Cheat Sheet for ASTR 257: Observational Astronomy
UC Santa Cruz, Fall Quarter 2023

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Contents

Section 0: Introduction

Contributors: *Diego Garza*

This was one of my first courses at UC Santa Cruz. The course included a week-long field trip to Lick Observatory the week before the fall quarter began. The lectures were all delivered in powerpoints by Professor Andy Skemer. We used Slack as a primary means of communication and submitted assignments through email.

The lectures covered lots of observational astronomy topics that I was familiar with, but provided lots of motivation. We usually had an hour-long morning lecture, spent the rest of the day preparing for that night's observationsm, and observed until about midnight. We got exposure to the Nickel Telescope and Shane Telescope (with adaptive optics and KAST spectrograph). The experience was particularly formidable because Andy went out of his way to introduce us to the many people who work there and their varied career paths.

The goal of this cheat sheet is to document the different observational astronomical concepts that I don't necessarily know off the top of my head (as I'm a computational astrophysicist :P). I believe that a second-year undergraduate can understand these notes. I attempt to make them agnostic to any specific telescope, instrument, or observatory.

To create this cheat sheet, I referenced lectures (presented by Andy, also created with Professor J. Xavier Prochaska), Lick Telescope manuals, and my own observation notes. I became much more comfortable with the topics covered through many discussions during and outside the field trip, so many thanks to my first-year cohort: Pedro-Jesus Quiñonez, Malik Bossett, Mika Lambert, Anna Gagnebin, Lordrick Kahinga, and Courtney Carreira. This was the first time I spent lots of time with them, and it was very fun bonding with them (:

Section 1: Observation Theory

Contributors: *Diego Garza*

Note: *LaTeX format adapted from template for lecture notes from CS 267, Applications of Parallel Computing, UC Berkeley EECS department.*

1.1 Astronomical Coordinates

The primary coordinates used in astronomy are the equatorial coordinate system that are defined by the right ascension (RA, α) and declination (DEC, δ). An example diagram is shown in Figure 1.1. These are equivalent to latitude and longitudinal coordinates on the celestial sphere. The celestial sphere is an imaginary sphere that is centered on Earth, with a fundamental plane that defines the 0° latitude at the Earth's equator.

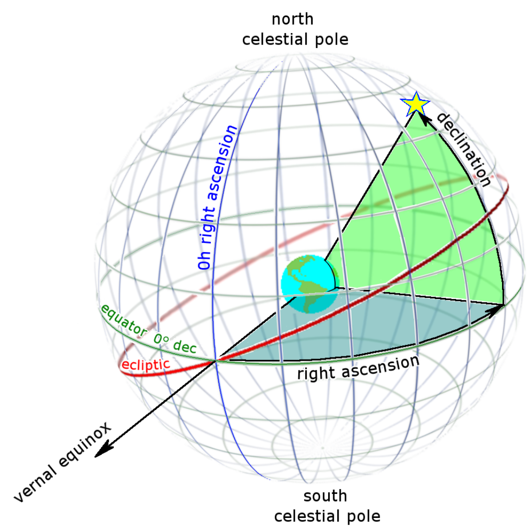

Figure 1.1: Diagram of a star's RA and DEC as seen from outside the celestial sphere. Depicted are a sample star, the Earth, lines of RA and DEC, the vernal equinox, the ecliptic, the celestial equator, and the celestial poles. (Source: Right Ascension Wikipedia)

RA is described in units of a total of 24 hours, which can be subdivided into minutes and seconds. Equivalently, the total RA of one rotation is 360°, so 24 hrs = 360°. DEC is described in units of degrees, which can be further subdivided into arcminutes (1°= 60′) and arcseconds (1′ = 60″).

The convention is such that

- On March 21, Sun sets RA to 0 hours and (equivalently) N-S overheard at midnight is 12 hours
- On September 21, Sun sets RA to 12 hours and N-S overheard at midnight is 0 hours

Another important feature to the equatorial coordinate system are the ecliptic plane. It is the plane where

