasts about 30 seconds, the amount of data to extract from them, depends on how quick the telescopes can relocate. One set of telescopes designed to execute this task, is the two 17m Cherenkov telescopes, that is a part of the MAGIC Collaboration (MAGIC). According to MAGIC, these two 64 tons telescopes can relocate their mirrors to any given point on the sky, above the horizon, within 25 seconds[16]. The MAGIC telescopes cover energies from 30 GeV to 100 TeV and were the first to detect gamma-rays of TeV energies from a GRB.

Mounted on the Very Large Telescope (VLT) in Chile is a spectrograph called X-Shooter. The X-Shooter detects light in the range 300-2480nm, covering the ultraviolet blue (UVB), visual (VIS) and near infrared (NIR) bands [17]. The X-Shooter has been used to observe numerous GRB afterglows, all within 48 hours of the GRB trigger [18]. This includes afterglows from the three GRBs of interest to this project, named at the beginning of this chapter.

2.1.2 GRB Afterglow Data

The GRB afterglow data we will analyse is collected with the X-Shooter spectrograph by the StarGate Collaboration, including partners in the UK, the Netherlands, Italy, Spain and Denmark[18]. It shows the measured afterglow flux density for each fifth of an ångström ($10^{-10}m$) in the UVB, VIS and NIR bands (though only UVB and VIS are provided for GRB19). As seen on the example of the afterglow spectrum of GRB19 (fig. 5), there is a general curved line with a noise width and numerous lines with flux density clearly standing out from the noise. Some of these lines are absorption (lower flux density) or emission lines (higher flux density), but there is also the possibility of lines that are caused by technical errors, due to noise in the spectrograph or due to telluric absorption from the Earth's atmosphere. The technical errors will often extent a single or just a few data-points, where the actual spectral lines will be wider. The telluric absorption will often consist of a multitude of lines, located just a few ångströms apart. More on this in section 2.2.4.

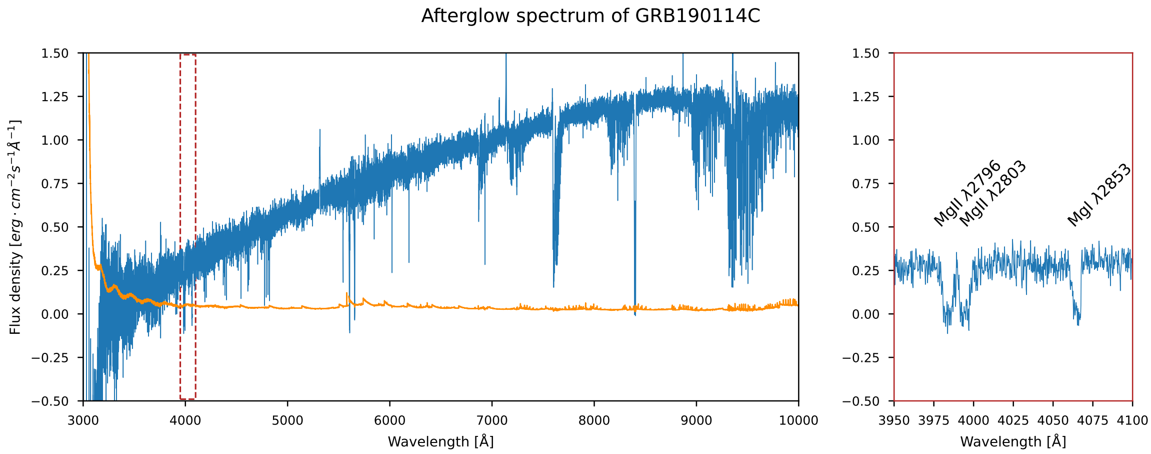

Figure 5: *Left: The full spectrum of the afterglow of GRB190114C over UV and VIS bands as observed by the X-shooter spectrograph. The 1-sigma noise is displayed as orange. Right: A zoom in on* $\lambda = [3950Å : 4100Å]$ *shows the characteristic MgII λ2796, MgII λ2803 and MgI λ2853 lines.*

2.2 Methodology

In this part we will explain the concepts and methodology of spectroscopic analysis, the equivalent width and the velocity profiles, as well as the method of estimating the redshift.

2.2.1 Spectroscopy & the Equivalent Width

As introduced in sections 1.2-1.3, we will be working with the continuous electromagnetic spectrum defined as the afterglow of Gamma Ray Bursts. We will be searching for peaks and troughs that corresponds to emission and absorption lines from various elements.

When examining these spectral lines we expect to see that they have a width. That is, the line spans over an interval of wavelengths. This is dominated by the effect of Doppler broadening, due to a dispersion of velocities within the potential well. This means that within the system of observation, being a gas cloud, galaxy et cetera, different sub systems moves with different velocities.

Being able to compare different spectral lines therefore require a standard measure, that is independent of the shape of the lines, and also the strength and variance in flux across the spectrum. The flux can vary from one spectrum to another as factors like distance, composition and temperature are non-identical for different stellar objects. We therefore introduce the EW. The EW is an expression of how wide a piece of continuum one needs to take, to get an area equivalent to that of the absorption line (see figure 6). The EW is a way to quantify the strength of the line in a manner, that is independent of the flux of the source.

This is a helpful tool to compare different spectral lines, or even the same line from different sources, in a quantitative way. For example, an ordinary absorption line from a warm gas cloud will show Doppler broadening, as a result of the Doppler effects of random motions of the atoms in the cloud. This means that less of the total amount of photons absorbed by the gas will be centered on the peak of the line. Therefore the height of the peak will be smaller compared to the line of the same amount of atoms in a cooler gas cloud. But the EW would be the same for the spectral lines of both clouds.

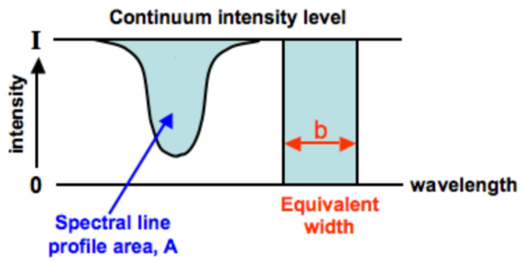

Figure 6: *The area, A, of a spectral line measured below the continuum level is related to a rectangular line profile with the same area, and Equivalent Width, b. Source: https://astronomy.swin.edu.au/cosmos/e/equivalent+width*

The EW is calculated as the integral of one minus the ratio of the spectral line flux, f_λ, to the continuum flux, f_0, over the area of the given peak (eq. 3).

$$W_\lambda = \int_{\lambda_a}^{\lambda_b} (1 - (\frac{f_\lambda}{f_0}))\, d\lambda \qquad (3)$$

The EW would be difficult to trust in scenarios where the continuum flux density is non-constant. For example, if the flux density is lower on the left side than on the right side of a spectral line. The width of a rectangle with the same area as the line would be different on either side of the line, since constant area and different heights must mean different widths of the rectangles. This is shown on figure 7, where the two yellow regions are of equal area, but the width (EW) of the left rectangle is bigger. An example of a non-constant flux density is seen on the spectrum of GRB19 (figure 5), where the continuum flux is increasing with wavelength.

2.2.2 *Normalization*

To work around this, we will therefore normalize the flux density of the local area, by fitting to a function and dividing the flux density with this function. This will not affect the EW as it is a measure of the relation between the peak and the surrounding continuum flux, therefore independent of the amplitude of the flux density. As seen on the spectrum of GRB19, the broad continuum is non-linear. But focusing in on a small area on the continuum will show an approximately linear line (see right side of fig. 5). It would therefore be adequate to normalize the spectral line and a small surrounding area with a linear fit. By doing so, the normalized area will have a constant continuum flux for the EW to be calculated against. If this is applied in the

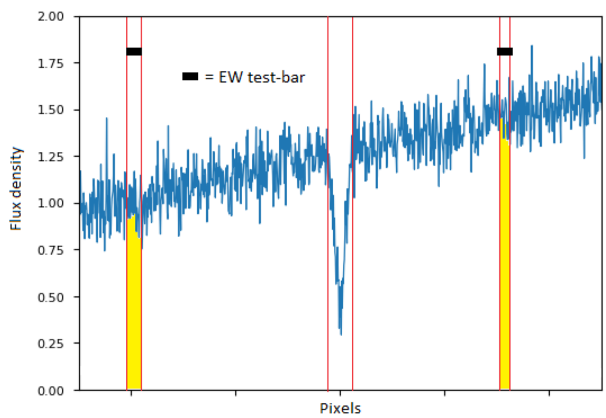

Figure 7: *Theoretical example peak showing the impact on the EW of an uneven, local flux area, illustrated with a test bar, fitting in the left marked area, not fitting inside the right marked area.*

presence of a line, and the line is not a part of the fitted function, the problem described in previous section is no longer present. In section 2.3 we will elaborate more on applying this method.

2.2.3 Velocity profiles

A velocity profile plot will show and compare the peculiar velocities of observed spectral lines. The peculiar velocity is the motion of an object relative to a rest frame. In cosmology, when observing very distant objects, this rest frame is the cosmological expansion. In other words, the peculiar velocity is the motion of the object we would observe, if we, as observers, were close enough, that the expansion of the universe was insignificant to the measure of wavelengths.

From the spectral analysis we can estimate the redshift we call z_{obs}. However, the shift in wavelength we measure will have contributions from both the cosmological expansion and the Doppler effect. This means we can split the observed shift into two parts; the cosmological redshift z_{cos} and the Doppler shift z_p. The observed redshift follows eq. 4. [19]

$$(1 + z_{obs}) = (1 + z_p)(1 + z_{cos}) \tag{4}$$

As the Doppler effect is a shift in wavelength due to the relative motion towards or away from us, it is consequently given that there is a relation between the two as given by eq. 5.

$$v_p = z_p \cdot c \tag{5}$$

When observing objects far from us, we also observe a relation described by Hubble's law. Hubble observed, that the further away an object is, the faster it moves away from us. This is due to the expansion of the space in between us and the observed objects. From this can then be described as 6, where H_0 is the cosmological constant.

$$d = \frac{v_{cos}}{H_0} \approx \frac{c \cdot z_{cos}}{H_0} \rightarrow v_{cos} \approx z_{cos} \cdot c \tag{6}$$

The problem we face is that we cannot tell how much each of the above velocities contribute to z_{obs}. However, knowing that the cosmological expansion is only significant at distances that are large between the observer and the emitter, we can choose a reference we believe to be close to the observed object. We can use this method, since all the light we receive is from the same line of sight. This means, that from the reference to the galaxy we observe, there will only be contributions from the Doppler effect, as z_{cos} is zero for the reference. The relation from eq. 1 (p. 6) makes it easy to choose the wavelength we should choose as reference. This should be the received wavelength of an element we believe is within the same galaxy we observe.

