Photometry and Spectroscopy

Learners' Space Astronomy

Contents

Astronomical Photometry

1.1 Unveiling the Radiant Energy of Celestial Objects

Astronomy, the study of celestial objects, relies heavily on the analysis of electromagnetic radiation they emit. This module explores the quantitative measurement of this radiation, specifically focusing on the visible and near-visible wavelengths, crucial for astronomical photometry.

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Key concepts to grasp are:

- **Luminosity(L)**: The intrinsic power emitted by an object as electromagnetic radiation, measured in Watts (W).

- **Radiant Flux (f)**: The rate at which this radiant energy flows through a unit area, typically expressed in Watts per square meter (W/m^2).

$$\mathrm{L} = 4\pi R^2 \mathrm{f}$$

[where R refers to the stellar radius i.e. the distance between the source and the point where flux is being calculated]

- **Inverse-Square Law**: This fundamental law dictates that the intensity (I) of radiation received from a source diminishes with the square of the distance (d) from the source, following the equation $I \propto 1/d^2$.

- **Absolute(M) and Apparent(m)** Magnitude: the measure of brightness of the object as it appears on Earth from its actual distance is referred to as Apparent Magnitude(m) while Absolute Magnitude represents what the brightness of .It is found using a special logarithmic system and found relative to a star of known brightness with

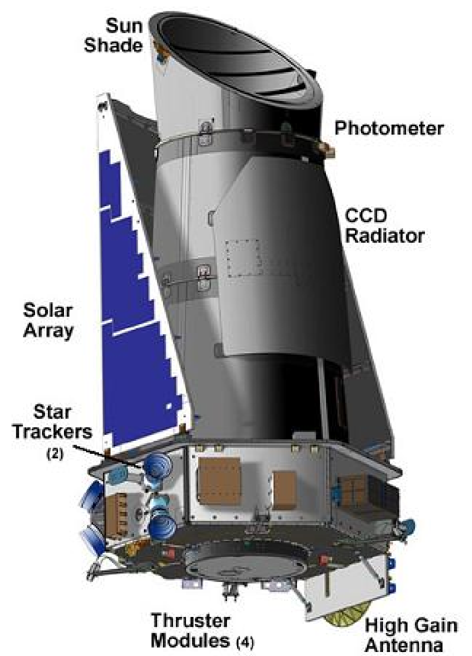

Figure 1.1: Image depicting the photometer on the Kepler Space Telescope which was it's sole scientific instrument

`Pogson's Equation:`

$$m_2 - m_1 = -2.50log(B_2/B_1)$$

[where B_1 and B_2 represents the brightness(Flux) of the objects while m_1 and m_2 represent their apparent magnitudes]

1.2 Demystifying Stellar Brightness: *Magnitude Systems and Calibration Stars*

Directly measuring a star's total radiant flux is challenging. Astronomical photometry overcomes this by employing standardized filter systems. These filters isolate specific wavelength bands within the electromagnetic spectrum, allowing us to focus on features of interest within the object's light signature. Common filter systems include the Johnson-Morgan-Cousins [Ultraviolet-Blue-Violet-Red-Infrared] (UBVRI) and Sloan Digital Sky Survey [Sloan Digital Sky Survey](SDSS) systems.On how these wavelengths are filtered, you can fin that information in `MODULE 5`.