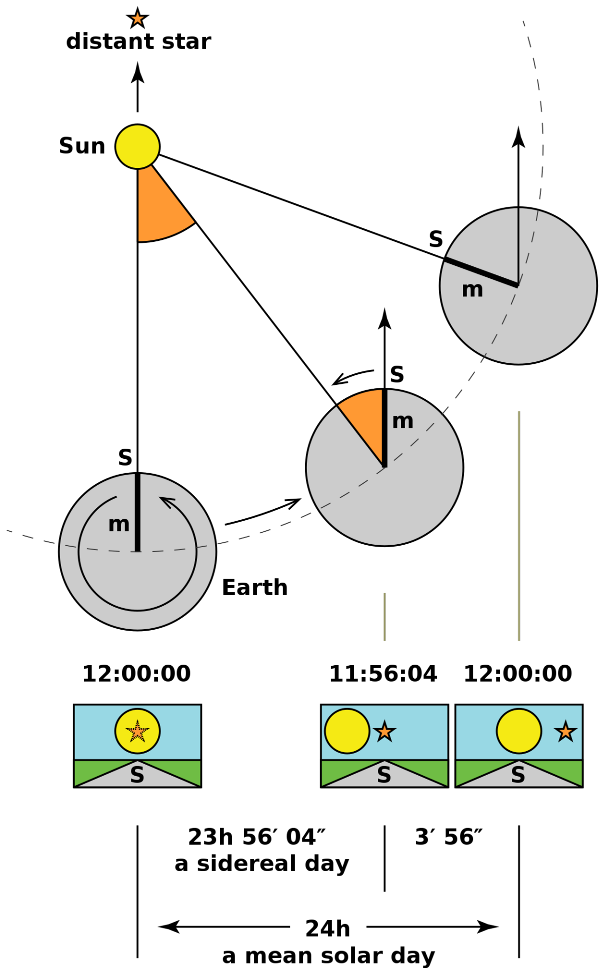

Figure 1.2: Diagram of a sidereal day. (Source: Sidereal Time Wikipedia)

all Solar System planets rotate around the Sun. Since the Earth is tilted, the ecliptic plane and the Earth's equator is not aligned.

An important feature of the equatorial coordinate system is the concept of a sidereal day, described in Figure 1.2. A solar day takes 24 hours and is with respect to the Sun. However, since the Earth is simultaneously orbiting the Sun, a solar day takes slightly more than 360° for the Sun to get back to where it was in the sky. A sidereal day, however, is *defined* as only taking 360° with respect to further away, "fixed" stars on the celestial sphere. Local Sidereal Time (LST) is the RA (longitude from vernal equinox) of the meridian (line connecting celestial poles) directly above the observer.

Astronomers have another helpful tool for a reference system (within the equatorial coordinate system) with the zenith (an imaginary point "above" an observer stretching from center of Earth to observer position on Earth) as a zero-point. The Local Hour Angle (LHA, h) is described in Figure 1.3 calculated as

$$\mathrm{LHA}_{\mathrm{object}} = \mathrm{LST}_{\mathrm{observor}} - \alpha_{\mathrm{object}} \tag{1.1}$$

A separate, but commonly used coordinate system is the Horizontal coordinate system, described in Figure

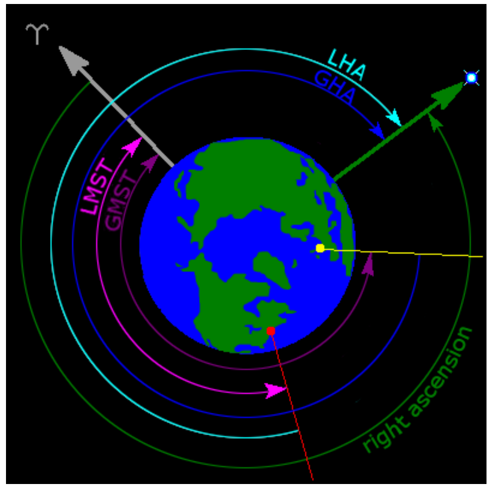

Figure 1.3: Diagram describing sidereal, hour angle, and RA. The gray line is pointing to the vernal equinox, green line is pointing to a sample star, the yellow line is pointing to the position of Greenwich, and the red star is the observer's position. (Source: Hour Angle Wikipedia)

1.4. This system is set with respect to an observer using their zenith and the direction to North. The two coordinates used are altitude and azimuth. Altitude, also known as elevation, is the angle made between the object and the observer's horizon. Azimuth is the angle around the horizon between the object and North, increasing to the East.

A helpful calculation to find whether an object is visible is the Air Mass (AM)

$$\mathrm{AM} = \sec\theta_{\mathrm{z}} \tag{1.2}$$

that is a number calculated from the angle between the object and zenith. An AM of 3 represents an observation with the equivalent of looking through 3 atmospheres compared to just looking straight at zenith.

The precession of the Earth also effects the sky position of distant stars that define a coordinate system on the celestial sphere. In effect, the North pole points at different stars as a function of time. To take this into consideration, observations are usually paired with an epoch and equinox. Epoch is the position of a star on a particular date. Equinox is the position of the coordinate system.

1.2 Charged Coupled Devices & Data Reduction 101

A Charged-Coupled Device (CCD) is a 2D array of light-sensitive pixels that read out in a particular sequence similar to a conveyor belt of water buckets, shown in Figure 1.5.

A CCD absorbs photons (usually only in a specific wavelength) and turns them into electrons that are then turned into a number with an analog-to-digital converter. Each time a pixel is read out from the converter, there is some read noise.