After this trick, the velocity plots becomes an useful tool to describe the peculiar velocities. If the received wavelength is lower than the emitted wavelength, the object is moving towards us and the wavelength is blue shifted and vice versa for higher emitted wavelengths and redshift. Equation 5 is used to convert the redshift and blueshift into positive or negative velocities. This means that in a plot with the velocities on the x-axis ranging from negative to positive, an object moving towards us will

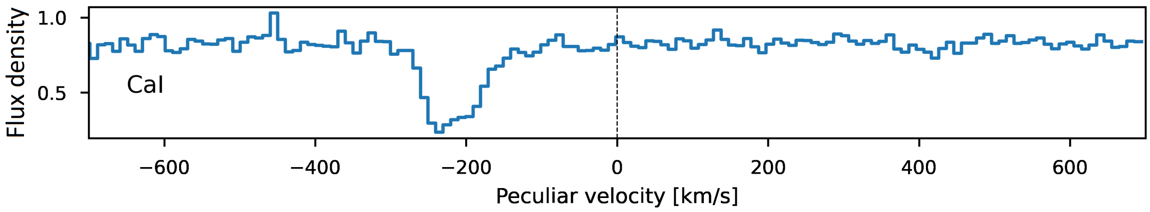

Figure 8: *CaI line blueshifted with respect to a reference. The reference chosen for this plot is an [OIII] line observed in the same spectrum as the CaI line.*

have negative velocities and will be placed to the left and vice versa. An example of this can be seen in figure 8.

From the velocity plots we can tell whether the object is spinning or not. If the object rotates and our line of sight is not parallel with the axis of rotation, we will see one side of the object moving towards us and the other side is doomed to move away from us. This is seen as Doppler broadening, which can be displayed in a velocity plot. This also means that with a spectrum showing different elements, it is possible to place those elements in a velocity plot and get information about how fast they are moving within the host galaxy. This could also be an indication of the distribution of the elements. The widths of the lines represents the minimal span in peculiar velocities. This could for example be due to the various velocities in a rotating galaxy.

There are two challenges with the velocity plots. The first being that the rotational velocities we observe for galaxies depends on the inclination. If we saw the galaxy face on, the velocities would be perpendicular to our line of sight and we would see no Doppler shift. The largest and true velocity would be observed by looking at the galaxy edge on. In conclusion, the actual rotation will be higher unless our line of sight is perfectly perpendicular to the axis of the rotation. We therefore call the inferred peculiar velocities a minimum.

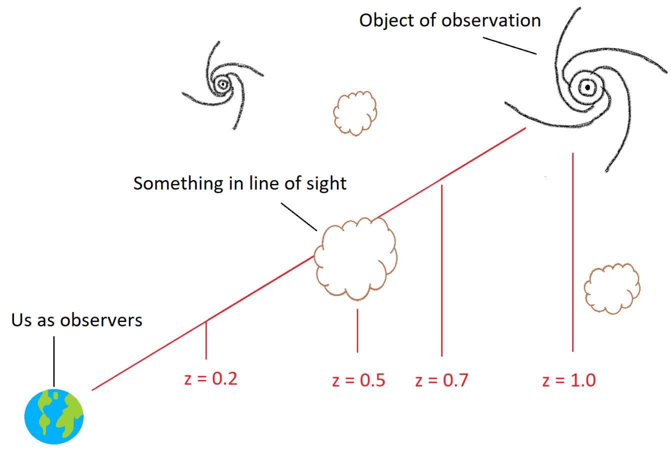

Figure 9: *Illustration of object being in line of sight between observer and object of observation.*

The other challenge is the fact that we can not tell from the velocity profiles whether what we observe is at a specific location. Since we receive all the light that is within the line of sight, we can also observe clouds that are in front of a galaxy we want to observe. If we observe an element moving towards us relative to the galaxy of observation, as the example of fig. 8, it indicates that the element is moving at different velocities than the chosen reference. One cause of this could be due to the merging of galaxies, as the gravitational forces can disrupt the motions within the galaxies. However, this observation could also mean, that the element comes from something else, that happens to lie in the line of sight, and may not be a part of the galaxy. As shown in figure 9, we would see an object, with a lower redshift than the observed galaxy, being in the line of sight. When the cosmological redshift is subtracted from the combined redshift, this cloud would appear as an object moving towards us, since it is less redshifted from the cosmological expansion, than the galaxy of observation. This can give absorption lines that are not part of the galaxy we intended to observe and it could therefore be misleading. The reference we choose could also happen to be shifted, but since it is used as reference, it would appear like the other lines in the spectrum are shifted.

2.2.4 Spectral line verification methods

Differentiating between actual spectral lines and lines due to noise in the spectra can be difficult, since these can look very similar. The presence of telluric absorption lines from the atmosphere of the Earth can have influence on our weighted average method of defining the wavelength of a spectral line. This could affect which element is best chosen as reference for the velocity plots.

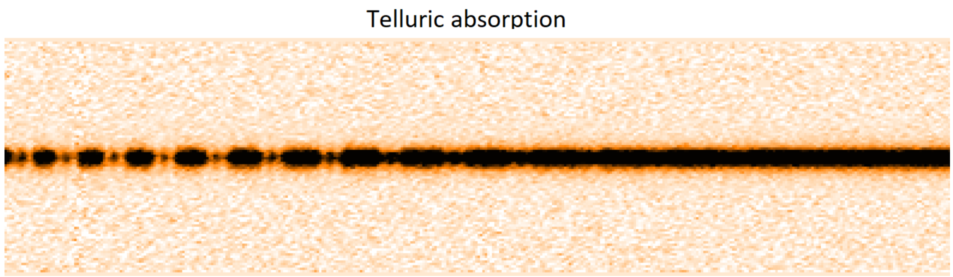

Figure 10: *An example of telluric absorption lines due to the atmosphere of the Earth.*

A few methods can be used to give more confidence in the selection of spectral lines. Firstly, we can identify telluric lines as a bunch of troughs closely gathered, as seen on fig. 10. Secondly, the very thin lines of widths less than a few wavelengths is often a sign of noise. To verify the spectral lines further, we can look at 2D spectra, where the lines due to noise are very sharply cut off. Figure 11 shows an example of this, where the left plot displays an actual absorption line, while the right plot displays two lines due to technical errors.

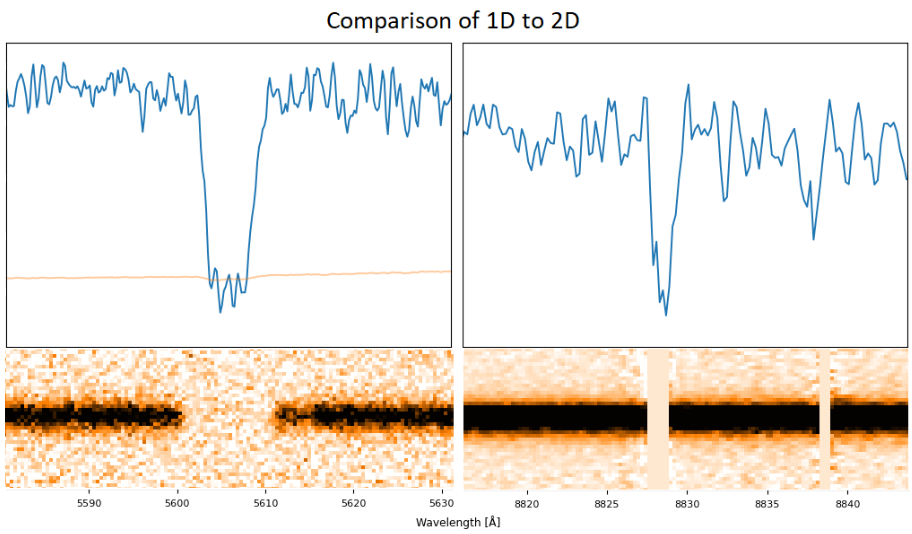

Figure 11: *A comparison between the 1D and 2D spectra, collected with the X-Shooter spectrograph. It shows how a technical error (right) can be hard to distinct from an actual absorption line (left) in the 1D spectra. Top plots are from the 1D spectra and the bottom plots are from the 2D spectra. The technical errors are probably regions with bright sky-background emission lines, removed directly by the spectrograph or in the processing.*

2.2.5 *Estimating the redshift*

To dig out the information mentioned in the introduction we use the programming language Python 3. In this language we program a script where we can choose between a set of different actions. Those actions activate different algorithms, that finds peaks, wavelengths and so forth.

Finding the redshift of the host galaxy is however done more manually. By exploiting the fact that some strong lines define easy identifiable patterns, e.g. doublets from MgII or CaII, we can start by looking for those. With a list of all the peaks from our data and the three known lines that we expect, we can find what the redshift would be, if the peak is from the given element. As the distances between the lines shifts differently dependent of the rest frame wavelength, as the shift is not constant, but multiplicative, we should expect to see a match of redshifts for the elements and not for other lines. So, when the redshift values match diagonally in a n X 3 matrix as in figure 12, where we look for three lines from Magnesium (MgII at 2796Å and 2803 and MgI at 2852 Å), there is quite good chance, that the three observed wavelengths correspond to the elements we are looking for, at a common redshift. However, as this is not a guarantee, we will afterwards manually check the other peaks to see if those match with other elements, whose appearance are realistic. If we can get a match to all or most of the peaks, we can be quite certain of the redshift. Our approach is therefore a combination of manual searching and the writing and use of automated scripts, with most weight on the latter.

z for Mg2	z for Mg2	z for Mg1
0,360	0,356	0,333
0,572	0,568	0,540
0,573	0,569	0,542
0,576	0,572	0,545
0,593	0,589	0,562
0,599	0,595	0,567
0,666	0,662	0,633
0,670	0,666	0,637
0,712	0,708	0,678
0,717	0,712	0,683
0,736	0,731	0,701
0,745	0,740	0,710
0,749	0,744	0,714
0,876	0,871	0,839
0,881	0,876	0,844
0,914	0,909	0,876
1,640	1,633	1,588
1,664	1,657	1,611
2,396	2,387	2,329
5,473	5,456	5,344

Figure 12: *Example of how we determined the redshift on GRB210204A. The yellow marked areas are the three lines that match in redshift. We searched for the lines in this spectrum as they would, if apparent, come quite close to each other, likely giving us a match on the diagonal, as they should all have the same redshift.*

2.3 Data analysis methods

This part describes the explicit methods of analyzing the spectroscopic data along with the EW-calculations, the creation of velocity profiles and calculation of the line strength parameter.

