A search for signs of late-time interaction between Type Ia supernovae and distant circumstellar material using the Zwicky Transient Facility

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... dedication ...

Acknowledgements

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Introduction

1.1 The final stages of stars

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Observing in the optical regime

Astrophysicists face the unusual challenge of not being able to control their experiments. The universe is our laboratory but all we can do is observe the results while often not knowing the exact setup of the experiment. Models are made to explain and predict the behaviour of planets, stars, galaxies, etc. but ultimately observations are needed to compare against and test our models. My work relies heavily on observational data, and in this chapter I will introduce the telescopes and instruments that are at the basis of this thesis. I will also give a general overview of what to consider when planning observations and different types of observations that can be done in the optical regime. add refs to sections, reduction and analysis in a separate chapter probably

2.1 Telescopes

Most of the data used in this thesis comes from the Zwicky Transient Facility (ZTF), and follow-up observations have been made using the Nordic Optical Telescope (NOT), and the Gran Telescopio Canarias (GTC), which will be introduced below. Some additional data comes from other sources, which we list for completeness. ow subsection or list here

2.1.1 Zwicky Transient Facility

The Zwicky Transient Facility (ZTF) is an optical large-sky survey observing the entire northern night sky above Dec $\sim -30°$every 2-3 nights in three broadband optical filters gri, which are very similar to the well-known SDSS gri filters. The efficiency of these filters is plotted as a function of wavelength in Fig. 2.1. The survey saw first light in October 2017 and the survey formally began scientific operation in March 2018 and has been running continueously until the time of writing this document.

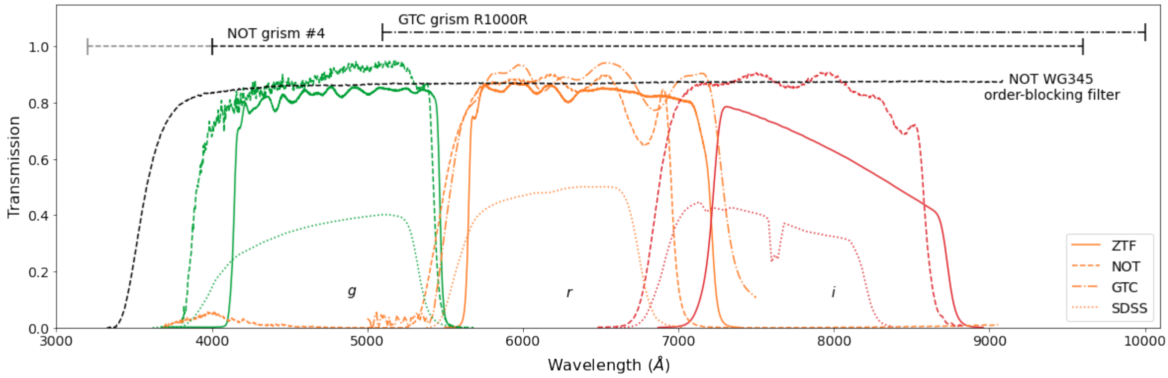

Figure 2.1: Throughput as a function of wavelength of the different filters used to gather the bulk of the data in this thesis $g$filters are shown in green, $r$in orange, $i$in red, and the different telescopes are shown with different line styles (Continuous for ZTF, dashed for NOT, dot-dashed for GTC). The SDSS filters (dotted lines) are shown for comparison. For the grisms the wavelength ranges are shown as only, not their efficiency as function of wavelength. Plot needs to be finished, see to-do list in the notebook

The observations are made using the 48″ aperture Schmidt-type design Samuel Oschin Telescope, which is based at the Palomar Observatory in Southern California. Each exposure, lasting 30 s, can go a limiting magnitude of $\sim$ 20.5 mag and covers an area of $\sim$ 47 deg^2 at a resolution of of 1.01″ per pixel. The camera is divided in a 4×4 grid of CCDs, each of which have 4 readout channels called quadrants. This result in each observation producing 64 separate images, each with their own quadrant identifier (qid). Similarly, the observed region of the sky is divided into different telescope pointings called fields (identified using fid) to ensure that the same region of the sky is observed in the same way each time, aiding with the reduction of the data. This results in each combination of filter, fid, and qid being a set of observations of a particular part of the sky using speciic setup. Add all the usual ZTF references