There are a couple of important pixel-by-pixel properties

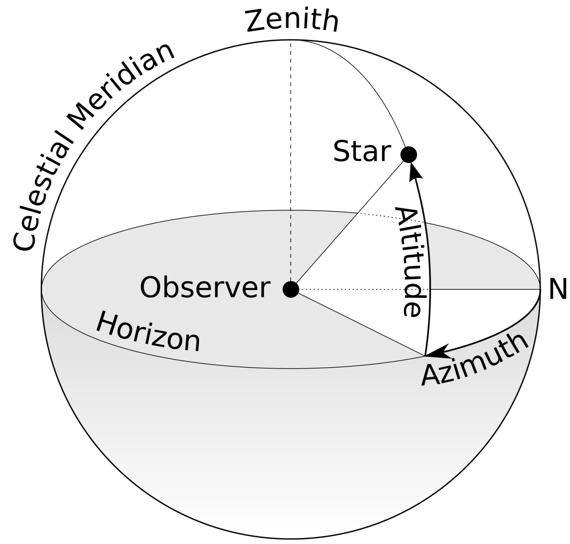

Figure 1.4: A schematic diagram of the terms "Azimuth" and "Altitude" as they relate to the viewing of celestial objects. (Source: Horizontal coordinate system Wikipedia)

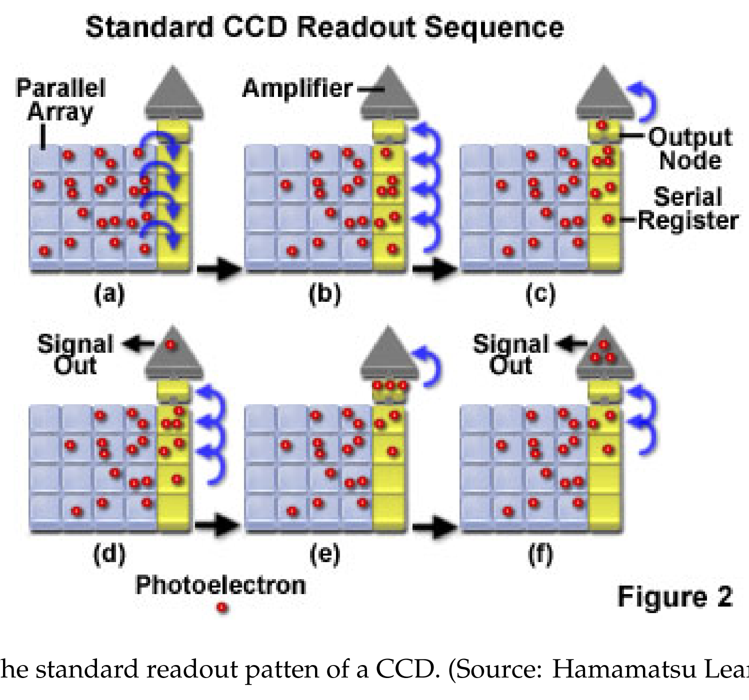

Figure 1.5: The standard readout patten of a CCD. (Source: Hamamatsu Learning Center)

- **Bias**: positive number added to each pixel as a base, doesn't change from frame to frame or integration time
- **Dark Current**: electron build up with time due to thermal effects
- **Gain**: number of photoelectrons produced per photon
- **Quantum Efficienty** (QE): fraction of photons detected

There are a couple of foundational data types

1. **Bias**: ideally a zero-second image that captures any biases in each pixel
2. **Darks**: frame with a non-zero integration time, taken with a closed camera shutter
3. **Flats**: frame with a non-zero integration time, taken of a twilight sky or special screen with relatively uniform brightness

where the bias is the base, darks include biases, and flats include darks and biases. Each pixel count in a science frame is calculated as

$$\text{counts} = \text{science} * \text{QE} + \text{darks} + \text{bias} \tag{1.3}$$

where the quantum efficiency is found from the flats. In effect, the actual science from an image is

$$\text{science} = (\text{counts} - \text{dark} - \text{bias})/\text{QE} \tag{1.4}$$

Issues that can be mitigated when taking an image include

- Cosmic Rays
- Bad Pixels
- Saturation

1.3 Photometry

Photometry is the study of astronomical objects using the flux, or intensity of light, collected from an observation, typically with CCDs.

The human eye differentiates between light sources in a logarithmic manner, so astronomers over the ages have developed the Magnitude System with respect to a reference object

$$m_1 - m_{\text{ref}} = -2.5 \log_{10} \left(\frac{F_1}{F_{\text{ref}}} \right) \tag{1.5}$$

where m is the magnitude of an object and F is the flux (units of energy per area per time). The goal of this system is essentially saying "Star is 10 times brighter than reference" is equivalent to "Star is 2.5 magnitudes brighter (lower number) than reference".

Usually, filters are placed in front of the detector to capture light at a specific wavelength range. There isn't one set system, and each filter will usually not be known perfectly.

To calibrate a star to an absolute magnitude and absolute flux count, a reference star with a known flux should be measured first. Thankfully, there are plenty of already measured fluxes of relatively stable stars from astronomer Arlo Landolt, referred to as Landolt stars. These are useful to convert a pixel flux count to an energy per unit area per unit time.