To process the data from GRB19 and GRB21 we have written a script in python. This makes it faster and smarter as the script will do the calculations and return which data we need. When plotting the data, we are plotting the wavelength against the flux and the error of the flux. This gives us something like figure 13, which is what we have written our script around.

2.3.1 *Locating the spectral lines*

At first, we want to locate troughs and peaks in the plot, as these are absorption and emission lines. For each line we want to determine the wavelength of the peak, and the EW, with the corresponding errors. As the spectrum spans quite wide in wavelengths, we create a definition that allows us to mark of a given part of the spectrum for locating spectral lines. We find these lines, simply by eye, by looking for something that differs from the local flux density, that is around the peaks.

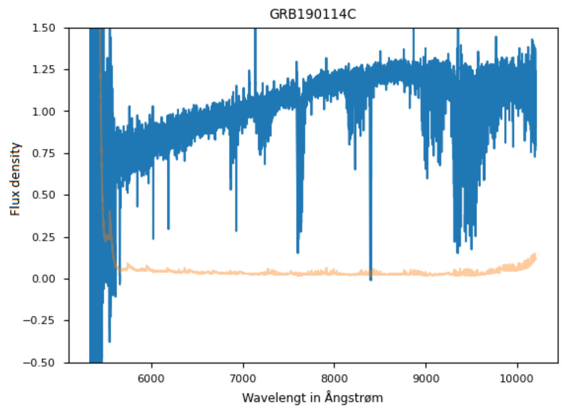

Figure 13: *The afterglow spectrum of GRB190114C in the visual band.*

Since we want to compare the flux density of the lines with the local flux densities for calculation of the EW, we have created a function that allows us to mark off six places, that is equivalent to three regions. A region before the peak, a region after the peak, and a region just around the peak. These are shown as the red and green areas in figure 14. Marking the regions like this will allow us to avoid inadequate data and differentiate peaks in the case there should be two of them side-by-side.

To find the wavelength of a peak the script does several things. First it normalizes the flux density of the local area, so we get a continuum which is located around the value 1. This way we have a flux which is not dependent of the distance to the GRB. Then the weighted average of the data points and their respective errors are found. This gives a wavelength that will be interpreted as the wavelength of the peak. This is later used to find the redshift of the spectrum and identify which elements are present.

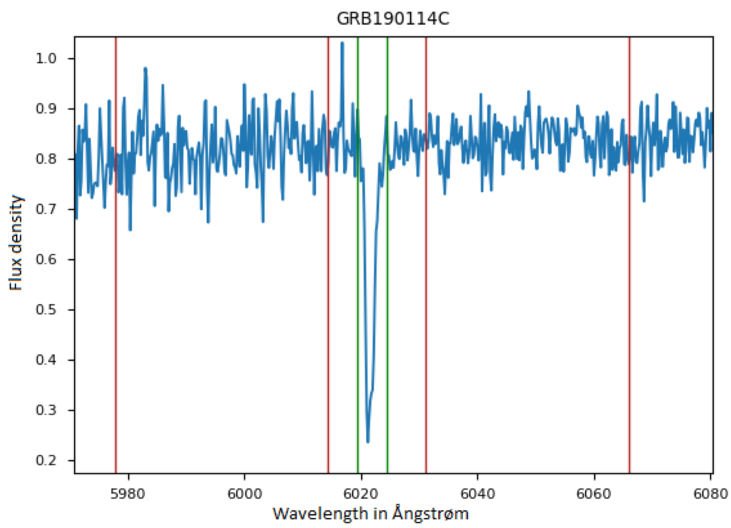

Figure 14: *Zoomed in on a peak in the afterglow spectrum of GRB190114C. The plots shows how the script is used to mark of areas for further data processing. Between the red markers are the areas used for normalization and in between the green markers is the area for which the script will do the EW calculations.*

The script also computes the EW for the individual peaks. Calculating the EW is done by following a numerical approach to eq. 3 (p.9), by summing up the normalized flux and multiplying it with the length between each data point. This is equivalent to taking the integral of the given area. The same principle is applied for the errors, however with the square root of the error squared, as it is the uncertainty of the data we are calculating. After this process, a plot like figure 15 (p.15) is given, which gives us a visual view of the data and the associated results.

We also use the script to create velocity plots of the peaks for later comparison. First, the peculiar redshift z_p is found by using the left side of eq. (7)[19]. z_{area} is a list of redshifts, computed from the region surrounding a peak, with respect to a reference. This means that a peak with a width will have a range of peculiar redshifts, which we will then transform into peculiar velocities by the relation of eq. 5 (p.10). This way we have extracted the cosmological redshift of the reference from the system.

$$z_p = \frac{z_{area} - z_{ref}}{1 + z_{ref}} \longrightarrow v_p = \frac{z_{area} - z_{ref}}{1 + z_{ref}} \cdot c \tag{7}$$

When we have the velocity profiles provided by our script saved in a folder, a separate script lets us choose which profiles we want to compare to each other. This way we can get profiles, as shown on figures 18, 19 and 21 (p.20-22). This makes it easy to see, if there should be any peculiarities or differences between the common and uncommon GRBs, that may reveal information about why we might observe TeV emission in some GRBs and not in others.

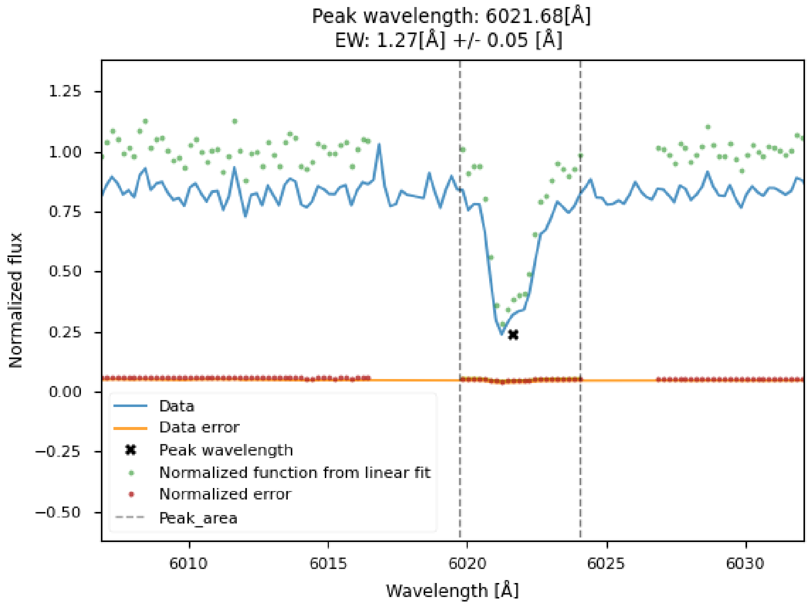

Figure 15: *A processed plot of a peak by our script, with information on the wavelength of the peak, determined by a weighted average. Also includes the normalization and the EW calculations, with corresponding errors, done by the script. Green points show how the data has been normalized.*

2.3.2 *Line Strength Parameter*

To compare the strengths of our spectral lines with other measures of GRB afterglow analysis, we introduce the line strength parameter (LSP). The LSP, introduced by A. de Ugarte Postigo et al. (2018)[20], is a measure for how strong the spectral lines in a spectrum are, compared with those of an average GRB. They have compared the elements from their table 3 in the same article [20] for 69 GRB-afterglow spectra, to get a sample from which they can compare the line strength of an arbitrary spectrum. The method of calculating the LSP is carried out by eq. 8, where we get $\langle logEW \rangle_i$ and $\sigma_{logEW,i}$ from table 3 in the article [20].

$$LSP = \frac{1}{N} \sum_{i=1}^{N} \frac{logEW_i - \langle logEW \rangle_i}{\sigma_{logEW,i}} \tag{8}$$

We only use the data from their table for the spectral lines that are also present in the GRB afterglow spectrum we are calculating the LSP for. A LSP value of zero means that the strength of the spectral lines is as the average for a GRB. If the value is positive, the strength of the lines are stronger than the average and the opposite for the negative values.

2.3.3 Testing the program

This part describes the testing of our script. It includes testing the uncertainty calculations of the EW and the normalization of the data. These tests have proven valid estimation of 1-σ uncertainties.

The spectroscopic data used in this project have been supplied with corresponding data of the error-bar in flux at each data point as derived by the X-shooter pipeline. We want to show that our method of calculating the total uncertainty on the EW follows a normal distribution. This means that about 68% of the data will deviate from the mean within one σ, which is defined as the standard deviation. Furthermore about 95.5% of the data will deviate from the mean within 2σ and about 99.7% within 3σ. The standard deviation, σ, is defined by eq. 9, where x_i represents each flux data point within the extent of the chosen area, μ is the mean of these data points, and so $x_i - \mu$ is the flux deviation.

$$\sigma = \sqrt{\sum_i (x_i - \mu)^2} \tag{9}$$

Our approach of estimating the error of the EW is by calculating the standard deviation from the mean. Following eq. 9, this is done by taking the square root of the sum of the total variance of the flux in the wavelength range over which the EW is calculated. When calculating the error on the EW, the flux deviation $(x - \mu)$ is a numerical value given by the obtained data.

Our method of testing consists of producing an artificial absorption line and adding a randomized, normally distributed noise, with a known size, to the flux. This means the flux will vary as seen on figure 16, representing a model of the deviation, that occurs in the original data (as seen in section 2.1.2). We will test this variance by computing a large number of calculations of the EW. These calculations will differ slightly due to the randomization and therefore we can find the standard deviation of the computed list of values for the EW. We call this standard deviation σ_{test}.

To compare this with our estimation of the error, we add a constant flux deviation of the same value as the range of the random deviation from the model. This deviation is then used to calculate the expected error of the EW, as done with our program. We name the resulting error $\sigma_{program}$ for comparison.

We should expect σ_{test} and $\sigma_{program}$ to be approximately equal if our error estimation program shows a normal distribution.

