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

A dissertation submitted to the University of Dublin
for the degree of Doctor of Philosophy

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# Summary

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*... dedication ...*

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# Introduction

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**Figure 1.1:** *gri* composite image of NGC4216 using observations taken by the Zwicky Transient Facility. **Left:** composite image of approximately XX observations in each filter, taken before 1 January 2024. **Right:** composite image of approximately YY observations in each filter, taken between 5 and 19 January 2024, the first two weeks after the first detection of the Type Ia SN 2024gy. (Credit: Benjamin Nobre Hauptmann) Use this as an example when introducing transients

# 2

# Observing in the optical regime

To do list: Add refs, run by John/Amanda for sanity check, get consistent with $g$ vs $g'$ (ask at NOT), check that Spanish name is properly written in Spanish, NOT filter numbers needed or can be removed? Sometimes slightly confused which tense to use, recheck carefully, opmaak, is there something to reference about the la palma light pollution restriction laws? Expand difference imaging and forced photometry a bit if possible, run credit by Sam and Benjamin to be sure

Astrophysicists face the challenge of not being able to set up and control their experiments. The universe is our laboratory but all we can do is see or detect 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 (section 2.1). I will also give a general overview of what to consider when planning observations (section 2.2) and some of the different types of observations that can be done in the optical regime (section 2.3).

## 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 are listed for completeness.

### 2.1.1 Zwicky Transient Facility

The Zwicky Transient Facility (ZTF, Bellm et al. 2019a,b; Graham et al. 2019; Masci et al. 2019; Dekany et al. 2020) is an optical large-sky survey observing the entire northern night sky above Dec $\approx -30^\circ$ every 2 to 3 nights in three broadband optical

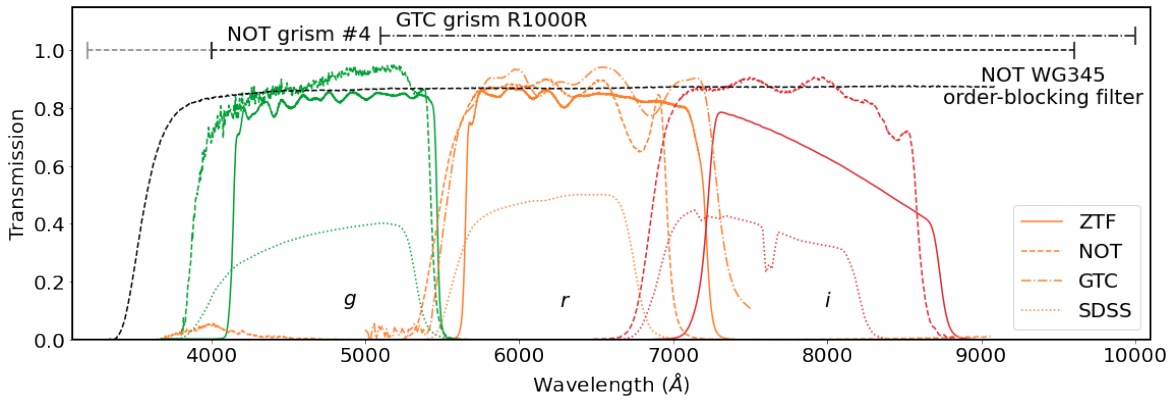


**Figure 2.1:** Throughput as a function of wavelength of the different filters used to gather the bulk of the data in this thesis *g*filters are shown in green, *r*in orange, *i*in red, and the different telescopes are shown with different line styles (Continuous for ZTF, dashed for NOT, dot-dashed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

filters (*gri*), which are 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.

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 is 30 s long, 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 $4 \times 4$ grid of CCDs, each of which have 4 readout channels called quadrants. This results in each observation producing 64 separate images, each with their own readout channel identifier (rcid). Similarly, the observed region of the sky is divided into different telescope pointings called fields 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, field, and rcid being a set of observations of a particular part of the sky using specific setup.