However, stars aren't just one pixel, they take over many pixels. How do we assign a pixel region to a star? In general, there are two methods

1. **Point Spread Function (PSF) Photometry**: apply a 2D Gaussian function, very precise but tricky because the function needs to be chosen correctly
2. **Aperture Photometry**: measure counts in a circular aperture, subtract sky background from a larger circular annulus, and place buffer. use different aperture/annulus sizes for robust science analysis

1.4 Statistics

The Central Limit Theorem states that for a distribution with a 1) random sample, 2) samples are independent from one another, and 3) there is a large sample size, the distribution tends to a normal / Gaussian distribution

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{\frac{-(x-\mu)^2}{\sigma^2}\right\} \tag{1.6}$$

where the variance and mean of the distribution are σ^2 and μ.

The Poisson distribution describes a sample of counting objects, which is valuable for photon counting errors

$$P(k) = \frac{\lambda^k \exp\{-\lambda\}}{k!} \tag{1.7}$$

where the variance and mean of the distribution are both λ. For large λ, this tends to a normal distribution.

When an astronomical dataset is limited by the photon noise, the Signal-to-Noise (S/N) is best described using the standard error analysis of the propogation of errors, resulting in

$$\mathrm{S/N} = \frac{\mathrm{R_* t}}{\sqrt{\mathrm{R_* t}}} \tag{1.8}$$

where t is the time of integration and R_* is the count rate of a star.

However, when things go south and systematic errors need to be taken into account, the almighty CCD equation is used

$$\mathrm{S/N} = \frac{\mathrm{R_* \times t}}{\left((\mathrm{R_* \times t}) + (\mathrm{R_{sky} \times t \times n_{pix}}) + ((\mathrm{RN}^2 + (\frac{\mathcal{G}}{2})^2) \times \mathrm{n_{pix}}) + (\mathrm{D \times t \times n_{pix}})\right)^{1/2}} \tag{1.9}$$

Variable	Description	Units
R_*	Count rate from star	e$^-$/ second
R_{sky}	Count rate from background	e$^-$/ second / pixel
t	Exposure time	seconds
r	Radius of aperture	pixels
n_{pix}	Number of pixels in aperture	$\pi \times r^2$
$\mathcal{G}$	Inverse gain	e$^-$/ DN
D	Dark current	e$^-$/ second / pixel

Table 1.1: Parameters for the CCD Equation

Table 1.4 describes the variables in CCD equation needed. In the denominator in the CCD equation, from the left to right, the terms cover

- Poisson noise from star
- Poisson noise from sky background
- Gaussian read noise (including digitation noise)
- Poisson noise from dark current

To estimate whether a sample is a good fit to a model, astronomers use chi-squared as a proxy

$$\chi^2 = \sum \frac{(x_i - e_i)^2}{e_i} \tag{1.10}$$

where x_i is the observed value and e_i is the expected value. Another diagnostic tool is the reduced chi-squared, which is the chi-squared divided by the degrees of freedom (number of data points – number of model parameters).

1.5 Spectroscopy

"A Picture is Worth a Thousand Words. A Spectrum is Worth a Thousand Pictures."

Imaging is taking brightness of a part of the sky, where the data is position vs position and each pixel value corresponds to some flux value. Spectroscopy replaces one position dimension with the wavelength of the light of the remaining position dimension.

Kirchoff's Laws of Spectroscopy, described in Figure 1.6, describe the properties of observed spectra:

1. A solid, liquid, or dense gas excited to emit light will radiate at all wavelengths producing a **continuous spectrum**.
2. A low-density gas excited to emit light will do so at specific wavelengths producing an **emission spectrum**.
3. If light composing a continuous spectrum passes through a cool, low-density gas, the result will be an **absorption spectrum**.

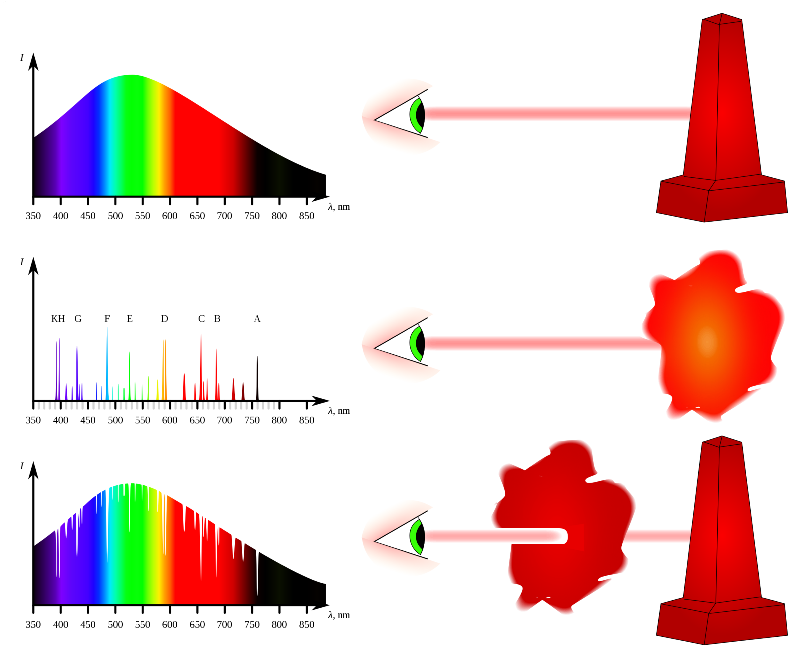

Figure 1.6: Kirchoff's Three Laws of Spectroscopy (Source: Gustav Kirchhoff Wikipedia)