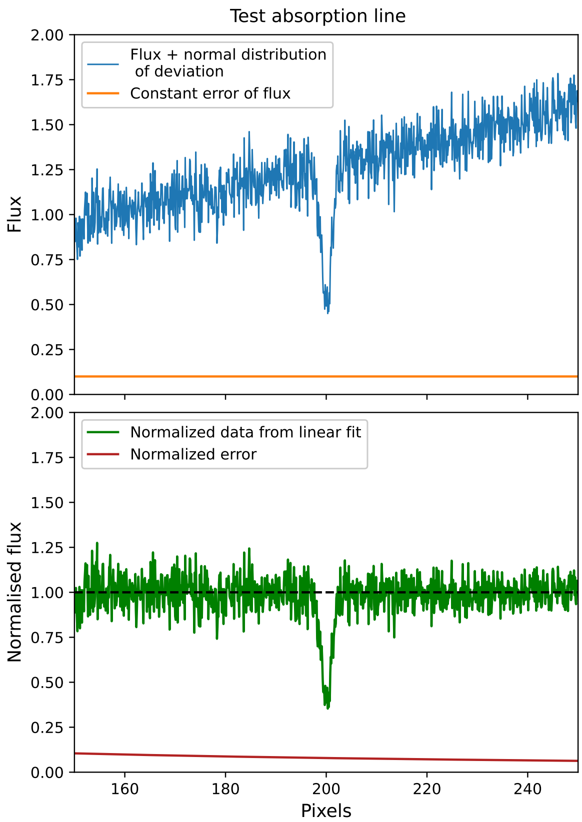

Figure 16: *Top: An increasing linear flux with an artificial absorption line and a constant error. Bottom: The same line normalized to create a continuum around the absorption line for calculation of the EW.*

Additionally, we have added our method of normalization to the test. We create a linear fit from the area around the spectral line and divide the data, including the line, with the fit. The result is a normalization around 1, as seen in figure 16 (bottom). The error is divided by the same linear fit to match with the normalized data.

For the test we add a constant error with a value of 0.1. Our program calculates the standard deviation to be about 0.07, as of eq 10, where η is the normalized error values.

$$\sigma_{program} = \sqrt{\sum_i (\eta_i)^2} = 0.0706 \approx 0.07 \tag{10}$$

Subsequently, we are calculating the EW from our randomized test data 500.000 times and finding the standard deviation of this list of values for the EW, σ_{test}. This is calculated by eq. 11, where X is the list values of the EW and μ is the mean of the list. σ_{test} approximates to 0.07, the same value as $\sigma_{program}$.

$$\sigma_{test} = \sqrt{\sum_i (X_i - \mu)^2} = 0.0721 \approx 0.07 \tag{11}$$

We have produced a histogram of the EW values, to show the distribution of our values of the EW. This shows the normal distribution of the randomized flux, and that the standard deviation of the EW corresponds to the expected 68% of data points.

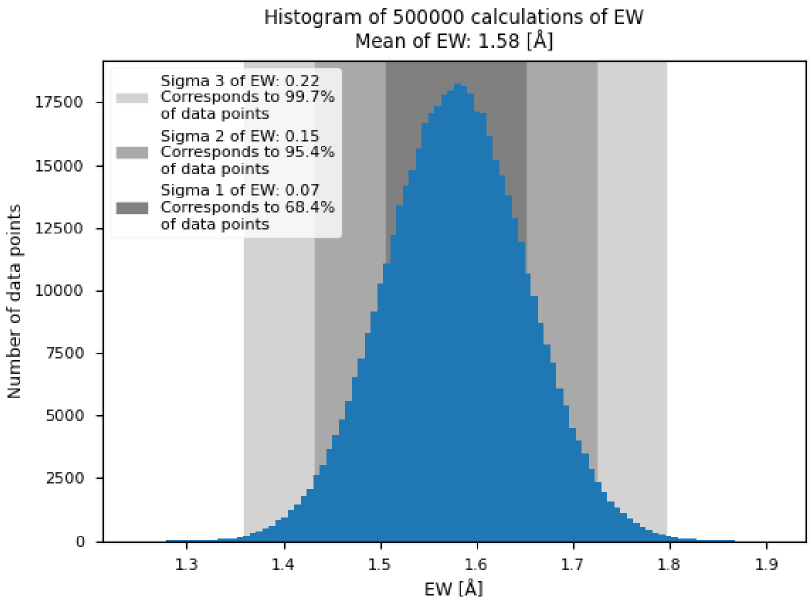

Figure 17: *Histogram of 500.000 EW calculations of a test absorption line with normal distribution standard deviation.*

In conclusion we see that our program calculates the same flux error as the standard deviation of a normal distribution. We can therefore expect our program to calculate errors corresponding to a 1-σ error, where about 68.4% of the time, the deviation in our flux data will be within the given error. Additionally 95.4% of the data will be within 2 σ and 99.7% within 3 σ.

3

RESULTS & DISCUSSION

3.1 Results

With the use of our script, we have identified several lines in the afterglow spectra of GRB19 and GRB21. We were unable to identify enough spectral lines from the afterglow of GRB20 to get any useful information. We identified one line, which is not enough to determine the redshift or create a velocity profile with our current method. Therefore, we have discarded the idea of comparing GRB20 with the other GRBs, and no results are presented on this. However, the existence of GRB20 is worth noting.

Feature	Rest [Å]	Observed [Å]	z	EW [Å]
MgII	2796.325	3984.00	0.4247	7.82 ± 0.26
MgII	2803.531	3994.57	0.4248	7.49 ± 0.26
MgI	2852.964	4064.58	0.4247	5.72 ± 0.22
TiII	3067.245	4371.04	0.4251	0.57 ± 0.09
TiII	3073.877	4380.31	0.4250	0.68 ± 0.09
TiII	3076.123	4383.39	0.4250	0.46 ± 0.07
TiII	3079.552	4388.85	0.4252	0.64 ± 0.08
TiII	3088.934	4402.17	0.4251	0.77 ± 0.09
CaII	3934.777	5606.32	0.4248	5.76 ± 0.16
CaII	3969.591	5655.78	0.4248	5.91 ± 0.10
HI-ϵ	3971.195	5659.45	0.4251	0.59 ± 0.04
HI-δ	4102.892	5847.44	0.4252	0.32 ± 0.04
CaI	4227.918	6021.70	0.4243	1.25 ± 0.05
HI-γ	4341.684	6187.79	0.4252	0.48 ± 0.04
HI-β	4862.683	6930.30	0.4252	0.45 ± 0.02
NaI	5891.583	8394.90	0.4249	6.10 ± 0.03
NaI	5897.558	8404.10	0.4250	4.90 ± 0.02
HI-α	6564.610	9355.63	0.4252	0.51 ± 0.02
OIII	5008.240	7137.98	0.4252	-2.57 ± 0.04

Table 1: *Results from spectral analysis of the afterglow of GRB190114C shows observed and rest wavelengths of absorption lines, along with the corresponding measures of the redshift (z) and the eqivalent width (EW). The bottom [OIII] line is an emission line, hence the negative sign on the EW.*

We have observed a total of 19 lines in the spectrum of GRB19, of which we felt confident were not an effect of noise in the data. Of those peaks, 18 are due to absorption and 1 from emission. These results are presented in table 1, along with our corresponding measures of the EW, redshift and information of the believed rest wavelength found from [21]. From the spectrum we identified five Ti lines and a total of eight lines from Mg, Ca and Na. We also identified five different lines from the Balmer series, which is an unusual sight for GRB afterglows. The resulting EW values show very strong lines for Mg, Ca and Na, and much lower values for the lines from Ti and the Balmer series. There seems to be a dispersion in the redshifts, with lower redshift for MgI/II and CaII, compared to the other elements, and an interestingly low redshift for CaI.

Feature	Rest [Å]	Observed [Å]	z	EW [Å]
MgI	2026.477	3800.68	0.8755	1.02 ± 0.20
FeII	2342.668	4393.65	0.8755	2.93 ± 0.11
FeII	2344.214	4396.89	0.8756	2.00 ± 0.10
FeII	2348.834	4405.20	0.8755	2.62 ± 0.13
FeII	2374.461	4453.87	0.8757	1.16 ± 0.09
FeII	2382.765	4469.46	0.8757	1.85 ± 0.11
FeII	2482.868	4656.98	0.8756	1.32 ± 0.09
FeII	2489.075	4668.79	0.8757	1.05 ± 0.08
FeII	2586.605	4851.84	0.8757	1.75 ± 0.11
FeII	2600.173	4876.91	0.8756	2.43 ± 0.11
MnII	2606.462	4889.09	0.8758	0.60 ± 0.08
MgII	2796.352	5245.04	0.8757	2.78 ± 0.10
MgII	2803.531	5258.56	0.8757	2.69 ± 0.10
MgI	2852.964	5351.33	0.8757	1.40 ± 0.08
CaII	3934.777	7380.65	0.8757	2.17 ± 0.10
CaII	3969.591	7445.91	0.8757	1.99 ± 0.09
MgII	2796.352	4786.68	0.7118	1.72 ± 0.15
MgII	2803.531	4798.79	0.7117	1.41 ± 0.13
OIII	5008.24	9395.012	0.8759	-8.40 ± 0.45
HI-α	6564.61	12314.44	0.8759	-2.90 ± 0.74

Table 2: *Results from spectral analysis of the afterglow of GRB210204A. The bottom two lines are emission lines, hence the negative sign on the EW.*

In the spectrum of GRB21 we found 20 lines, presented in table 2. Most of them are due to Fe absorption lines, but like in GRB19, there are also lines from Mg and Ca, however none from Na, Ti nor the Balmer series. Of the twenty lines, two are emission lines from [OIII] and H_α. The differences in EW are not as great as we see from GRB19, except for the [OIII] emission line, which is quite strong. There is also no noticeably dispersion of the redshift between the elements, except for two MgII lines, observed at a lower redshift. This indicates, that a system other than the host galaxy of GRB21 is in the line of sight, however closer to us.

GRB	LSP
190114C	1.64 ± 0.04
210204A	0.20 ± 0.06

Table 3: *LSP values for GRB190114C and GRB210204A*

For the spectral lines of each burst, we have also calculated the LSP, presented in table 3. The results shows that the strength of the lines of GRB21 lies just a bit above the average LSP of previous GRB afterglows. The LSP for GRB19 is a lot higher, indicating that GRB19 is stronger than any of the systems in de Ugarte Postigo et al. (2018).