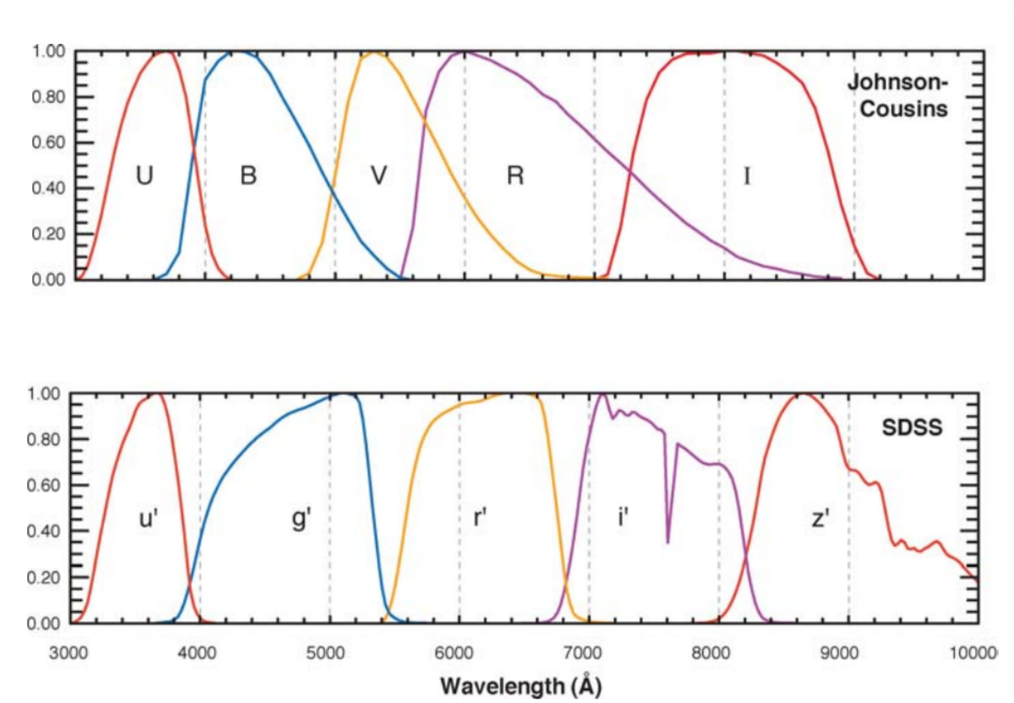

Figure 1.2: Filer System Passbands for UBVRI ans SDSS systems.

SDSS has been in more widespread use today as it has higher transmission,broader bandwidths and much less overlap than what you'd get with UBVRI.

Calibration is paramount for accurate photometry. We rely on standard stars, celestial objects with precisely measured apparent magnitudes, to convert instrumental magnitudes obtained from our specific telescope and detector setup into true astronomical magnitudes.Some examples of these are *Cepheids* and *Supernova las*. These are also referred to as **Standard Candles**. More on these is given in our *Distance Ladder* module. But we'll cover details relevant to photometry later on in this module as well.

By comparing our observations of these standard stars with their known values, we can calibrate our instruments and derive the true brightness of our target object.we'll cover details relevant to photometry later on in this module.

1.3 Unveiling the Secrets: *Data Reduction and Instrumental Effects*

Once the data is acquired, meticulous noise reduction techniques are employed to extract the true signal from the raw data. This involves removing unwanted noise caused by factors like cosmic rays, detector dark current, and sky background emission. Sophisticated software tools are employed to correct for these effects and isolate the light emanating from the celestial object of interest.

Furthermore, no instrument is perfect. Telescopes and detectors introduce their own subtle biases and limitations. Understanding these instrumental effects is essential for accurate photometry. Techniques like *flat-fielding* (correcting for spatial variations in detector sensitivity) and *dark current subtraction* (accounting for thermally generated electrons in the detector) are employed to mitigate these systematic errors, ensuring reliable measurements.

1.3.1 Flat Fielding and Dark Current Subtraction

To know what Flat Fielding is We should first study about Gains, Offsets and Dark Currents.

Gain:

- In CCD/CMOS imaging, *gain* refers to the magnitude of amplification a given system will produce. *Gain* is reported in terms of electrons/ADU (analog-to-digital unit). A gain of 8 means that the camera digitizes the signal so that each ADU corresponds to 8 photo-electrons.
- ADU corresponds the the digital value which the computer can process as being proportional to the photo-electrons falling on the MOS. This helps to calculate the brightness the pixel will have in the image. More details on this are given in `MODULE 3`.
- Now, generally in a CCD, you have uniform gains for every pixel, but in CMOS, gains for every pixel can be varied which may give you more control in image processing but this increases the noise level as each pixel now has its own amplifier and circuitry.
- Also in general, when you increase the gains, say 4x, `(done when the sensor is photon starved and high sensitivity is required)` you also amplify the noise levels. Now you want the Signal/Noise level to be as low as possible. This is where Flat Fielding comes in.

Offsets:

- Every digital image sensor has light-insensitive cells next to the active image area. These dark pixels are used to measure a reference voltage (black level) which is subtracted from the image signal. This compensates thermally generated voltages on the sensor which would otherwise falsify the signals.

- Normally, the sensor adjusts the black level automatically. If the environment is very bright or if exposure times are very long, it may be necessary to adjust the black level manually.

Dark Currents:

- Dark current is defined as the current flowing through the detector when there is no incident photon flux. This may be due to to thermionic emissions or leakage current. The dark current is an important parameter because it determines the base current level that photo-current must exceed in order to be detected.

- Dark current is one of the main sources for noise in image sensors. The pattern of different dark currents can result in a fixed-pattern noise.