To take a spectra of an object, a slit is placed to limit the light from the sky that goes into the detector to that of only the object. The slit has some "width" attributed to it. To further limit the light, a decker can be placed on top of the slit, acting as the "length" of the image. A common light path is shown in Figure 1.7 where light takes the path

1. Light is limited by decker and slits
2. Light is "straightened" out by a collimator (mirror or lens)
3. Light is "spread" out by a grating or prism
4. Light is focused by a camera lens or mirror
5. Light hits detector

To ensure that spectra aren't overlapping, the slit is usually orthogonal to the dispersion before it hits the grating or prism. Typically, there is a dichroic mirror that splits the "red" and "blue" light between steps 1 and 2. This way, astronomers can concentrate on a certain region of light or take two spectra of the same object simultaneously. Also, instruments usually have a filter wheel in front of the collimator between steps 2 and 3 to look at specific wavelengths. The use cases are specific to the science goals of the observation.

Cutting down and limiting the amount light of an observation doesn't take full advantage of the resources at hand. A CCD will be mostly empty. With preparation, astronomers prepare large slit masks where they expect objects to fall. A diagram showing off this ability is shown in Figure 1.8. This way, we can take full advantage of a telescope's capabilities, resulting in a multi-object spectra on the detector. However, this process requires fabrication of a slit mask, and is observation-specific.

The most comprehensive (time-independent) study of an object is done by taking into account the 2D spatial distribution and the wavelength spectrum. This is the goal of Integral Field Spectrographs: create a

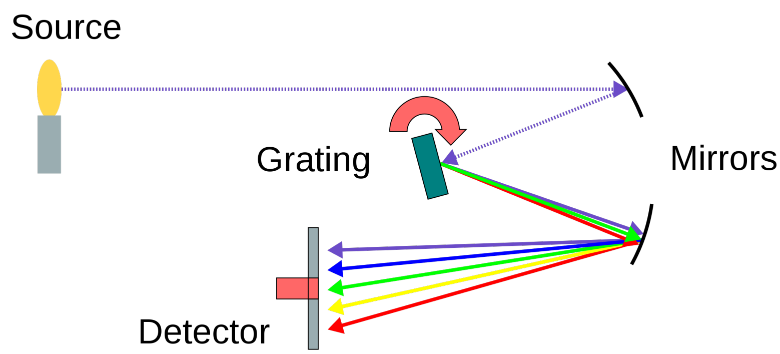

Figure 1.7: Spectrometer Schematic (Source: Optical Spectrometer Wikipedia)

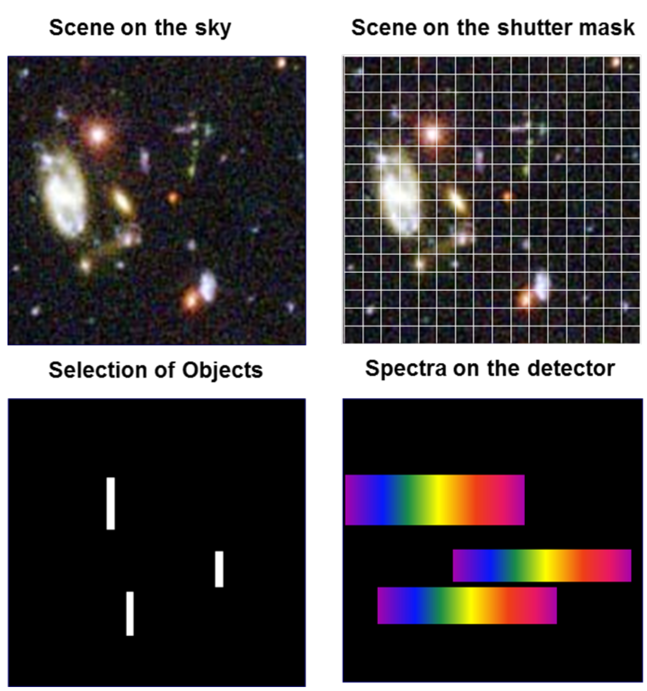

Figure 1.8: Diagram of a multi-object spectrometer (Source: Multi-Object Spectrometer Wikipedia)