### 2.1.2 Nordic Optical Telescope

The Nordic Optical Telescope (NOT) is a 2.56 m telescope located at Observatorio Roque de Los Muchacos in La Palma, Spain, at an elevation of 2382 m above sea

level. It hosts several instruments for observing in the optical and near infrared, both for imaging and spectroscopy. The Alhambra Faint Object Spectrograph and Camera (ALFOSC) was used to obtain the data used in this thesis. I will only discuss the parts relevant to this thesis, further details on this instrument and details on the other instruments can be found at the NOT website [1].

ALFOSC is a versatile instrument mounted in cassegrain and can be used for imaging, spectroscopy, and (spectro)polarimtery. As there are several wheels equipped to hold a variety of optical elements, the instrument 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 photometry. 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.

### 2.1.3 Gran Telescopio CANARIAS

The Gran Telescopio CANARIAS (GTC [2]) is a 10.4 m telescope at Observatorio Roque de los Muchachos 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: the 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 $2 \times 2$ binning, the resolution can be increased

[1] https://not.iac.es
[2] https://www.gtc.iac.es

**Table 2.1:** Optical elements used for observations taken with NOT/ALFOSC and GTC/OSIRIS+. Check the ′ symbols necessity and make sure to stay consistent

| Filter | $\lambda_{\text{center}}$ (Å) | FWHM (Å) | $T_{\text{max}}$ |
|---|---|---|---|
| $g'$ 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 | $\lambda$ 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 the spectra in this thesis.

to 0.127″ per pixel if so desired. Like ALFOSC, this instrument 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 the optical elements are given in Table 2.1, and they are shown in Fig. 2.1.

### 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, Buzzoni et al. 1984) 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+, Smartt et al. 2015).

To complement ZTF data of several SNe, observations from the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS, Chambers et al. 2016), (intermediate) Palomar sky Survey (PTF, Law et al. 2009; Rau et al. 2009, iPTF, Kulkarni

2013), All Sky Automated Survey for SuperNovae (ASASSN, Shappee et al. 2014; Jayasinghe et al. 2019), Asteroid Terrestrial-impact Last Alert System (ATLAS, Tonry et al. 2018), Global Astrometric Interferometer for Astrophysics (Gaia, Gaia Collaboration et al. 2016), and Wide-Field Infrared Survey Explorer (WISE, Wright et al. 2010) are used.

## 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 to target is already known, as well as what type of data to collect, an observing plan can be made. A well constructed observing plan should allow to obtain 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 choosing where to observe from:

- 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, decreasing atmospheric influence.

- Light pollution: The darker the sky, the fainter objects can be observed. (Artificial) light greatly hinders the observation of faint objects by outshining them many times over. Even the the presence of a (partially) illuminated moon significantly changes the depth that can be reached with the same exposure time.

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 horizon for long enough during the night in order to be observable. Additionally, the closer to zenith an observation is made, the better quality data is obtained as it decreases the amount of atmosphere between the target and telescope. The atmosphere reduces the data quality through turbulence (seeing), broadband absorbtion (clouds, dust), narrowband interference (tellurics, skylines), and differential diffraction (different colours diffracting at in different amounts when entering the atmosphere at an angle, Filippenko 1982), 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 nearby population 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 sea level, 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 paths over the island.

### 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 hardware to be used. Telescope, intsrument, observing mode, and desired setup(s) have to be considered together, as some choices will 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 mea-

sure of requested versus available observing time), but are more limited in observation depth even with long exposure times. Small telescopes are however ideal for bright targets that would instantly saturate the detector of a larger telescope if no filter was used.

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

Lastly, the specific setup has to be considered as well. For photometry, which filters are desired? If a very specific or rare filter is needed this may 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 second order blue light from red parts of the spectrum.

### 2.2.3 Night plan

Lastly, it is recommended to have a plan of what to observe at each point during the night, in order 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 to request observation time, 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 experience and tiredness of the observer. With photometry a field is observed, so usually a small offset is not disastrous for the science. With spectroscopy more time to acquire the target is needed as it needs to be identified and placed in the slit or fiber before the exposure can start. Readout times are specific to each detector, but if only a part of the CCD is needed, or a slightly worse resolution is acceptable, windowing and binning during readout can shorten this significantly. Considering readout times 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 suddenly to not meet the requirement for some observations, technical problems can occur, a high priority target could be discovered during the night, 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 with some space for adaptibility built in.