  `[ FPN (also called non-uniformity) is the spatial variation in pixel output values under uniform illumination due to device and interconnect parameter variations (mismatches) across the sensor].`

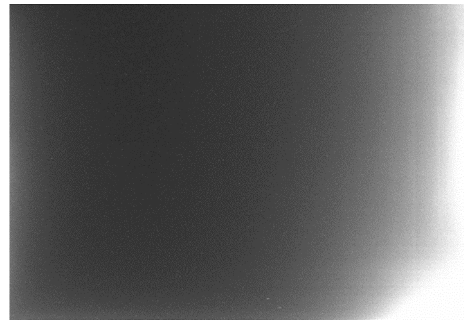

Figure 1.3: Thermal build-up and dark current noise at the edges of a camera sensor. This noise will spread across the camera as the heat increases over long exposures and will impact image quality.

- It is fixed for a given sensor, but varies from sensor to sensor, so if v_0 is the nominal pixel output value (at unifrom illumination), and the output pixel values (excluding temporal noise) from the sensor are v_{ij} for $1 \leq i \leq n$ and $1 \leq j \leq m$, then FPN is the set of values

$$\Delta v_{\text{oij}} = v_{\text{oij}} - v_0$$

- FPN consists of offset and gain components – increases with illumination, but causes more degradation in image quality at low illumination. CMOS (PPS and APS) sensors have higher FPN than CCDs and suffer from column FPN, which appears as "stripes" in the image and can result in significant image quality degradation.

- Unlike CMOS, CCD image sensors only suffer from pixel FPN due to spatial variation in photo-detector device parameters and dark current.

- *dark frame subtraction* can remove an estimate of the mean fixed pattern, but there still remains a temporal noise, because the dark current itself has a shot noise(noise due to the discrete nature of electric charge). You can read about it more on:

  https://www.rp-photonics.com/shot_noise.html

- To know more about FPN and get into the maths of it, Here are some lecture notes from Stanford about it:

  https://isl.stanford.edu/~abbas/ee392b/lect07.pdf

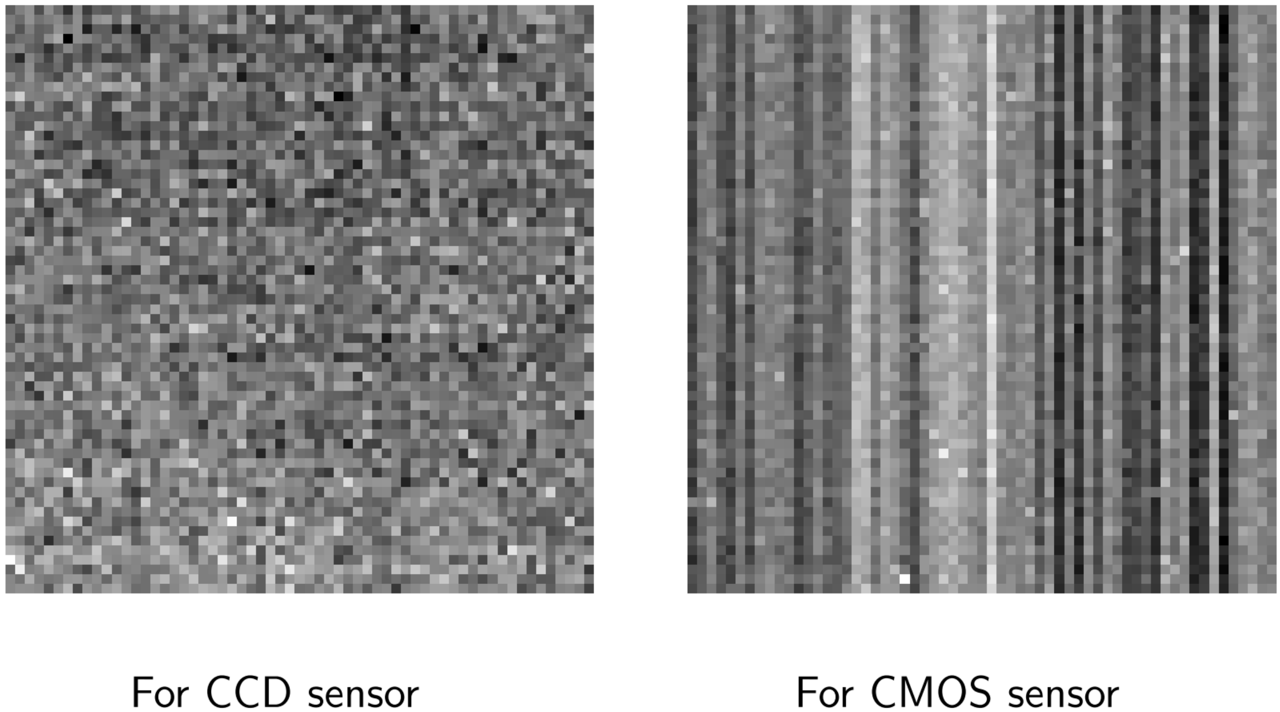

Figure 1.4: Images showing Fixed pattern Noise for CCD and CMOS.We can especially see the column FPN for CMOS as the readout circuits for CMOS are different for every column