2.1.2 Nordic Optical Telescope

The Nordic Optical Telescope (NOT) is a 2.56 m telescope located at Roque de Los Muchacos Observatory in La Palma, Spain. Add elevation and coords? It hosts several instruments for observing in the optical and near infrared, both for imaging and spectroscopy. The main instrument is the Alhambra Faint Object Spectrograph and Camera (ALFOSC), which was used to obtain the data used in this thesis. I will only

Table 2.1: Optical elements used for observations taken with NOT/ALFOSC and GTC/OSIRIS+. Finish it, check if R1000R also has an effective range (think I used it all though)

Filter	λ_{center} (Å)	FWHM (Å)	T_{max}
g' NOT	4800	1450	0.92
r' NOT	6180	1480	0.90
r' GTC	6410	1760	0.94
i' NOT	7710	1710	0.91
WG345	3560	-	0.88

Grism	λ range (Å)	resolution (Å/ pixel)	Orientation
#4	3200* - 9600	3.3	vertical
R1000R	5100 - 10000	2.62	horizontal

slit	Telescope	Orientation
1.0″	NOT	horizontal
1.0″	GTC	vertical
1.3″	NOT	horizontal

* The detector response is limited at low wavelengths, so in practice a lower limit of 4000 Å is used for faint targets.

discuss the parts relevant to this thesis, further details on this instrument and details on the other instruments can be found at [1].

ALFOSC is a versatile instrument mounted in cassegrain that can be used for imaging, spectroscopy, and (spectro)polarimtery. As there are several wheels equipped to hold a variety of optical elements, the instruments can switch quickly between different setups between observations. The images can cover up to $6.4' \times 6.4'$ per exposure at a resolution of $0.2138''$ per pixel. In this thesis filters 120 (g'), 110 (r'), and 111 (i') are used for spectroscopy. For spectroscopy grism 4 is used together with a $1.0''$ slit if the seeing was $\leq 1.3''$ or a $1.3''$ slit if the seeing was $\geq 1.3''$. For some spectra an order-blocking filter (WG345) is used as well to avoid second order diffracted blue light to overlap with first order diffracted red light on the detector. Details on these optical elements are given in Table 2.1, and they are shown in Fig. 2.1.

[1] https://not.iac.es

2.1.3 Gran Telescopio CANARIAS

The Gran Telescopio CANARIAS (GTC) is a 10.4 m telescope at the Roque de los Muchachos Observatory in La Palma, Spain, and is the largest optical / near infrared telescope on the island. Its primary mirror is made up from 36 hexagonal pieces creating an effective collection area of 73 m^2, ideal for observing very faint targets. The GTC can host up to six instruments at a time in various focal positions, allowing for a large variety of observations to be made. One of the most commonly used instruments is OSIRIS+, the upgraded version of OSIRIS, Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy.

OSIRIS+ has an unvignetted field-of-view of $7.8' \times 7.8'$ at a resolution of $0.254''$ per pixel. Since the standard readout has 2×2 binning, the resolution can be increased to $0.127''$ if so desired. Like ALFOSC, this isntrument is also built to easily switch between different setups between observations. For photometry the r'' filter is used in this thesis, and for spectroscopy the R1000R grism with a $1.0''$ slit is used. Details on these optical elements are given in Table 2.1, and they are shown in Fig. 2.1. Add refs

2.1.4 Other observations

Small amounts of data coming from other telescopes and surveys are presented in this thesis as well. This includes a follow-up observation of SN 2019ldf in $g$and $r$using the ESO Faint Object Spectrograph and Camera version 2 (EFOSC2) imaging spectrograph on the ESO New Technology Telescope (NTT) in La Silla, Chile as part of the extended Public ESO Spectroscopic Survey of Transient Objects+ (EPESSTO+).