## 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.

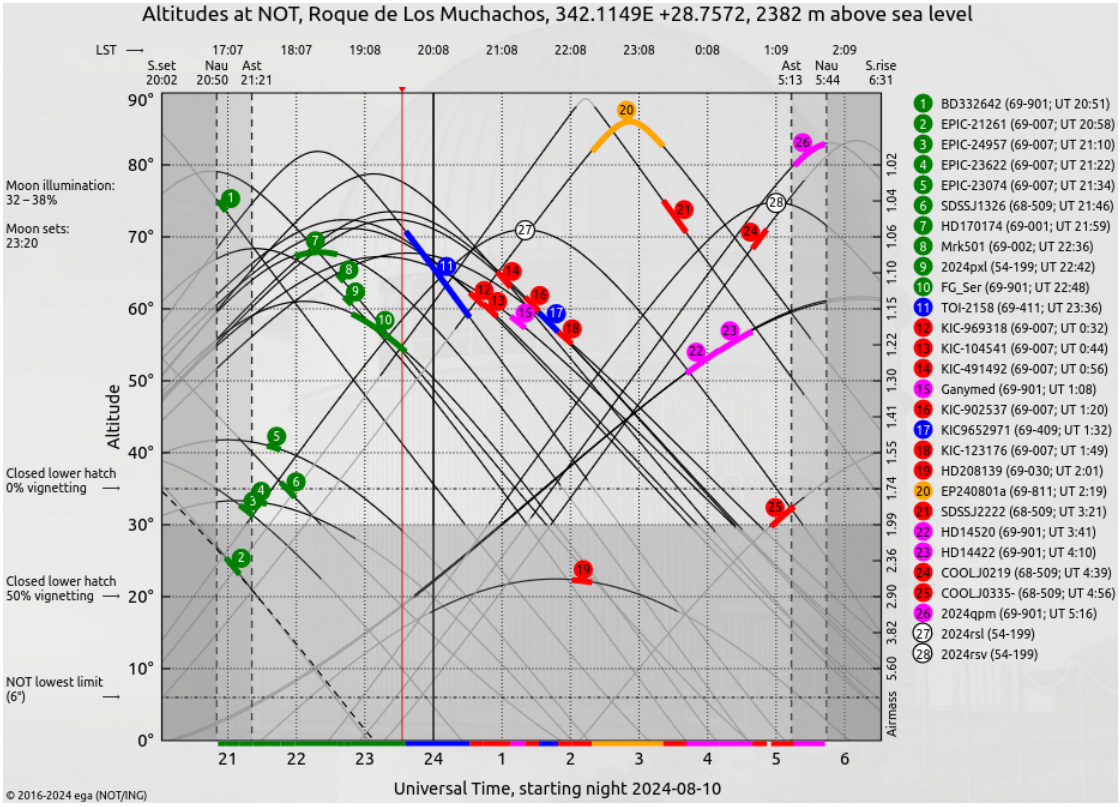


**Figure 2.2:** Night plan for the NOT on the night of 10 August 2024. Targets are plotted with their altidute as a function of universal standard time. Local stellar time is shown on top. The target priority has been colour coded, with the coloured bars showing the amount of time each observation is expected to take. Green targets have already been completed, and the red vertical line shows the current time. Several unscheduled backup targets are shown in case the plan has to be updated during the night.

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, there is a linear relation between the received flux and final count. It is then possible to calculate the observed flux from the target by using calibration images. The different types of calibration images are described below and their usage is explained in section 2.4 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 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 using different filters and combined to represent different colours. Faint objects can be observed by increasing the exposure time in a single image, or by 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.