3.2 Discussion

From our measures of redshift, we can show interesting behaviour of some of the elements identified from the afterglow of GRB19. For the sake of comparison, we will first introduce the velocity profiles of GRB21. The velocity profiles of selected elements from the GRB21 are all distributed close to zero, with the H_α line as reference (fig. 18). They are all slightly shifted towards the left, however with roughly the same amount. This must be because the elements, that emits light in the line of sight, are all moving with the same peculiar velocities. This seems normal and there does not seem to be anything peculiar about that, in our understanding. This GRB belongs in the group of typical GRBs.

The peculiar velocities of the elements in GRB21 spans about 200km/s. For comparison, our Sun moves around the Milky Way with about 200km/s. It therefore seems reasonable for GRB21 to be within a massive galaxy like the Milky Way. Also, acknowledging the fact that the rotation velocity we observe is a minimum, because of the inclination of the galaxy from our line of sight, the actual rotation could be much faster.

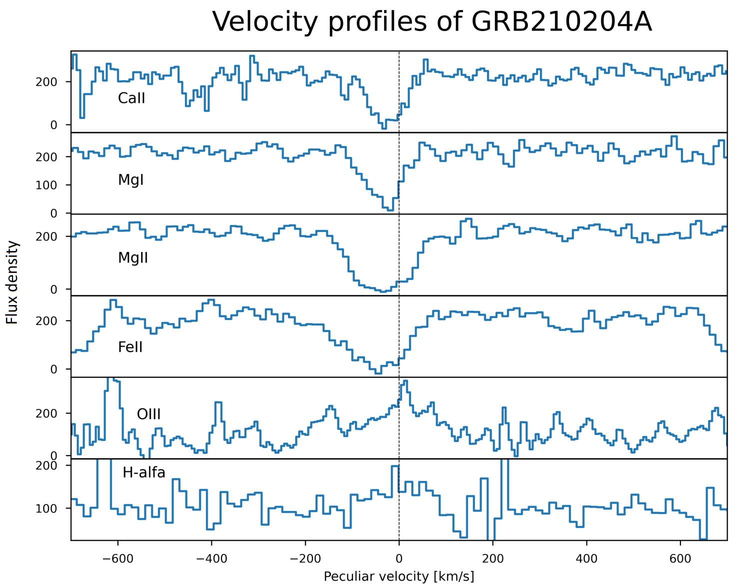

Figure 18: *Velocity plot of some the elements found in GRB210204A afterglow spectrum, all with the H_α used as reference.*

The velocity profiles of GRB19 indicates that something special is going on (fig. 19). With [OIII] as reference, the profiles are all shifted towards the left, however not with the same amount. CaI is shifted more than the other elements. With [OIII] as reference, CaI is also the only element in the velocity profiles of GRB19, that has a well-defined peak. The peaks of MgI and CaII are spread out over a larger range of peculiar velocities, whereas the range for TiII has a resemblance to the profiles of GRB21. This observation may indicate that different parts of the host galaxy of the GRB19 are moving with different velocities. We believe this is only expected if the galaxy somehow has been disrupted, as we would expect the matter in a galaxy to be close to evenly distributed, since galaxies are slowly formed from big rotating clouds. This may indicate that the galaxy has merged with another galaxy or maybe is in the process of merging.

Since we see the stuff that absorbs light within the line of sight, this could also be a situation where a cloud, that is closer to us, is moving through the line of sight. However, as we do not see the CaI absorption lines appear several times across the spectrum, as we did with MgII for GRB21 (table 2), it tells us that the cloud, if there, should be very close to the galaxy. Otherwise the lines of the cloud would have been less redshifted compared to the host galaxy, and the lines would therefore appear both for the galaxy and for the cloud, at different wavelengths. This is not the case. Also, it is unlikely to see CaI outside galaxies, since it is easily destroyed by UV-radiation. And in the intergalactic space outside the galaxies, an UV background, radiated by active galactic nuclei, exists [22].

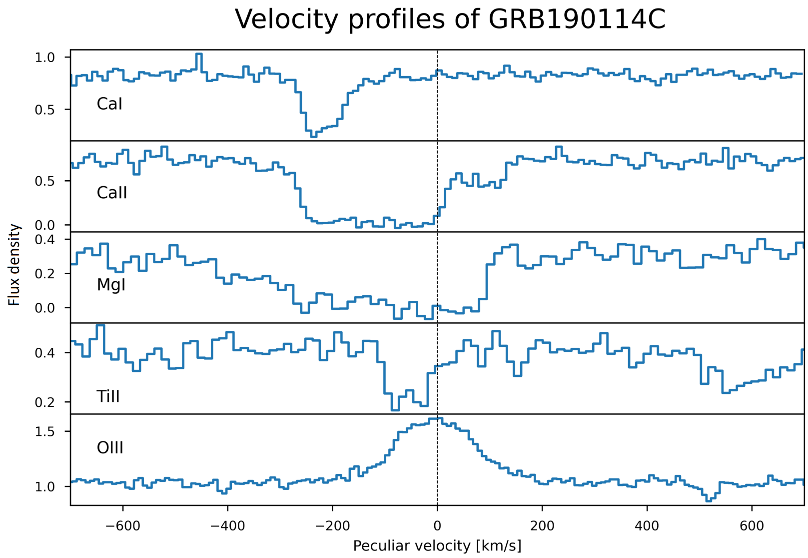

Figure 19: *Velocity plot of some the elements in found in the GRB190114C afterglow spectrum, all with the* $[OIII]$ *used as reference.*

We also notice the presence of Balmer lines from hydrogen (fig. 21), which is not found in GRB21. These lines are nicely distributed around zero, with a small shift to the left, which may as well be because of the choice of reference. This indicates that the light we observe has been passing through an area with plenty of hydrogen. It should be noted that the Epsilon-line is located just to the right of the CaII line, and is consequently difficult to see, but nonetheless not odd compared to the other Balmer lines. Where the hydrogen is located within the host galaxy is difficult to say, but as the redshift of the lines are the same as for the lines we expect to be inside the host galaxy (MgI/II, CaII and NaI), we believe the host galaxy likely is rich on hydrogen. This suggests, that there are star forming regions withing the galaxy.

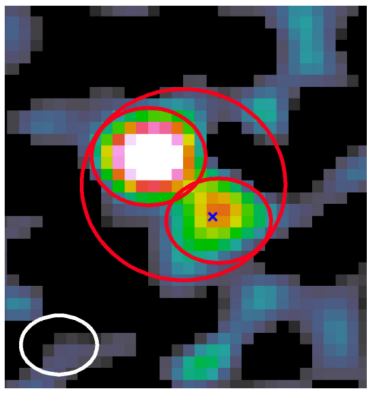

Figure 20: *Image of the CO(3-2) emission obtained by ALMA. The spatial resolution (indicated by the white ellipse at the lower left) is just enough to resolve the two interacting galaxies. Source: A. de Ugarte Postigo et al. (2019) [23]*

This is in compliance with the thoughts made by A. de Ugarte Postigo et. al [23]. They are in the believe, that the host of GRB19 are two galaxies merging (fig. 20). They also believe the galaxy has active star formation. That we are observing the Balmer-lines is very uncommon. The only other GRB observation we are aware of, that also had the Balmer absorption lines present in the afterglow spectrum, is the GRB140506A (GRB14). Whether GRB14 had TeV emission is not possible to say, as the prompt emission observations were not executed for higher energy ranges. Nonetheless, there are plenty of observations of GRBs, but the only two with observed Balmer-lines are the GRB19 and GRB14, where we know for sure that GRB19 had TeV emission. This leads to the speculation on whether there is a relation between observing the Balmer-lines in the afterglow spectrum and observing GRBs with TeV emission. One thing we can derive is, that the presence of the Balmer-lines indicate, that there must be an area of recombination, and something that keeps the hydrogen in an exited state.

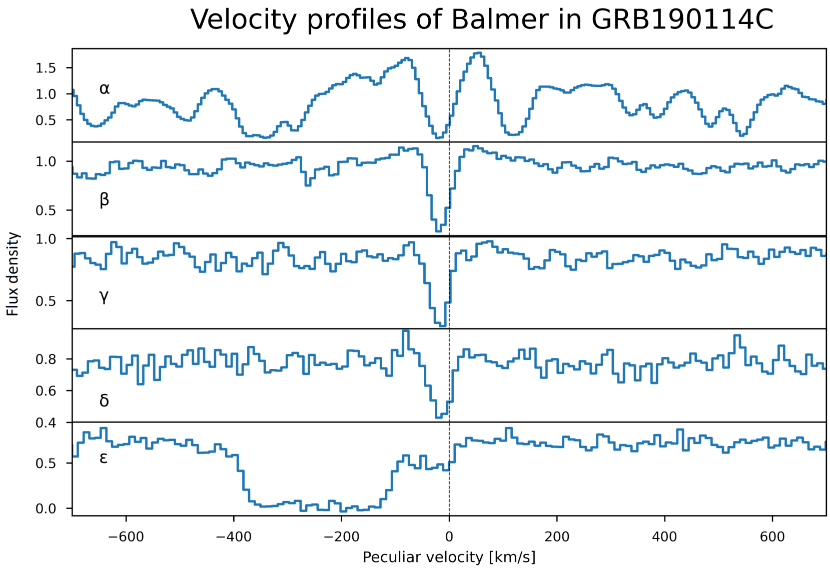

Figure 21: *Velocity plot of the Balmer series found in GRB190114C afterglow spectrum, all with the* [OIII] *used as reference. The* ϵ *line (bottom) is the small absorption just to the left of zero. The bigger area of absorption to the left of the profile is from CaII. The multiple lines seen on the profile of H-*α *(top) is due to telluric lines from the atmosphere of the Earth.*

What the relation between the Balmer-lines and the TeV emission could be, is not known. We will likely get many more observations of GRBs with TeV emissions in the future, when the Cherenkov Telescope Array (CTA) is finished. If we see a pattern of the occurrence of TeV GRBs, along with the Balmer-lines, this could be very interesting. However, it could also likely be a pure coincidence that we observe this weird afterglow spectrum in this particular TeV GRB. Unfortunately, we could not say much about the very recent GRB201216C (GRB20), which also had TeV emission, since its afterglow spectrum was not strong enough and with too few lines. It might have revealed some interesting information, if the afterglow spectrum had also shown differences to that of GRB21. As we get more observations from CTA and others, we expect more useful information to provide understanding of the events that cause the powerful TeV emission.