To complement ZTF data of several SNe observations from the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS, (intermediate) Palomar sky Survey (PTF, / iPTF), All Sky Automated Survey for SuperNovae (ASASSN), Asteroid Terrestrial-impact Last Alert System (ATLAS), Global Astrometric Interferometer for Astrophysics (Gaia), and Wide-Field Infrared Survey Explorer (WISE) are used. add refs

2.2 General considerations for observing

To observe astronomical objects one has to consider several things. Assuming that the location or region on the sky that we are interested in to observe is already known, as well as the desired type of observation, an observing plan can be made. A well constructed observing plan should give the best quality data possible while making efficient use of the resources available.

2.2.1 Location

Although this is normally already done before constructing a telescope, the first thing to consider is the location from where to observe. When purely aiming for the best observations possible, there are three main things to consider when chosing a location:

- Weather: Clear skies for most nights throughout the year, stable conditions, and low atmospheric distortion (seeing) are vital to ensure good quality data on a regular basis. By going higher above sea level, lower hanging clouds can be avoided while simultaneously decreasing the amount of air starlight has to travel through to reach the detector.

- Light pollution: The darker the sky, the fainter objects can be observed. Artificial light sources from humans greatly hinder the observation of faint objects by outshining them many times over. Even the the prescence of a (partially) illuminated moon greatly changes the depth that can be reached. For this reason many observatories have (inter)national laws to control the ligth pollution and ensure good quality data can be obtained.

- Target observability: The target needs to be high enough above the sky for long enough during the night for observations to be made. Additionally, the closer to zenith an observation is made, the better quality data as it decreases the amount of atmosphere between the target and telescope. The atmosphere reduces the data quality seeing, broadband absorbtion (clouds, dust), narrowband interference (tellurics, skylines), and achromatic diffraction (different colours diffracting differently when entering the atmosphere at an angle, Check name and cite that specific paper) among others.

Combined, this means that observatories should be located on top of high mountains that are in areas with stable and clear weather, with as small a population nearby as possible while still being accessible enough for transporting materials and observing staff. One of the best locations in the world that meets these requirements is Roque de los Muchachos on La Palma, a small Spanish island in the Atlantic ocean off the coast of Morocco. At around 2300 m above sealevel, the telescopes are built on the highest peak of the mountain, far from most communities on the island which are much closer to sea level, and the temperate climate ensures good sky conditions for most nights around the year. Additionally, the government has put laws in place to minimize light pollution, e.g. by limiting the use of street lights and restricting flight patterns over the observatory.

2.2.2 Telescope, instrument, mode, and setup

Depending on the type of observations and the brightness of the target there is a choice of telescopes to be used. Telescope, intsrument, observing mode, and desired setup(s) have to be considered together, as some choices affect other ones.

Bigger telescopes can observe fainter targets, but it is also more difficult to obtain observing time. On the other hand, smaller telescopes are less oversubscribed (a measure of requested versus available observing time), but are more limited in observation depth even with longer exposure times. Smaller telescopes are however more ideal for brighter targets that will instantly saturate the detector of a larger telescope.

Secondly, different instruments, which are often telescope specific, have different observing capabilities. Even though ALFOSC and OSIRIS+ can both do photometry and spectroscopy, there are still differences in data quality and resolution even if the same object is observed at the same time. Spectroscopy and photometry are very standard observing modes, and most telescopes have an instrument can offer this. However, for polarimetric observations OSIRIS+ cannot be used but ALFOSC can, limiting the options for this mode of observation.

Lastly, the specific setup has to be considered as well. For photometry, which filters are desired? If a very specific or rare filter is required this may again limit the options of telescopes and instruments. For spectrocopy there are other choices, such as fiber or slit spectroscopy, different gratings or grisms depending on the desired resolution and wavelength range, neutral density filters to observe targets that are otherwise too bright for the instrument, and order-blocking filters to remove blue light from red parts of the spectrum.