- The solution is to expose the chip to a uniform level of light and record its response. If we know that the same amount of light strikes each pixel, but measure different pixel values, we can determine the relative sensitivity of each pixel. The usual method is to normalize the pixel values to the mean level over the entire frame
- Then, before we start to measure the properties of stars on a target image, we can correct each pixel's value for this relative sensitivity by dividing the measured pixel value by its pixel's relative sensitivity
- one must create a flat-field frame for a camera/filter combination, and then divide by the flat-field to correct for pixel-to-pixel variations in sensitivity.
- More about Flat frames and how to get them is given in `MODULE 4`.You can also refer to the link here for more info:

  http://spiff.rit.edu/classes/phys445/lectures/darkflat/darkflat.html

1.4 The Power of Astronomical Photometry*: Unveiling the Universe's Mysteries*

Astronomical photometry serves as a cornerstone for unlocking the secrets of the cosmos. Here are a few examples of its diverse applications:

1.4.1 Stellar Evolution

By meticulously studying the variations in a star's brightness over time (light curves), astronomers can track its evolutionary stages. From hot, luminous blue giants to cooler, red dwarfs, photometry helps map the life cycle of stars.

`Figure 1.5` depicts a luminosity vs time graph of a variable star. The time period of the star can be found through this graph which when compared to other known stars gives us its physical properties like mass and radius.

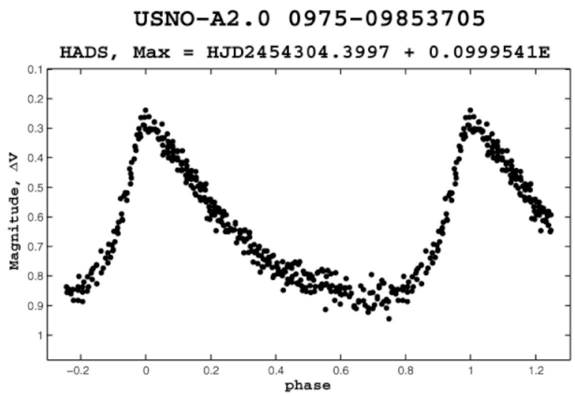

Figure 1.5: Absolute Magnitude vs time for Delta-Scuti(Cepheid like Variable stars).

1.4.2 Exoplanet Detection

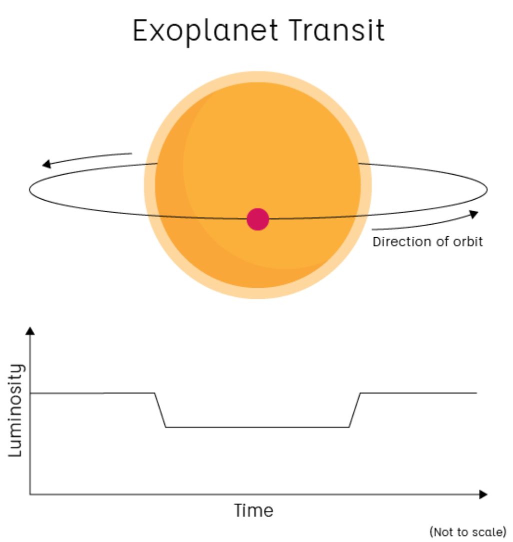

Figure 1.6: Image depicting a planet passing in front of it's star form the viewer's perspective resulting in slight dimming of light which can be observed through a graph `[this is a simplified version of the graph]`

- The transit method, a cornerstone technique in exoplanet discovery, relies on precise photometry. When a planet transits its host star, a minute dip in the star's brightness occurs, allowing astronomers to detect the presence of an orbiting exoplanet.
- This dimming can be seen in light curves – graphs showing light received over a period of time. When the exoplanet passes in front of the star, the light curve will show a dip in brightness.
- The size of the exoplanet's orbit can be calculated from how long it takes to orbit once (the period), and the size of the planet itself can be calculated based on how much the star's brightness lowered.

1.4.3 Galaxy Classification and Cosmology

- Photometry plays a crucial role in classifying galaxies and studying large-scale structures in the universe. By measuring the overall brightness and color distribution of a galaxy, astronomers can determine its type (spiral, elliptical, etc.) and gain insights into its formation and evolution.