An additional interesting comparison to make of future TeV GRBs would be the LSP calculations. It would be interesting to see if there is a correlation between stronger spectral lines and TeV emission, as this is unknown due to the lack of TeV-GRB detections.

4

CONCLUSION

The mysterious events of Gamma-Ray Bursts with extremely energetic prompt emission, compared to the more common GRB prompt emission energies, has led to the question of what may be the cause of this type of event. As of now, no theoretical model fits with the TeV gamma-ray emission and afterglow of the burst observed January 14th 2019. To compare this event with a burst of more common energy output, spectral analysis of the afterglow of TeV emitting GRB190114C and MeV emitting GRB210204A has been made. This resulted in the identification and comparison of several absorption lines and a total of three emission lines. Additional analysis of the second TeV burst, GRB201216C, showed only one apparent spectral line, which was not enough to make comparisons with the other bursts. The creation of velocity profiles, from the estimated redshifts, shows signs of disruption of the host galaxy of GRB19, indicating that there might be a galaxy merge occurring. Our data processing and analysing of the spectra leads to the idea, that something peculiar seems to be happening in the events of TeV GRBs. With this said, it is difficult yet to be sure of anything, or theorize what might be happening, due to the fact that only two TeV bursts have been detected. We expect the detection of more TeV bursts in the future, which would provide more information on what may be the reason behind those events. It could be speculated, that there is a relation between the absorption of Balmer lines and TeV emission. Otherwise, there seems to be a strange coincidence, that those lines would be present in GRB19, which has TeV emission, and GRB140506A for which we have no constraints on TeV emission. The Balmer lines indicate regions with active star formation, and it could be interesting to explore the possibility that this could be one of the contributing factors to the TeV event. Therefore, it may be very interesting to see, if the pattern will continue as we get more observations. A relation between the TeV GRBs and the Balmer-lines would, at current understanding, be peculiar. It might reveal new perspectives and improvements of current models of GRBs.

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Appendices

SCRIPTS

First script is used for finding Peaks, EW and corresponding errors. [7 pages]

Second script tests our EW uncertainties and the normalisation method. [3 pages]

Third script creates the velocity profiles. [4 pages]

Fourth script combines the velocity profiles into one plot. [1 page]