2.2.3 Night plan

Add a NOT night plan as a plot? Could be a good visualization and I make them anyway so its easy to screenshot

Lastly, it is recommended to have planned what to observe when to avoid losing observing time during the night. While most proposals already have a list of targets and standard stars to observe and exposure times when they are submitted, the detailed plan is usually made mere hours before the night starts as it depends on e.g. the current weather conditions and stability, which targets have already been observed a previous night, specific time constraints (e.g. for transits), and target priority. Calibration images need to be taken as well, and although some can be taken during the day others can only be taken during a short window in twilight, or have to be taken directly before or after the target. All of these things need to be taken into concideration when trying to maximize the time used to expose and observe targets, and minimize the overheads from e.g. positioning, target acquisition, and readout.

Time spent repositioning the telescope can be reduced by trying to find the path between targets that minimizes telescope and dome movement throughout the night. The time spent acquiring the target depends on the observing mode but also on the

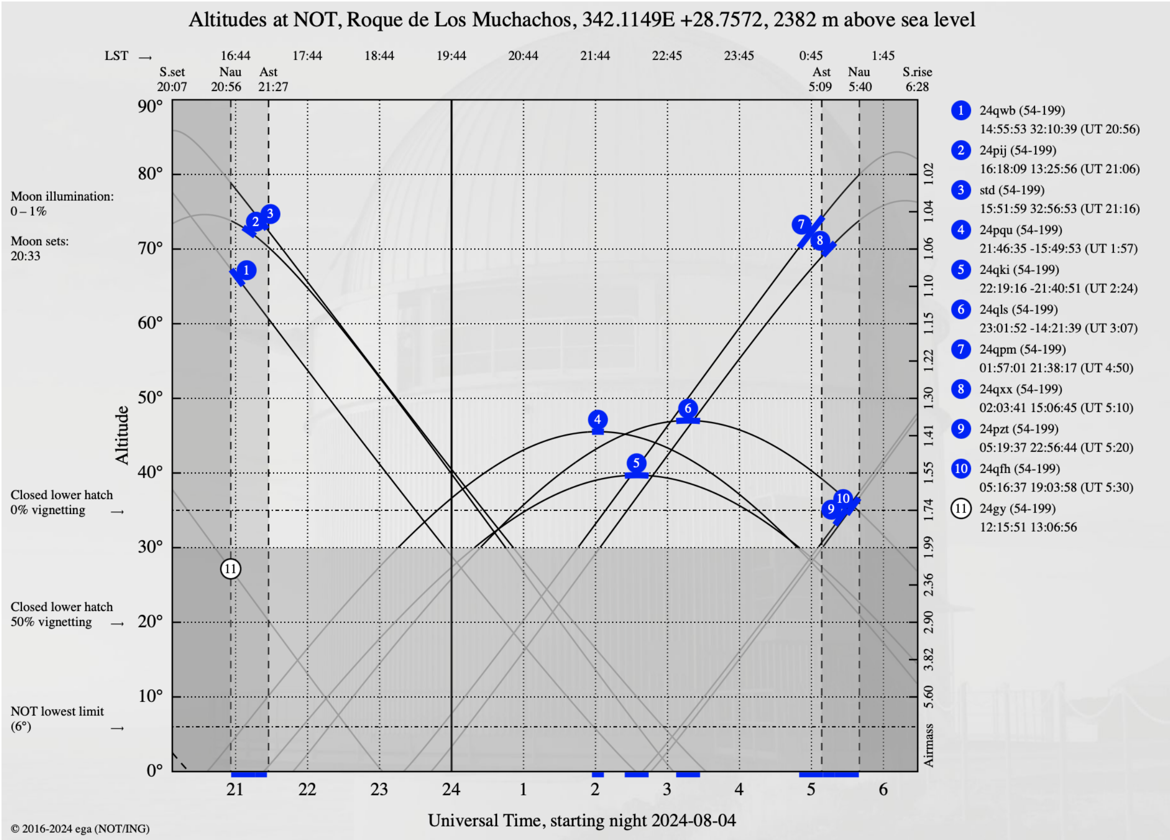

Figure 2.2: Night plan for the NOT on the night of XXX. Targets are plotted with their altidute as a function of universal standard time and local stellar time on top. The target priority has been colour coded, with the coloured bars showing the amount of time each observation is expected to take. Green targets have already been completed, and the red vertical line shows the current time. Not all targets fit into the schedule but are still shown in case the plan has to be ammended during the night.Temp version, find and make a proper one