### 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

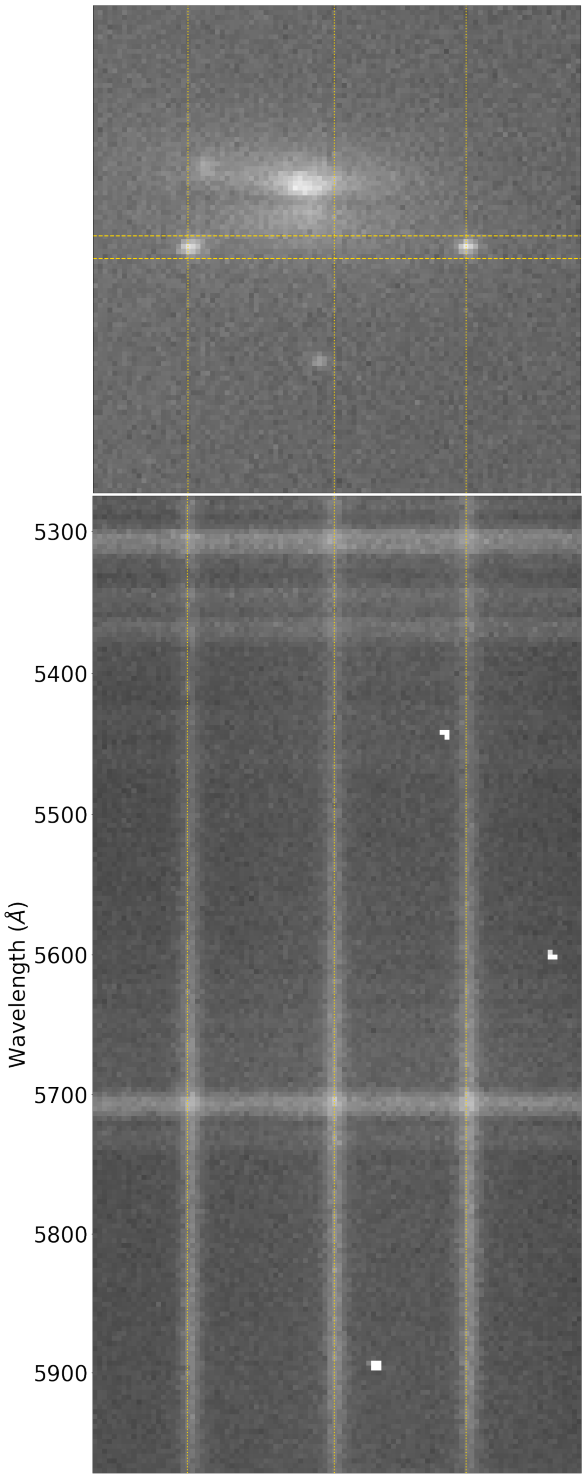


**Figure 2.3:** Image and partial spectrum of SN 2024nqr (left) and SN 2024pgd (right), two SNe Ia active simultaniously in the same galaxy. The image was taken without a filter and used to align the 1.0″ slit (horizontal dashed lines) over both SNe. The resulting spectrum, taken with grism #4, shows 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

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. Extended sources create extended traces.

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, and prevents losses from differential diffraction due to the atmosphere. The trace will only be slightly diagonal on the CCD.

The bottom panel of Fig. 2.3 shows a section of the spectrum taken of the SNe in the top panel image. 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 telescope 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, resulting in an image called a flat or flatfield. By ensuring that each pixel receives the same amount of light, the different counts will reflect the varying responses per pixel.

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, perfect for taking flats. As a general rule, narrowband filters need a brighter sky and in the evening these 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 axes has low wavelength at one end and high wavelength at the other end of the image. To know where each wavelength falls on the detector, 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.

Usually arcs can be taken during the day, when the telescope is idle. However in some cases the mechanical flexure of the telescope from being in a different position during observing can introduce uncertainty in the wavelength calibration unless an arc is taken with the telescope in the same position as for the target. In these cases an arc is usually taken directly before or after the target is observed, or between exposures of the target.

After all observations have been taken it is time to analyze them. The first step 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.

## 2.4 Reduction

Before the observations can be used for science, the images need to be calibrated using the calibration images. As seen before there are generally 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.

$$R_{ij}(f, t, \lambda) = B_{ij} + D_{ij}(t) + F_{ij}(\lambda) \times f \times t, \tag{2.1}$$

where $R_{ij}$ is the CCD response of pixel $i, j$ as a function of the integrated flux of the target $f \times t$ during the exposure which lasted a time $t$. The goal is to measure the flux $f$, which requires knowing $B_{ij}$, $D_{ij}$, and $F_{ij}$. 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. 2.1, 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. 2.1 making it much more difficult or even impossible to measure the observed flux.