Fifth script combines the velocity profiles into one plot. [1 page]

```python
"""This script is used for finding Peaks, EW, and corrosponding errors.
"""

from astropy.io import fits
import numpy as np
import matplotlib.pyplot as plt
from scipy.optimize import curve_fit
import pandas as pd
import keyboard
import xlsxwriter
import pathlib
from scipy.stats import binned_statistic


plt.close('all')                #Closing all open plots.

                                #Choosing files we want to open
gamma_name = "Fullreduction"        #weak,  Fullreduction  or  stargate
spectra_range = "VIS"               #UVB, VIS og NIR

                                #Choosing plotrange
xplot_range = [0, 45],False       #True gives plotrange and False or empty dont.
yplot_range = [-500, 500],False


                                #Making some list for later use.
Val = ([])
na1 = ([])
na2 = ([])
nb1 = ([])
nb2 = ([])
x1 = ([])
x2 = ([])


"""
Underneath the next four sections, the script load data dependent on what
has been choosen above as the input. It then plots the loaded spectra.
"""

if gamma_name == "weak":
                                #Loading file names
    VIS = 'ToO_GRBtrigger_4x600_JHslit_SCI_SLIT_MERGE1D_VIS.fits'
    UVB = 'ToO_GRBtrigger_4x600_JHslit_SCI_SLIT_MERGE1D_UVB.fits'
    NIR = 'ToO_GRBtrigger_4x600_JHslit_SCI_SLIT_MERGE1D_NIR.fits'

    if spectra_range == "UVB":
        file_name = UVB
    if spectra_range == "VIS":
        file_name = VIS
    if spectra_range == "NIR":
        file_name = NIR

    sn_file = fits.open(file_name)

    hdr = sn_file[0].header
    hdrr = sn_file[1].header
    flux = sn_file[0].data
    err_flux = sn_file[1].data
    wave = 10*(np.arange(len(flux))*hdr['CDELT1']+hdr['CRVAL1'])
    lstep=wave[1]-wave[0]
```

```python
if gamma_name == "Fullreduction":
                                #Loading file names
    VIS = 'VISOB1.fits'
    UVB = 'UVBOB1.fits'

    if spectra_range == "UVB":
        file = UVB
    if spectra_range == "VIS":
        file = VIS

    hdul = fits.open(file)
    data = hdul[1].data
    hdr = hdul[1].header
    wave = 10.*data['WAVE'][0]
    flux = data['FLUX'][0]*1.e16
    err_flux = data['ERR'][0]*1.e16
    lstep = wave[1]-wave[0]

                                #Plotting the data loaded
if gamma_name == "weak" or gamma_name == "Fullreduction":
    df_frame = {'wave':wave[:], 'flux':flux[:], 'err_flux':err_flux[:]}
    df = pd.DataFrame(df_frame,dtype='float64')

    smooth_grade = 8
    fig = plt.figure()
    plt.title("""Afterglow spectrum of GRB190114C""")
    ax = fig.add_subplot()
    ax.plot(wave, flux ,picker=1)
    ax.plot(wave,err_flux,'-',alpha=0.4)
    plt.xlabel('Wavelength [Å]')
    plt.ylabel('Flux [$erg\cdot cm^{-2} s^{-1} Å^{-1}$]')

                                #If we wanted to smooth the spectra.
    #plt.title(f'Smooth: {smooth_grade}')
    #ax.plot(wave, smooth(flux,smooth_grade),picker=1, label='smooth')

    if xplot_range[1] == True:
        plt.xlim(xplot_range[0][0], xplot_range[0][1])
    if yplot_range[1] == True:
        plt.ylim(yplot_range[0][0], yplot_range[0][1])
    elif gamma_name == "Fullreduction":
        plt.ylim(-0.5, 1.5)


"""
Underneath, the same as above is done, however the files had to be opened in
a different way than the others and it is therefor in a section for it self.
Still taking in the inputs from beginning of script.
"""
if gamma_name == "stargate":

    UVB = 'ToO_GRBtrigger_4x600_JHslit_SCI_SLIT_FLUX_MERGE1D_UVB.dat'
    VIS = 'ToO_GRBtrigger_4x600_JHslit_SCI_SLIT_FLUX_MERGE1D_VIS.dat'
    NIR = 'ToO_GRBtrigger_4x600_JHslit_SCI_SLIT_FLUX_MERGE1D_NIR.dat'

    if spectra_range == "UVB":
        file = UVB
    if spectra_range == "VIS":
        file = VIS
```

```
if spectra_range == "NIR":
    file = NIR

data = np.genfromtxt(file,delimiter='', dtype=None)

wave = data[:,0]#/(1+5.57)
flux = data[:,1]*1.e16
err_flux = data[:,2]*1.e16

lstep=wave[1]-wave[0]

df_frame = {'wave':wave[:], 'flux':flux[:], 'err_flux':err_flux[:]}
df = pd.DataFrame(df_frame,dtype='float64')

                            # Alternative way of smoothing, trough binning.
bins = 6000        #variable
statistic = 'mean'  #mean or median
x_data = df['wave']
y_data = df['flux']
y_bins,bin_edges, misc = binned_statistic(x_data,y_data, statistic=statistic,
                                          bins=bins)
x_bins = (bin_edges[:-1]+bin_edges[1:])/2

plt.figure(1)
plt.plot(x_bins, y_bins,  color= 'red')
plt.ylim(-5,3)
if xplot_range[1] == True:
    plt.xlim(xplot_range[0][0], xplot_range[0][1])
if yplot_range[1] == True:
    plt.ylim(yplot_range[0][0], yplot_range[0][1])
else:
    plt.ylim(-5, 3)

plt.title(f'GRB201216C \n Binning: statistic={statistic}, bins={bins}')
plt.show()

smooth_grade = 3

fig = plt.figure(2)
plt.title("""1. Zoom to desired absorptionline
2. Hold shift and click mouse to mark normalization regions (4 clicks left to right)
3. Hold shift and click mouse to mark absorption region (2 clicks)""")
ax = fig.add_subplot()
ax.plot(wave, flux, '-', picker=1, alpha=0.8, label='dataline')
ax.plot(wave, flux, '.', alpha=0.8, label='datapoints')
ax.plot(wave,err_flux,'-',alpha=0.4, label='error')

#ax.plot(wave, smooth(flux,smooth_grade),picker=1, label='smooth')
#plt.title(f'Smooth: {smooth_grade}')


if xplot_range[1] == True:
    plt.xlim(xplot_range[0][0], xplot_range[0][1])
if yplot_range[1] == True:
    plt.ylim(yplot_range[0][0], yplot_range[0][1])
else:
    plt.ylim(-5, 3)

plt.legend()
plt.savefig('Test1.eps', format='eps')
```

```python
"""
Defining a function we can use, so that we can click the plot we get.
And so we can mark regions, and do calculations by holding certain keys pressed.
"""
def Mouse(event):

                                #Making sure no lines already has been found.
    if gamma_name == "weak":
        filnavn = 'PeakList_GRB210204A_TEST'
    if gamma_name == "Fullreduction":
        filnavn = 'PeakList_GRB190114C_NY'
    if gamma_name == "stargate":
        filnavn = 'PeakList_GRB201216C_TEST'

    knownpeaks = ([])
    knownEW = ([])
    knownEW_err = ([])
    if pathlib.Path(f"{filnavn}.xlsx").exists ():   #checking if file already exist.
        loadexcel = pd.ExcelFile(f"{filnavn}.xlsx").parse("Sheet1")
        for i in range(len(loadexcel)):
            if loadexcel['Peak Wavelength'][i] > 0:
                knownpeaks.append(loadexcel['Peak Wavelength'][i])
                knownEW.append(loadexcel['EW'][i])
                knownEW_err.append(loadexcel['EW_err'][i])



    slitregions = list(range(100))      #We can make 100 markings in a plot.
    nregions = 0
    count = 0
    peaklist = ([])
                                    #Creating a new file to append peaks
    docu = xlsxwriter.Workbook(f"{filnavn}.xlsx")
    sheet = docu.add_worksheet()
                                    #Appending old peaks to new sheet
    if pathlib.Path(f"{filnavn}.xlsx").exists ():
        for i in range(len(knownpeaks)):
            sheet.write(i+1, 0, knownpeaks[i])
            sheet.write(i+1, 1, knownEW[i])
            sheet.write(i+1, 2, knownEW_err[i])

    Names = (["Peak Wavelength", "EW", "EW_err"])
    for n in range(len(Names)):
        sheet.write(0, n, Names[n]) #y should be given before x in xlwriter

    while True:
                    #Making so we only mark regions if a key is pressed.
                    # - This way we can still zoom without missclick.
        if keyboard.is_pressed("shift") or keyboard.is_pressed("command"):

            click = event.artist
            xdata = click.get_xdata()

            ind = event.ind
            xmean = np.mean(xdata[ind])
            Val.append(round(xmean,2))

            slitregions[count+2] = xmean
            plt.axvline(slitregions[count+2], ymin=-1., ymax=2., color='b', lw=0.5)
```

```
                                            #Drawing our markings
        plt.draw()
        nregions += 1
        if len(Val) % 6 == 1:
            na1.append(xmean)
            plt.axvline(slitregions[count+2], ymin=-1., ymax=2.,
                        color='firebrick', lw=1)
        if len(Val) % 6 == 2:
            na2.append(xmean)
            plt.axvline(slitregions[count+2], ymin=-1., ymax=2.,
                        color='firebrick', lw=1)
        if len(Val) % 6 == 3:
            nb1.append(xmean)
            plt.axvline(slitregions[count+2], ymin=-1., ymax=2.,
                        color='firebrick', lw=1)
        if len(Val) % 6 == 4:
            nb2.append(xmean)
            plt.axvline(slitregions[count+2], ymin=-1., ymax=2.,
                        color='firebrick', lw=1)
        if len(Val) % 6 == 5:
            x1.append(xmean)
            plt.axvline(slitregions[count+2], ymin=-1., ymax=2.,
                        color='g', lw=1)
        if len(Val) % 6 == 0:
            x2.append(xmean)
            plt.axvline(slitregions[count+2], ymin=-1., ymax=2.,
                        color='g', lw=1)



    emptylinefix = 0

#If pressed e and clicing on the plot, all the data get processed by the following.
    if keyboard.is_pressed("e"):


        for i in range(len(na1)):
            Na1 = na1[i]
            Na2 = na2[i]
            Nb1 = nb1[i]
            Nb2 = nb2[i]
            X1 = x1[i]
            X2 = x2[i]


            #Normalise
            def func(x, a, b):
                return a * x + b
            norm_region = (df[(df.wave >= Na1) & (df.wave <= Na2)|
                              (df.wave >= X1) & (df.wave <= X2)|
                              (df.wave >= Nb1) & (df.wave <= Nb2)])
            df_fit = df[(df.wave >= Na1) & (df.wave <= Na2) |
                        (df.wave >= Nb1) & (df.wave <= Nb2)]
            Parameter_guesses = [0.,1.]
            val, cov = curve_fit(func, df_fit.wave, df_fit.flux,
                                 p0=Parameter_guesses)
            a = val[0]
            b = val[1]
            norm = norm_region.flux/(a*norm_region.wave+b)
            norm_err = norm_region.err_flux/(a*norm_region.wave+b)
```

```python
#Now calculate the Equivalength width
df_region = df[(df.wave >= X1) & (df.wave <= X2)]
profile = 1.-(df_region.flux/(a*df_region.wave+b))
profile_err = (df_region.err_flux/(a*df_region.wave+b))
EW = lstep*np.sum(profile)
EWerr = lstep*np.sqrt(np.sum(profile_err**2))

#printing values
print('EW: ',f'{EW}','AA +/- ',f'{EWerr}','AA')

wave_peak = (np.sum(df_region.wave*profile/df_region.err_flux**2)
             /np.sum(profile/df_region.err_flux**2))

#plot figure
plt.figure()
plt.title(f"""Peak wavelength: {wave_peak:.2f}[Å]
          \nEW: {EW:.2f}[Å] +/- {EWerr:.2f} [Å] """)
plt.plot(df.wave, df.flux, '', alpha=0.8,label='Data')
plt.plot(norm_region.wave, norm_region.err_flux,'', alpha=0.8,
         color='darkorange',label='Data error')
plt.plot(df_region.wave, profile_err, color='y')
plt.plot(wave_peak,min(df_region.flux.values),'.',color = 'k',
         marker='X',label='Peak wavelength')
plt.plot(norm_region.wave,norm, '.',color='g', alpha = 0.5,
         label='Normalized function from linear fit')

plt.plot(norm_region.wave,norm_err,'.',alpha=0.8,
         color='firebrick',label='Normalized error')



plt.axvline(X1, ymin=-1., ymax=2. ,linestyle='--' ,color='k',
            lw=1,alpha=0.5, label='Peak area')
plt.axvline(X2, ymin=-1., ymax=2. ,linestyle='--' ,color='k',
            lw=1,alpha=0.5)
plt.legend()
plt.xlim(min([X1,Na1,Nb1]),max([X2,Na2,Nb2]))
plt.ylim(min(df_region.flux)-2,max(norm_region.flux)+2)
plt.xlabel('Wavelength [Å]')
plt.ylabel('Normalized flux')
plt.savefig(f'ImagesGRB210204A/{wave_peak:.2f}.png')
print(f'Peak wavelength: {wave_peak:.2f}')

plt.show()


peaklist.append((wave_peak))


#Writing the data into the sheet.
if np.mean(wave_peak) not in knownpeaks:
    if len(peaklist) > 0:
        sheet.write(i+1+len(knownpeaks)+emptylinefix, 0,
                    np.mean(wave_peak))
        sheet.write(i+1+len(knownpeaks)+emptylinefix, 1,
                    np.mean(EW))
        sheet.write(i+1+len(knownpeaks)+emptylinefix, 2,
                    np.mean(EWerr))
else:
```

```
                    emptylinefix -= 1


        docu.close()


        return
    # Smooth spectra

#Defining a function that smoothens our script
def smooth(y, box_pts):
    box = np.ones(box_pts)/box_pts
    y_smooth = np.convolve(y, box, mode='same')
    return y_smooth


#Connecting our click function with our plot.
fig.canvas.mpl_connect('pick_event', Mouse)

plt.show()
```

```
"""This script tests our EW uncertainties and the normalisation method.
"""

import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from scipy.optimize import curve_fit
from numpy.random import normal
from tqdm import tqdm

plt.close('all')