experience and tiredness of the observer. Photometry observes a field, so usually a small offset is not disastrous for the science. Spectroscopy takes longer as the correct target needs to be identified and placed in the slit or fiber before the exposure can start. Readout times are specific to each detector, though if only a part of the CCD is needed windowing and binning during readout can shorten this significantly. This can be especially important in cases where multiple shorter exposures are taken instead of a single long one. This can be done to e.g. reduce cosmic ray interference, avoid overexposure of a bright source close to a fainter target, or for constructing time series.

Nothing is certain during the night. Weather conditions can change or not meet the conditions required for some observations, technical problems can occur, or observations might go so smoothly that they are completed faster than expected. A flexible schedule with a priority list and backup targets helps to adapt to these situations as fast as possible. After all, an idling telescope in (half-)decent observing conditions is a waste of resources. Fig. 2.2 shows an example night plan for the NOT.

2.3 Types of obeservations

All optical observations are, in esssence, images taken by a camera. Light falls onto a pixel on the CCD, and frees some amount of electrons. The more light that hits the pixel, the more electrons are freed. At readout these electrons are counted per pixel, or group of pixels if binning is applied, and turned into a digital number called a count. During this process there are contributions from different noise sources, but as long as the total count rate is in the linear regime of the CCD, i.e. there is a linear relation between the received flux and final count, it is possible to calculate the flux by using calibration images. The different types of calibration images are described below, but their usage is explained in section 3.1 when discussing image reduction.

reference some books or so about observing techniques or something

2.3.1 Photometry

Photometry is one of the simplest observing modes as it is just taking a photo of a part of the sky. The difference with the camera in a phone is that the telescope instrument is much more sensitive. The top of Fig. 2.3 shows a raw photometric image, taken with NOT/ALFOSC without the use of a filter. The images are monochromatic, i.e. they only have a value for the intensity. For colourful images multiple observations have to be made in different filters and combined to represent different colours. Faint objects can be observed by increasing the exposure time in a single image, or stacking multiple images together to increase the effective exposure time. When stacking images it is common practice to dither the telescope: applying a small offset between exposures to ensure that the target hits a different part of the CCD, avoiding issues with bad pixels ruining otherwise good observations. While this decreases the effective size of the fully stacked image, as long as the edges are not needed there is no issue.