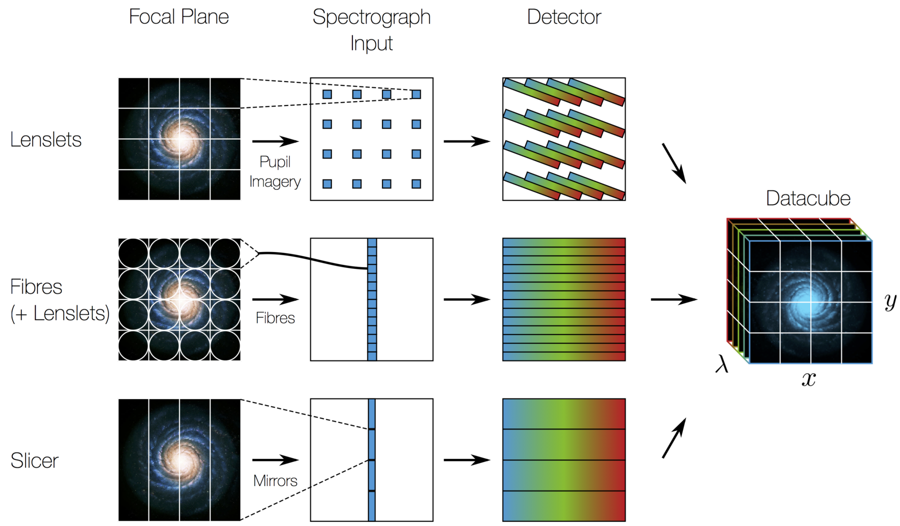

Figure 1.9: Methods to construct an integral field spectrograph unit (Source: Integral field spectrograph Wikipedia)

spectrum at each pixel. Figure 1.9 describes three methods of accomplishing this goal. These datasets are extremely useful, but the spectral resolution is usually much less than that of traditional spectrographs.

1.6 Adaptive Optics

Over the last couple decades, instruments have become so precise that what is most limiting to an observation is no longer instrument dependent, but atmospheric turbulence, which results in "seeing". This is what causes the "twinkling" of stars at night.

The result of atmospheric turbulence is that plane waves (which is a good approximation for the sort of light reaching Earth from far away objects like stars) are perturbed with wavefronts no longer being parallel. A collimator won't produce a good spectra.

To increase sharpness of astronomical images, instruments use a **deformable mirror** (wild ?!) to correct atmospheric turbulence with a reference star that astronomers know is close to a single point. The idea, shown in Figure 1.11, is that we know how this reference star looks like, and can use very tiny pistons and quick computers to deform a mirror. Typically, the pistons are so quick to make wavefront corrections at a rate of around a thousand a second.

In practice, the reference star is a bright star near to an object being observed. However, over the last couple decades, technology has been developed to create a laser that can excite sodium atoms in the atmosphere and create an *artificial* reference star. This layer of sodium in the atmosphere is high enough in altitude such that it is effected by atmospheric turbulence.

With adaptive optics (AO) being used, astronomers are now limited by the speed of correction. The deformable mirror is usually placed where the dichroic is.

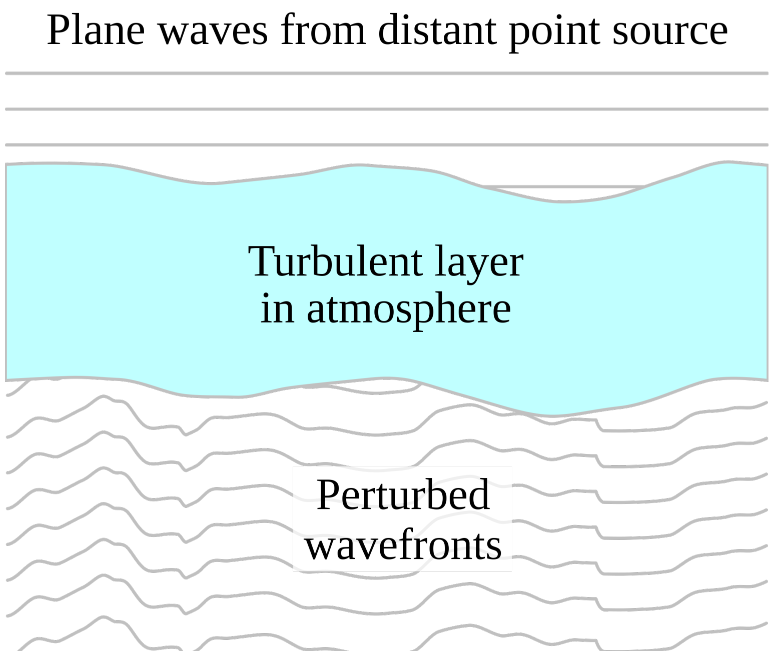

Figure 1.10: Schematic of what occurs to plane waves through the atmosphere (Source: Astronomical seeing Wikipedia)

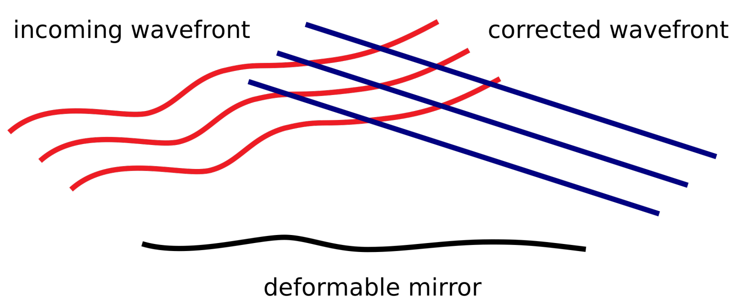

Figure 1.11: The goal of a deformable mirror is to get back the plane waves from a distant source (Source: Adaptive optics Wikipedia)