### 2.4.1 Bias, dark, and flat corrections

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 combined into a master frame to average out and remove outliers due to e.g. cosmic rays. First the master-bias is created and subtracted from every other image.

As both $F$ and $t$ are 0, the bias measures $B_{ij}$ directly and can then immediately be removed.

With the bias gone, the dark frames measure $D_{ij}$ for a specific $t$, but the master-dark can only be used on sciene observations with the same exposure time. Alternatively it is possible to subtract $B_{ij} + D_{ij}(t)$ in a single step by not separating out the bias term using bias images first.

Finally every science image is divided through the normalized master-flat to equalize the pixel responses. There is still a factor $F(\lambda)$ present, but the value is now indepentent of the pixel position, allowing values from across the CCD to be compared.

### 2.4.2 Cosmic-ray removal and image stacking

At this point it is often good practice to run a cosmic-ray removal algorith to remove this source of noise as much as possible. This can be done using e.g. L.A.Cosmic (van Dokkum, 2001), which I used through Astro-SCRAPPY (McCully et al., 2018) when reducing follow-up photometry of several objects in this thesis.

If multiple images are taken of the same field or object they can be stacked to reduce background noise and increase the SNR of the observed objects. Sometimes the observations have been taken with slightly different telescope pointings (dithering) to avoid the same objects being on the same pixels every time, which has to be taken care of to make sure that the images are stacked correctly.

### 2.4.3 Flux calibration

Filters are never 100% transparent at any wavelength, and the CCD responds differently to different wavelengths. To correct for this, one last type of calibration image is used: the standard star. This was not mentioned in section 2.3 as observing a standard star is exactly the same as observing the actual science target, the only difference is that the expected result of the observation is known and can be used to correct for the wavelength depent efficiency of the telescope.

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 finding the offset using the standard star. If the filter is commonly used, there is a good chance many stars in the field have known magnitudes in that filter, which can be used for calibration instead of a dedicated standard star.

The arcs are used to find the wavelength solution for the spectra, after which the trace from the standard star can be extracted and divided by the known spectrum of the star to obtain the sensitivity function of the detector $F(\lambda)$. The trace of the target can be extracted as well to get its spectrum, which can then be flux-calibrated using

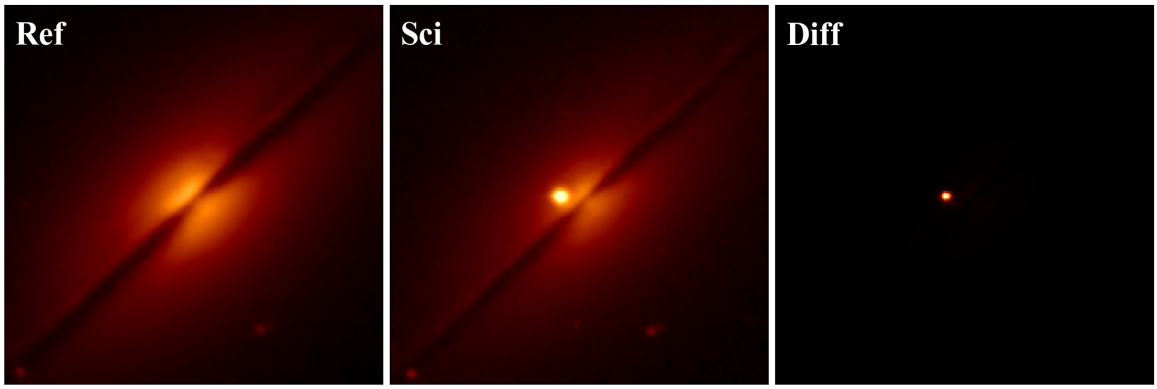


**Figure 2.4:** Example of a $r$-band reference image of NGC 7814, the science image of the same region, and the resulting difference image with the host galaxy removed and only the transient (SN 2021rhu, SN Ia 86G-like) remaining. Credit: Luke Harvey

the sensitivity function.