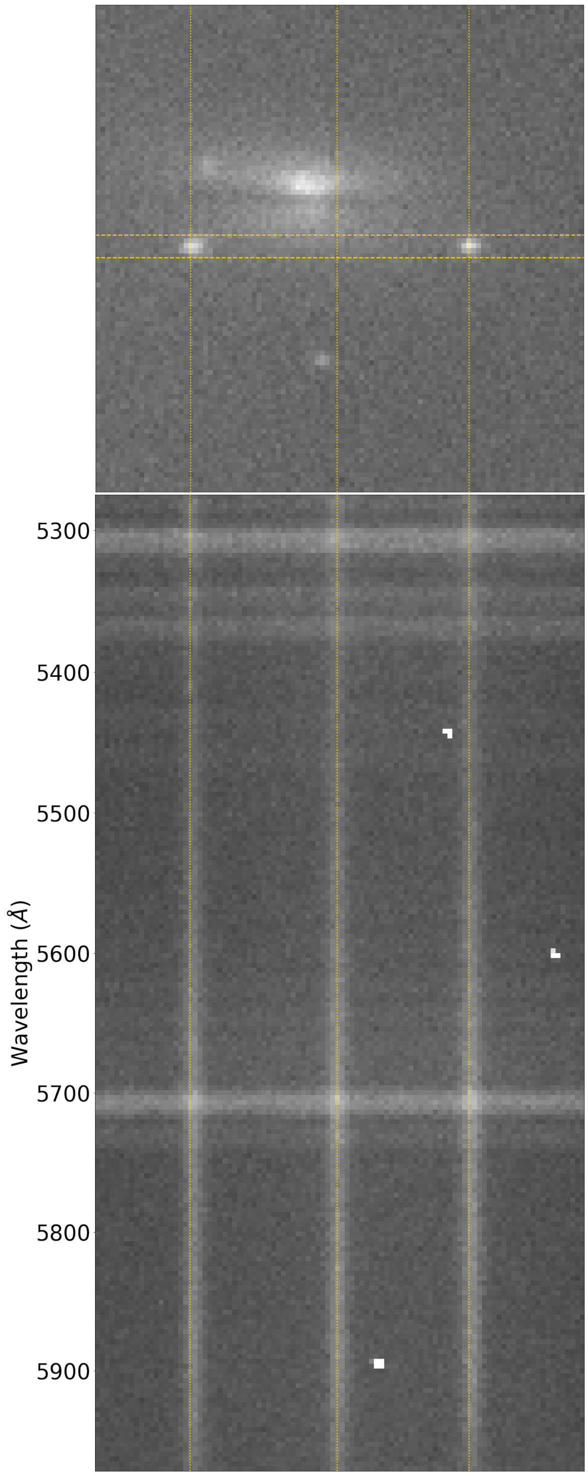

Figure 2.3: Image and partial spectrum of SN 2024nqr (left) and SN 2024pgd (right), two SNe Ia active simultaniously in the same galaxy. The image was taken without a filter and used to align the 1.0″ slit (horizontal dashed lines) over both SNe. The resulting spectrum, taken with grism #4, shows three traces as white vertical stripes. The outer two line up with the two SNe, while the middle trace is from the host galaxy edge in the slit (vertical dotted lines for guidance). The horizontal lines in the spectrum are sky lines coming from atmospheric emission. This data was taken with NOT/ALFOSC on the night of 28 July 2024 while testing an experimental rapid response mode (RRM, credit: Samuel Grund Sørensen). check AT/SN status weirdness

2.3.2 Spectroscopy

Spectroscopy goes one step beyond just taking a photo. Assuming that this is slit spectroscopy, instead of a filter to select a wavelength range to observe now a slit restricts the observable region of the sky to a narrow band along one axis of the detector (e.g. horizontal). After the slit the light hits a grating or grism (a grating and prism combined) which diffracts the light based on wavelength across the second axis of the detector (vertical). The rule density on the grating / grism dictates the wavelength spread of the light: the more rules per unit distance, the bigger the diffraction, and the higher the spectral resolution of the resulting image. The tradeoff is that a smaller part of the spectrum can be observed at a time, and there is less light being received per pixel which reduces the SNR unless the exposure time is increased to account for this. Any point-like source that is observed becomes a line in the spectral direction, called a trace.

There is some freedom in the orientation of the slit. This is called the position angle of the slit. If there are multiple targets near each other, and they can be in the slit at the same time, the required position angle can be calculated from the two target positions. If there is a single target to be observed the position angle can be anything, but usually the parallactic angle is chosen. In this orientation the slit is perpendicular to the horizon, as this minimizes losses from the achromatic diffraction due to the atmosphere at different wavelengths.

The bottom panel of Fig. 2.3 shows a section of the spectrum taken of the image in the top panel. The two SNe are drawn out into vertical traces and a third trace belonging to the edge of the host galaxy can be seen in the middle. The horizontal lines are sky emission lines, and while these can technically be used to estimate the conversion from pixel position to wavelength, standardized arc frames will result in a much better wavelength calibration (see below).