Section 2: Observing Practices

Contributors: *Diego Garza*

2.1 Observing Preparation

The goal of preparing for observing is to limit the amount of on-the-spot decision making required, but also be ready to make those decisions. This is why an observing preparation document is useful, which should include

- Where is the object (IRSA Finder Chart)
- When is the object observable: ephemeris (JPL Horizon) and airmass tables (Hourly Table)
- Instrument Configurations
  - Filters
  - Integration time
  - Slit width, decker length, dichroic
  - Grating, grating tilt
- Specify the telescope and instrument limits
  - RA limitation
  - DEC limitation
  - Zenight angle of limitation
  - Saturation
- Be aware of telescope/observation safety practices
  - Weather limits (Wind, Humidity, Ash, Lightning, Clouds)
  - Astronomer on call

Telescopes and observatories usually have a manual with guides on how to best prepare, but these are general things to be aware of. Furthermore, observers need to prepare what calibration data needs to be taken before science collection including

1. Darks
2. Biases
3. Flats (Twilight vs Dome screen)
4. Focusing
5. Lamps (wavelength calibration)
6. Guide star (artificial vs natural)

2.2 Observation Logs

Astronomers want to limit the amount of problem solving and hassle when actually observing, but a valuable trait (when looking back on the data in the future) is the ability to document. An observing log should cover all the information to piece together what observations happened when after an observing session. The goal is to be organized and prepared to know if there are any mistakes that occurred. Observing logs should have

- Observer(s)
- Local Time and UTC at start of exposure integration
- Observation number
- Object or file name
- Exposure or integration time
- Filter
- Slit width, decker length, grating, grating tilt, dichroic, collimator
- Seeing
- Comments

To best prepare, an expected observation log should also be created.

2.3 Techniques, Expectations

Each observatory and telescope will have its own observation checklist. In general, observers should expect to complete a general list of tasks before the start of any observations

- Check weather against limits
- Open the dome
- Turn on any fans
- Lower the windscreen
- Open mirror cover
- Focus camera lens

Most observatories are built at a high elevation, so it will get cold and their heaters will be off to limit any thermal noise. Bring appropriate clothes and blankets (:

When observing, observers should understand how to take a quick test exposure and linearly extrapolate the expected counts against the integration time the observers prepared for. If I expect to take a 120 second exposure, I can take a 20 second test exposure and linearly extrapolate the test exposure to a 120 second exposure. To make these tests, the observer should understand what counts they need for their science objective.

Section 3: Data Reduction

Contributors: *Diego Garza*

The goal of data reduction is to have a calibrated image dataset. There are three types of astronomical data

1. spatial vs spatial (photometry)
2. spatial vs wavelength (spectroscopy)
3. spatial vs spatial vs wavelength (integral field spectroscopy)

3.1 Standard Calibration

Standard calibration refers to getting rid of dark current from the CCD and biases that were filled onto a CCD's wells. Since a dark frame will already have the counts from the bias, the relationship between the science data and the actual counts measured is

$$\text{science} = (\text{counts} - \text{dark}) \tag{3.1}$$

To also take into account the *relative* quantum efficiency of pixels, we divide by the normalized flat field

$$\text{science} = (\text{counts} - \text{dark})/\text{flats} \tag{3.2}$$

In practice, the flats and science images are not necessarily of the same integration time, so both are divided by their respective integration time. In effect, the result will be a science rate image.

To convert to a sky separation, instruments have a pixel to arcsecond plate scale.

To limit the effect of cosmic rays, observers will usually dither the telescope by a small amount, and take the median average after stacking.

3.2 Flux Calibration

The magnitude system

$$m_1 - m_2 = -2.5 \log_{10} \left(\frac{F_1}{F_2} \right) \tag{3.3}$$

uses fluxes that are of the same units. To use a photon pixel count to convert to a magnitude, a reference m_2 magnitude and F_2 flux are needed. For example, m_2 is set to 0 with the bright star Vega. So observers point their telescope to Vega and use the total photon pixel count as flux for that star.

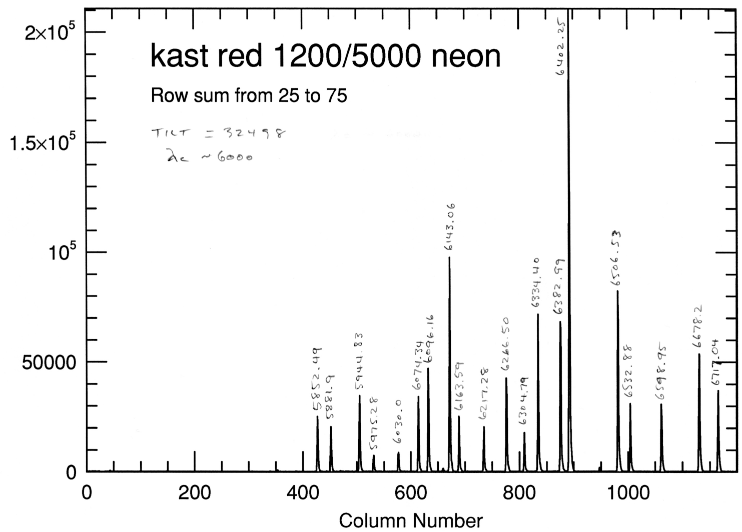

Figure 3.12: Example calibration lamp spectra from the Kast Double Spectrograph at the Shame 3-meter (Source: Shane 3-meter manual)