## 2.5 Difference imaging

Transients are, by definition, objects that appear on the sky for a limited amount of time. A popular and effective way to search for new objects is difference imaging. If there is a map or image of how a part of the sky looked some time ago, it can be used as a reference and subtracted from an image of the current sky. Constant sources such as most stars and galaxies (except variable ones) 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 where different sources are superimposed, such as a SN superimposed on top of its host galaxy. Figure 2.4 Shows an example of the resulting difference image after subtracting the reference image from the science image.

## 2.6 Forced photometry

The two most common methods to measure flux from as source in an image are PSF photometry and aperture photometry. A good explanation of these can be found in Da Costa (1992). 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.

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

# Analysis techniques

This chapter has been absorbed into the observing chapter

# References


Bellm, E. C., Kulkarni, S. R., Barlow, T., et al. 2019a, *Publications of the Astronomical Society of the Pacific*, 131, 068003 (Cited on page 3.)

Bellm, E. C., Kulkarni, S. R., Graham, M. J., et al. 2019b, *Publications of the Astronomical Society of the Pacific*, 131, 018002 (Cited on page 3.)

Buzzoni, B., Delabre, B., Dekker, H., et al. 1984, The Messenger, 38, 9 (Cited on page 6.)

Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv e-prints, arXiv:1612.05560 (Cited on page 6.)

Da Costa, G. S. 1992, in Astronomical Society of the Pacific Conference Series, Vol. 23, Astronomical CCD Observing and Reduction Techniques, ed. S. B. Howell, 90 (Cited on page 20.)

Dekany, R., Smith, R. M., Riddle, R., et al. 2020, *Publications of the Astronomical Society of the Pacific*, 132, 038001 (Cited on page 3.)

Feindt, U., M., R., V., B., & J., N. 2019a, ufeindt/simsurvey: 0.6.0 (Not cited.)

Feindt, U., Nordin, J., Rigault, M., et al. 2019b, , 2019, 005 (Not cited.)

Filippenko, A. V. 1982, *Publications of the Astronomical Society of the Pacific*, 94, 715 (Cited on page 8.)

Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, *Astronomy & Astrophysics*, 595, A1 (Cited on page 7.)

Graham, M. J., Kulkarni, S. R., Bellm, E. C., et al. 2019, *Publications of the Astronomical Society of the Pacific*, 131, 078001 (Cited on page 3.)

Jayasinghe, T., Stanek, K. Z., Kochanek, C. S., et al. 2019, *Monthly Notices of the Royal Astronomical Society*, 485, 961 (Cited on page 7.)

Kulkarni, S. R. 2013, The Astronomer's Telegram, 4807, 1 (Cited on page 6.)

Law, N. M., Kulkarni, S. R., Dekany, R. G., et al. 2009, *Publications of the Astronomical Society of the Pacific*, 121, 1395 (Cited on page 6.)

Masci, F. J., Laher, R. R., Rusholme, B., et al. 2019, *Publications of the Astronomical Society of the Pacific*, 131, 018003 (Cited on page 3.)

McCully, C., Crawford, S., Kovacs, G., et al. 2018, astropy/astroscrappy: v1.0.5 Zenodo Release (Cited on page 18.)

Rau, A., Kulkarni, S. R., Law, N. M., et al. 2009, *Publications of the Astronomical Society of the Pacific*, 121, 1334 (Cited on page 6.)

Shappee, B. J., Prieto, J. L., Grupe, D., et al. 2014, *Astrophysical Journal*, 788, 48 (Cited on page 7.)

Smartt, S. J., Valenti, S., Fraser, M., et al. 2015, *Astronomy & Astrophysics*, 579, A40 (Cited on page 6.)

Tonry, J. L., Denneau, L., Heinze, A. N., et al. 2018, *Publications of the Astronomical Society of the Pacific*, 130, 064505 (Cited on page 7.)

van Dokkum, P. G. 2001, *Publications of the Astronomical Society of the Pacific*, 113, 1420 (Cited on page 18.)

Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, *Astronomical Journal*, 140, 1868 (Cited on page 7.)