2.3.3 Calibration: Bias

The first calibration image is the bias, which is made by reading out the CCD without exposing. The resulting image contains the amount of counts that will be in every exposure regardless of what has been observed or with what exposure time. In other words, measuring the bias can be tought of as measuring the offset to correct for in every other image.

2.3.4 Calibration: Dark

Any detector that is not at a temperature of 0 K will have some amount of noise due to thermal effects. This can free electrons in pixels over time, creating a dark current and increasing the noise over time. The effect can be measured by exposing for the same amount of time as the science images taken, but without letting any light hit the CCD. This is called a dark frame.

As this is a thermal effect, it can be reduced to negligible amounts by cooling the instrument. This saves precious observing time, as otherwise dark frames would ideally have to be taken at the same temperature as the target was observed, which is easiest to do directly after the science exposure. By cooling the detector with e.g. liquid nitrogen this noise source can be avoided instead of having to correct for, saving time and the amount of images that need to be taken in the process.

2.3.5 Calibration: Flats

The amount of light that the CCD receives is converted into a digital number, but there is no guarantee that this conversion rate is the same for each pixel. This can be due to intrinsic differences between the pixels, or outside effects such as dust reducing the amount of light recieved on a part of the detector. To correct for this an evenly illuminated field has to be observed called flats or flatfields. By ensuring that each pixel receives the same amount of light, the different counts will reflect the varying responses per pixel.

While any evenly illuminated object can be used for this, such as the the inside of the telescope dome to create dome flats. A more perfect evenly lit source however is the sky, and using this sky flats can be taken. While it is usually too bright during the day and the CCD will saturate even with the narrowest filter and shortest exposure time, there is a window during twilight where the sky is darker but not dark enough to observe stars yet. As a general rule, narrowband filters need a brighter sky and in the evening need to be done before the broadband filters. After that, assuming similar efficiencies between filters, blue filters need brighter skies than red filters, forcing a specific order in which the sky flats need to be taken during the short window where this is possible. Of course if flats are taken in the morning the order has to be reversed.

2.3.6 Calibration: Arc

In spectroscopy, one of the CCD axes is spectral with red light at one end and blue light at the other end of the detector. To know where on the detector each wavelength falls, so-called arc frames are needed. These are taken by observing a lamp filled with a known set of elements (e.g. He, Ne, or TH and Ar). The wavelengths of the emission lines are known very precisely, and by matching these with the observed lines in the arc image a pixel-to-wavelength conversion can be found, called the wavelength solution.

3

Analysis techniques

After all observations have been taken it is time to analyze them. The first step in this is to reduce the raw data into the required format to work with. After that, additional analysis technique can manipulate the reduced images directly or the data that has been extracted from them. I will briefly discuss difference imaging and forced photometry, as these are important for this thesis. More techniques that need discussion? Might want to make this its own chapter separate from observing.

3.1 Reduction

copied, not edited yet To get the cleanest signals it is important to reduce noise as much as possible. Several sources of noise originating from the instrument can be removed using different types of calibration images. Generally speaking there are three types of calibration images for photometry, and one extra for spectroscopy. The response function of a detector can be written as Probably good to go over with someone at some point to be sure there's no mistake here, also need references of course. make sure CCD is properly introduced somewhere above. Need to talk about gain and read noise as well somewhere, read up on that and add.

$$R_{ij}(F,t) = B_{ij} + D_{ij} \times t + A_{ij} \times F, \tag{3.1}$$

where R_{ij} is the CCD response of pixel i, j as a function of the integrated flux F during the exposure which lasted a time t. The goal is to measure the flux $f = F/t$, which requires knowing A_{ij}, B_{ij}, and D_{ij}. Each type of calibration image is used to measure one of these values. Note that it is assumed that there are no cross or higher order terms in Eq. 3.1, in other words, the CCD is in its linear regime. When a pixel receives too much light and gets close to saturation it is no longer in its linear regime, and more terms appear in Eq. 3.1 making it much more difficult or even impossible to measure the observed flux.