3.3 Wavelength Calibration

A spectra will look differently on a CCD detector depending on the instrument configurations (usually dichroic and grating). How spread out a spectra is and the wavelength coverage can be gathered from a telescope's calibration lamp spectra. An example shown in Figure 3.12.

The goal is to take a sample spectra of an observatory's calibration lamp using the configurations set. Then wavelength comparison can be done by looking at relevant strength of lines to convert from a pixel to a wavelength value.

3.4 RGB Images

A true color image is created when an image reproduces results that are representative of what a human eye would see. However, humans can't see all parts of the electromagnetic spectrum. To visualize a patch of the sky in those other parts, astronomers create a false-color image that assigns red, blue, and/or green to different parts of the electromagnetic spectrum. Most astronomical images are false-color images to emphasize different features caught from the electromagnetic spectrum.

3.5 General Tips

Working with lots of data files can get overwhelming and using different methods to calibrate can make the analysis portion easily get out of hand. So here are a couple useful tips (from Professor J. Xavier Prochaska and my experience)

1. Organize data file names in simple lists and directories (like observation dates or filters used)
2. Create a method to stack a set of files (with the ability to subtract a given bias)
3. Create a method to calibrate and process an image
    - Return the processed data and a header
    - Bias and flats should be passed in and used
    - Option to create and save a FITS file
4. Make conservative cuts to get rid of junk
5. Write final images to disk
6. Make modular python scripts to facilitate short notebooks
7. View images as they are generated
8. Beware of NANs ... they're scary
9. Document (docstrings, comments, markdown) work to be easily legible months after use

Not everything needs to be practiced perfectly, but the development towards efficient coding practices is a helpful skill in astronomy.

Section 4: Writing Practices

Contributors: *Diego Garza*

I am combining the observations and reductions section here. If lots of calibration and manipulation is completed for an image that isn't part of standard calibrating procedures, a separate reduction section is warranted. Most of the time, it can be a subsection under observations.

The goal of an observing section is to provide all of the details required for another astronomer to interpret and/or reproduce the observations.

4.1 Required Information

An observing section should include

1. Date of observation
    - Date should be in UTC
    - Time should be included if it is relevant
2. Observatory / Telescope / Instrument
    - Brief description of instrument
    - Avoid links to telescope manuals as they can become out of date
3. Instrument Configuration
    - Filter, grating, slit, decker, dichroic used
    - For movable items, provide position/tilt or central wavelength
    - Field of view and plate scale of instrument
    - Detector configuration (binning, windowing)
4. Weather Conditions
    - No clouds is "photometric", else "spectroscopic" conditions
    - Mention cloud types if relevant
    - Describe the seeing in arcseconds
    - Mention nearby bright objects that may bleed into observation (moon)
5. Calibrations taken
6. Observation Description
    - Name of object and position in RA and DEC
    - Abnormal instrument setups
    - Number of exposures
    - Time of exposure

7. Reduction Process
    - Statement saying darks, bias, and flats were used on data
    - Any other calibration (wavelength)
    - How artifacts or background noise was removed
    - How multiple exposures were stacked

With multiple objects or configurations, a table may be appropriate.

Instrument configurations should be paired with a motivation for those choices.

At the end of the observation and reduction description, there should be a final image or spectrum. This final figure should have a compass, be captioned, and with any necessary legends.

4.2 Personal Workstyle

I have a couple tips that I have adopted as I have written a couple labs on Overleaf

- Use the AASTex class file to emulates the style of The Astrophysical Journal (ApJ)
- Use the Facilities and Software command to share that information
- Use the texttt command to write something in `code` format
- Be as blunt and straight-forward as possible
- Create a new command for placeholder citations you will find later
- Very rarely is a figure too large. It is much more common for a figure to be too small

There should be a total of two documents

1. Observing Preparation Document
2. Observing Log

A well-documented observing session will have all of the required information in these documents and the justification for their choices.

4.3 Proposal Writing

The final lab for this course was a JWST proposal's technical section. The goal of this document is for the time allocation committee (TAC) to determine if the observing plan 1) is likely to achieve the science goals, and 2) requesting the appropriate amount of time.

Technical sections should include

1. Science goal reiterated in a sentence or two

2. Every instrument configuration and its justification (both optics and detector setups)
3. Table for multiple sources (position and instrument configuration for each)
4. Estimate of integration time (instrument may have an Exposure Time Calculator)

A good proposal will include model / expected observations.

References