"Here we define variables for artificial flux spectrum with an absorption line"
lam = np.arange(100,300,0.1)
err_flux = lam-lam+0.1
lstep = lam[1]-lam[0]
lam0 = 200.
sig0 = 1.
laml = lam0 - 4.*sig0
lamr = lam0 + 4.*sig0
flux_= (1.9-3./(sig0*np.sqrt(2.*np.pi))*np.exp(-0.5*(lam-lam0)**2
                                              /(sig0**2)))*lam/300



N = 100000 #Nr. of repeats
EWtable = []
EWerrtable = []


"""For each calculation, we add a random normal distributed error to the flux.
We fit a linear function to the data to normalize it. Then we calculate the
EW and the error, and append it to seperate lists. These are used to determine
the standard deviation of the EW results."""
for n in tqdm(range(0,N)):
    flux = flux_ + normal(loc=0, scale=0.1, size=len(lam))
    df_frame = {'wave':lam, 'flux':flux, 'err_flux':err_flux}
    df = pd.DataFrame(df_frame,dtype='float64')

    def func(x, a, b):
        return a * x + b

    df_fit = df[(df.wave >= 150) & (df.wave <= 190) |
                (df.wave >= 210) & (df.wave <= 250)]
    Parameter_guesses = [0.,1.]
    val, cov = curve_fit(func, df_fit.wave, df_fit.flux, p0=Parameter_guesses)
    a = val[0]
    b = val[1]


    norm_region = (df[(df.wave >= 150) & (df.wave <= 190)|
                      (df.wave >= 190) & (df.wave <= 210)|
                      (df.wave >= 210) & (df.wave <= 250)])
    norm = norm_region.flux/(a*norm_region.wave+b)
    norm_err = norm_region.err_flux/(a*norm_region.wave+b)



#Now we calculate the Equivalent width
    df_moment = df[(lam > laml) & (lam < lamr)]
    profile = 1.-(df_moment.flux/(a*df_moment.wave+b))
```

```python
    profile_err = (df_moment.err_flux/(a*df_moment.wave+b))
    EW = lstep*np.sum(profile)
    EWerr = lstep*np.sqrt(np.sum(profile_err**2))
    EWtable.append(EW)
    EWerrtable.append(EWerr)

sigma = np.std(EWtable)
meanEW = np.mean(EWtable)


"""Here we sort the EW values that belong within 1-,2- and 3-Sigma, and create
a histogram of the EW values, with these groupings marked."""
EWsigma2 = []
EWsigma1 = []
EWsigma3 = []
for i in tqdm(range(len(EWtable))):
    if EWtable[i] >= meanEW-sigma and EWtable[i] <= meanEW+sigma:
        EWsigma1.append(EWtable[i])
    if EWtable[i] >= meanEW-(2*sigma) and EWtable[i] <= meanEW+(2*sigma):
        EWsigma2.append(EWtable[i])
    if EWtable[i] >= meanEW-(3*sigma) and EWtable[i] <= meanEW+(3*sigma):
        EWsigma3.append(EWtable[i])

perc1 = (len(EWsigma1)/len(EWtable))*100
perc2 = (len(EWsigma2)/len(EWtable))*100
perc3 = (len(EWsigma3)/len(EWtable))*100


fig, ax = plt.subplots()
plt.title(f"""Histogram of {N} calculations of EW\nMean of EW:
          {np.mean(EWtable):.2f} [Å]""")
plt.axvspan(meanEW-(3*sigma), meanEW+(3*sigma), color='lightgrey', alpha=1,
            label=f"""Sigma 3 of EW: {3*sigma:.2f}\nCorresponds to
            {perc3:.1f}%\nof data points""")
plt.axvspan(meanEW-(2*sigma), meanEW+(2*sigma), color='darkgrey', alpha=1,
            label=f"""Sigma 2 of EW: {2*sigma:.2f}\nCorresponds to
            {perc2:.1f}%\nof data points""")
plt.axvspan(meanEW-sigma, meanEW+sigma, color='grey', alpha=1,
            label=f"""Sigma 1 of EW: {sigma:.2f}\nCorresponds to
            {perc1:.1f}%\nof data points""")

n, bins, patches = ax.hist(EWtable, bins=100, linewidth=0.2)
plt.xlabel('EW [Å]')
plt.ylabel('Number of datapoints')
#plt.xlim(2.5,3.5)
plt.legend(loc=2)
plt.show()



"Here we create the double plot to show the normalization."
fig, (ax1, ax2) = plt.subplots(nrows=2, sharex=True,sharey=True, figsize=(6,9)
                               ,gridspec_kw = {'hspace':0.05})
fig.subplots_adjust(top=0.95)
fig.suptitle('Test absorption line')
fig.add_subplot(111, frameon=False)
plt.tick_params(labelcolor='none', top=False, bottom=False, left=False,
                right=False)
plt.xlabel('Wavelength $\lambda$', fontsize=12)
plt.ylabel('Normalised flux', fontsize=12)
ax1.plot(lam, flux, label='Flux + normal distribution\n of deviation', lw=1)
```

```python
ax1.plot(lam, err_flux, label='Constant error of flux')
#plt.yticks([-0.2,0,0.1,0.2,0.4,0.6,0.8,1,1.2,1.4])
ax1.legend(loc=2, fontsize=10)
ax1.set_xlim([150, 250])
#plt.axvspan(lam0-meanEW/2,lam0+meanEW/2,color='lightgrey')

#ax2.plot(df.wave, df.flux, '', alpha=0.8,label='Data')
#ax2.plot(lam,err_flux,'-',alpha=0.4, label='Data error')
ax2.plot(norm_region.wave,norm, '',color='g',
         label='Normalized data from linear fit')
ax2.plot(norm_region.wave,norm_err,'',color='firebrick',
         label='Normalized error')
ax2.legend(loc=2, fontsize=10)
ax2.set_xlim([150, 250])
ax2.set_ylim([0, 2])
ax2.axhline(y=1,xmin=0,xmax=1, ls='--',color='k')
plt.savefig('testplot.png',bbox_inches='tight', dpi=600)
plt.show()

print('mean EW: ',f'{np.mean(EWtable):.2f}','AA , Scatter:',
      f'{np.std(EWtable):.2f}','AA')
print('EW: ',f'{EW:.2f}','AA +/- ',f'{EWerr:.2f}','AA')
```

```python
""" These scripts is used for finding the velocity plots.
"""

from astropy.io import fits
import numpy as np
import matplotlib.pyplot as plt

import pandas as pd
import keyboard
import xlsxwriter
import pathlib
from scipy.constants import c


plt.close('all')


def Mouse(event):

                    #This is almost the same as for the peakfinding
    filnavn = 'PeakList_GRB210204A_test'

    knownpeaks = ([])
    knownEW = ([])
    knownEW_err = ([])
    if pathlib.Path(f"{filnavn}.xlsx").exists ():   #Tjekker om filen eksistere.
        loadexcel = pd.ExcelFile(f"{filnavn}.xlsx").parse("Sheet1")
        for i in range(len(loadexcel)):
            if loadexcel['Peak Wavelength'][i] > 0:
                knownpeaks.append(loadexcel['Peak Wavelength'][i])
                knownEW.append(loadexcel['EW'][i])
                knownEW_err.append(loadexcel['EW_err'][i])

    slitregions = list(range(100))
    nregions = 0
    count = 0

    docu = xlsxwriter.Workbook(f"{filnavn}.xlsx")
    sheet = docu.add_worksheet()

    if pathlib.Path(f"{filnavn}.xlsx").exists ():
        for i in range(len(knownpeaks)):
            sheet.write(i+1, 0, knownpeaks[i])
            sheet.write(i+1, 1, knownEW[i])
            sheet.write(i+1, 2, knownEW_err[i])

    Names = (["Peak Wavelength", "EW", "EW_err"])
    for n in range(len(Names)):
        sheet.write(0, n, Names[n]) #y skal gives før x i xlsxwriter

                    #This is almost also the same.

    while True:
        if keyboard.is_pressed("shift") or keyboard.is_pressed("command"):

            click = event.artist
            xdata = click.get_xdata()

            ind = event.ind
            xmean = np.mean(xdata[ind])
```

```
            Val.append(round(xmean,2))
            slitregions[count+2] = xmean
            plt.axvline(slitregions[count+2], ymin=-1., ymax=2., color='b',
                        lw=0.5)

            plt.draw()
            nregions += 1
            if len(Val) % 6 == 1:
                na1.append(xmean)
                plt.axvline(slitregions[count+2], ymin=-1., ymax=2., color='g',
                            lw=1)

            if len(Val) % 6 == 2:
                nb2.append(xmean)
                plt.axvline(slitregions[count+2], ymin=-1., ymax=2., color='g',
                            lw=1)



        if keyboard.is_pressed("e"):
            for i in range(len(na1)):

                Na1 = na1[i]
                Nb2 = nb2[i]


                area = df[(df.wave > Na1) & (df.wave < Nb2)]

                    #Reference redshift.
                z_sys = 12314.44/6564.61 - 1   #H-alfa

                    #z_area in our report.
                    #this[0] is rest wave of observation peak.
                z = area.wave/this[0] -1.

                    #Calculating the peculiar velocity in km/s.
                v = (z-z_sys)/(1+z_sys)* c * 1/1000

                    #Plotting velocity plot.
                plt.figure(frameon=False, figsize=(8, 1), dpi=600)
                plt.step(v,area.flux)
                plt.axvline(linewidth=0.5, color = "k", linestyle="--")

                    #Can be used for title.
                #plt.title(
#"""Velocity profile: """ + str(dat[1]) + """
#Rest wavelength: """ + str(round(dat[0], 2)) + """ [Å] """
#                                                         )

#Obs wavelength: """ + str(round(peak_obs, 2)) + """ [Å] """
 #                                                    )
                plt.xlim(-700, 700)
                plt.ylim(25,215)
                plt.xlabel("Peculiar velocity [km/s]")
                #plt.ylabel("Flux [Erg/s/cm\N{SUPERSCRIPT TWO}/Å]")
                plt.text(-590, 172, str(dat[1]), fontdict=None)


                    #Saving plot
                plt.savefig(f"VelprofileGRB21A/{dat[1]}_{nr}.png",
                            bbox_inches="tight")
```

```
                plt.show()


        docu.close()

        return


                #Open the data for spectra.
Val = ([])
na1 = ([])
na2 = ([])
nb1 = ([])
nb2 = ([])
x1 = ([])
x2 = ([])


VIS = 'ToO_GRBtrigger_4x600_JHslit_SCI_SLIT_MERGE1D_VIS.fits'
UVB = 'ToO_GRBtrigger_4x600_JHslit_SCI_SLIT_MERGE1D_UVB.fits'
NIR = 'ToO_GRBtrigger_4x600_JHslit_SCI_SLIT_MERGE1D_NIR.fits'

file_name = NIR
sn_file = fits.open(file_name)

                #Underneath is used for quickly finding the peak.
z = 0.876
datnavn = "PeakList_GRB210204A_final"
datimport = pd.ExcelFile(f"{datnavn}.xlsx").parse("Sheet1")

nr = 24         #The peak number in the our list of peaks, that we are searching for.

this =  [datimport['Rest [Å]'][nr-2],datimport['Feature'][nr-2]]#


dat = [this[0] , this[1] ]

teori_peak = dat[0]*(z+1)
bredde = 50
højde = 400

hdr = sn_file[0].header
hdrr = sn_file[1].header
flux = sn_file[0].data
err_flux = sn_file[1].data
wave = 10*(np.arange(len(flux))*hdr['CDELT1']+hdr['CRVAL1'])
lstep=wave[1]-wave[0]

df_frame = {'wave':wave[:], 'flux':flux[:], 'err_flux':err_flux[:]}
df = pd.DataFrame(df_frame,dtype='float64')

#plotting the figure for marking.
fig = plt.figure()
plt.title("""1. Zoom to desired absorptionline
2. Hold shift and click mouse to mark normalization regions (4 clicks left to right)
3. Hold shift and click mouse to mark absorption region (2 clicks)""")
ax = fig.add_subplot()
ax.plot(wave, flux, '-', picker=1, alpha=0.8)
ax.plot(wave,err_flux,'-',alpha=0.4)
```

```python
#Zooming on x and y axis for easy acces.
plt.ylim(-højde, højde)
plt.xlim(teori_peak-bredde, teori_peak+bredde)

fig.canvas.mpl_connect('pick_event', Mouse)


plt.show()


"""
This script is for GRB210204A, and for GRB190114C the script is almost identical,
however with the only change, that we are opening different files.
"""
```

```python
""" Those scripts making the individual velocity profiles into 1 plot for
    comparison
"""

import matplotlib.pyplot as plt     #Importing packages
from PIL import Image

plt.close()                         #Closing all plots


                                    #Chosing the files names for later import
files = (["a_23.png", "g_22.png", "γ_21.png", "δ_20.png", "ε_19.png" ])
LIST = ([])

                                    #Appending the image files to the list "LIST"
for i in range(len(files)):
    LIST.append(Image.open(files[i]))

                                    #Creating a subplot the image files
fig, axs = plt.subplots(len(LIST),1)
fig.suptitle('Velocity profiles of Balmer in GRB190114C')
plt.gca().axis("off")
plt.subplots_adjust(hspace=-0.49)

                                    #Adding each image at a time to the subplot.
for i, a in enumerate(axs):
    a.imshow(LIST[i])
    a.axis('off')

                                    #Saving the final plot.
plt.savefig("Velocity profiles of GRB190114C_Balmer", bbox_inches="tight",
            dpi = 600)

plt.show()
```

```python
import matplotlib.pyplot as plt     #Importing packages
from PIL import Image

plt.close()                         #Closing all plots


                                    #Chosing the files names for later import
files = ([ "CaII_19.png", "MgI_17.png", "MgII_16.png", "FeII_13.png",
          "OIII_23.png", "H-alfa_24.png" ])
LIST = ([])

                                    #Appending the image files to the list "LIST"
for i in range(len(files)):
    LIST.append(Image.open(files[i]))

                                    #Creating a subplot the image files
fig, axs = plt.subplots(len(LIST),1)
fig.suptitle('Velocity profiles of GRB210204A')
plt.gca().axis("off")
plt.subplots_adjust(hspace=-0.44)


                                    #Adding each image at a time to the subplot.
for i, a in enumerate(axs):
    a.imshow(LIST[i])
    a.axis('off')


                                    #Saving the final plot.
plt.savefig("Velocity profiles of GRB210204A_alfa", bbox_inches="tight",
            dpi = 600)
plt.show()
```