Using the calibration images from above, the raw science images can be reduced to something a flux level can be measured from. Usually several calibration images of a type are taken to average out and remove outliers due to e.g. cosmic rays, which is usually called the master image. First the master-bias is created and subtracted from every other image. Then the same can be done with the master-dark if needed. Lastly every science image is divided through the normalized master-flat to equalize the pixel responses. Once the images are reduced it is often good practice to run a cosmic-ray removal algorith to remove this source of noise as much as possible Check name and add references .

If multiple images are taken of the same field or object. one can stack them at this stage do reduce noise and increase the SNR of the observed objects. Sometimes the observations were taken with slightly different telescope pointings (dithering) to avoid the same objects being on the same pixels every time. This is good to keep in mind to make sure that the images are stacked correctly.

With photometry the observed brightness can be measured for each star in the image to get a list of instrument magnitudes. The relative differences between the magnitudes of objects are correct, but there is still an absolute offset across all objects. This is corrected by comparing with known values from the literature.

For spectroscopy, after the calibrations above the wavelength solution is added in the spectral direction of the image. The trace is extracted and converted into a 1D spectrum, but is not yet calibrated for the detector efficiency at different wavelengths. This is where the standard star comes in. By comparing the observed spectrum to the known one, the detector wavelength response function can be recovered. Applying this to the science observation provides the flux calibration, ensuring that the observed flux at different wavelengths can be compared.

3.2 Difference imaging

A popular method for discovering and isolating transients is to look at what has changed on the sky. If there is a map of how a part of the sky looked some time ago, the constant sources such as most stars (except variable ones) and galaxies can be removed. To computers, images are nothing more than big matrices. This means that, if properly aligned, subtracting the reference from the science images is an easy operation that leaves only those sources whose brigthness has changed between the two observations in the so-called difference image. This also ensures that only the transient light is measured in cases such as a SN superimposed on top of its host galaxy.

3.3 Forced photometry

The two most common methods to measure flux from an image are PSF photometry and aperture photometry. PSF stands for point spread function, and with this method a function is fitted to model the source. This function describes how an infinitely small point of light is spread over the detector, and through its spatial size and peak value the flux of the light source can be measured. Aperture photometry sums up the signal in a given radius around the source center and subtracts the contribution from the background in the same region.

See https://coolwiki.ipac.caltech.edu/index.php/Aperture_Photometry_Overview for references

Large surveys such as ZTF observe the night sky to find new transients and monitor known ones. Difference imaging is used to reveal active transients, as these are the main sources that should be left in the difference image. Through PSF photometry the location and strength of each source in the image is determined, which are then compared to the locations of known sources to separate new from known ones. Each location has however been observed for the entire duration of the survey, which means that it is also possible to measure the flux of a known transient before and after it was visible in the images, creating a light curve for the full duration of the survey.

This is called forced photometry, because the PSF function is forced to center on a specific location instead of finding the best-fitting position for the centroid. When there is nothing but noise at that location the measured flux will be 0 within the error. When there is a source at the target location it will be measured, but if the source is not at the center of the PSF the fit will have trouble converging, resulting in a large uncertainty.

3.4 The SuperNova Animation Program

The light curve that is the result of the forced photometry above can contain bad data points. Many of these will be flagged for having a bad PSF fit, bad weather conditions, etc. But even after filtering these out it can be helpful to check the difference images themselves for unexpected behavouir that might be captured in the light curve. For this I created the SuperNova Animation Program (SNAP)

SNAP collects image cutouts of the specified location during the specified time period(s) and in the specified filter(s). It then matches these with the individual data points in the light curve and puts the images in an animation in chronological order with the reference images at the start. This enables easy identification of bad points due to image defects, off-center sources, residual from imperfectly subtracted sources, cosmic rays etc.

3.5 Simulations

Some experiments are difficult or even impossible to do multiple times, one cannot rerun a survey to observe the same transient events. So to understand the biases in the data as well as the effective size of the survey, it needs to be simulated.

References