- Measuring the spatial distribution of brightness within the galaxy rather than simply measuring the galaxy's total brightness is what we are looking to do here. An object's surface brightness is its brightness per unit solid angle as seen in projection on the sky, and measurement of surface brightness is known as `surface photometry`.

- Additionally, photo-metric red-shifts, estimated distances based on a galaxy's spectral energy distribution, aid in mapping the large-scale structure of the universe.

1.5 Complications

The atmosphere is part of our 'Optical system', so although you'll find `m` easily but finding `M` involves removing the irregularities caused by factors such as the atmosphere, Cosmic Rays etc.

- Scintillation noise(flickering of light) due to the Earth's turbulent atmosphere can be a dominant noise source in high-precision astronomical photometry when observing bright targets from the ground.

- the era of wide field surveys means that the well calibrated magnitudes are available for large number of stars all over the sky.There are many stars in our exposure that can be used for flux calibration here.

1.6 Beyond the Basics: Aperture Photometry and PSF Photometry

We'lll delve deeper into various other methods of Photometry. We have already discussed relative photometry and surface photometry in some details, we'll delve deeper into some other types in this section.

1.6.1 Aperture Photometry

- A well-established technique that measures the flux typically, but not necessarily within a defined circular aperture centered on the target star.
- It involves subtracting the sky background contribution calculated with the help of a surrounding annulus and choosing an optimal aperture size to maximize the signal-to-noise ratio.
- use the same aperture to measure the flux from a standard star (remember `Dogson's formula here`).Sometimes A light growth curve is used to account for the light that gets scattered during its travel.
- Different sized aperture are used in case the standard is much bigger than the target. Aperture correction(`a scaling factor`) is used for such cases.

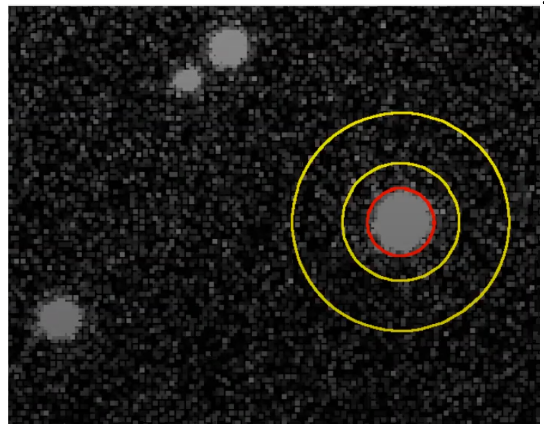

Figure 1.7: The red ring depicting the aperture that measures the flux and the yellow rings show the aperture used to calculate background noise and subtract it.the size of the yellow ring is decided to reduce the noise-to-signal ratio [NSR].

$$\boldsymbol{Signal} = \Sigma\ obj_{ij} + sky_{ij} - \boldsymbol{NB}$$

`[where N represents the number of pixels ans B the sky background(per pixel) noise that needs to be removed]`

However, it can be challenging for crowded stellar fields where stars are closely spaced.

1.6.2 Point Spread Function (PSF) Photometry

- This is a more sophisticated technique designed for crowded fields. Stars are treated as Point source here and their resolution is too low for us to resolve their apparent size.
- It utilizes a model of the telescope's point spread function (PSF),which describes how light from a point source (ideally a star) is spread out on the detector due to factors like diffraction and atmospheric seeing.
- By fitting the PSF model to each star in the image, astronomers can separate the light from individual stars and perform accurate photometry even in dense stellar regions.
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Spectroscopy

Optical and infrared spectroscopy are two powerful tools used by scientists to study the composition of materials. They both involve shining light on a sample and analyzing how the light interacts with the material. However, they use different regions of the electromagnetic spectrum to do this. We will be looking at application of spectroscopy in astronomy. The spectra acheived using spectroscopy can provide information about astronomical bodies such as their:

- Temperature
- Composition
- Line-of-sight velocity

2.1 Principle of working

The process depends on the phenomenon of dispersion of light to get a spectrum of wavelengths with various intensities. Optical instruments such as a Prism, Grating Mirror or Grating spectrometer are used to get this dispersion. Grating mirrors and spectrometers work on the principle of diffraction and interference of light. Thus, the spectrum is achieved in the form of intensity vs wavelength and position. The tabular 2-D data is worked on to filter the noise due to the sky or background. The 1-D data is standardised against lamps of known wavelength and stars of known intensities to calibrate wavelength and intensity, respectively.

2.2 Setup

The setup, as explained earlier is shown below:

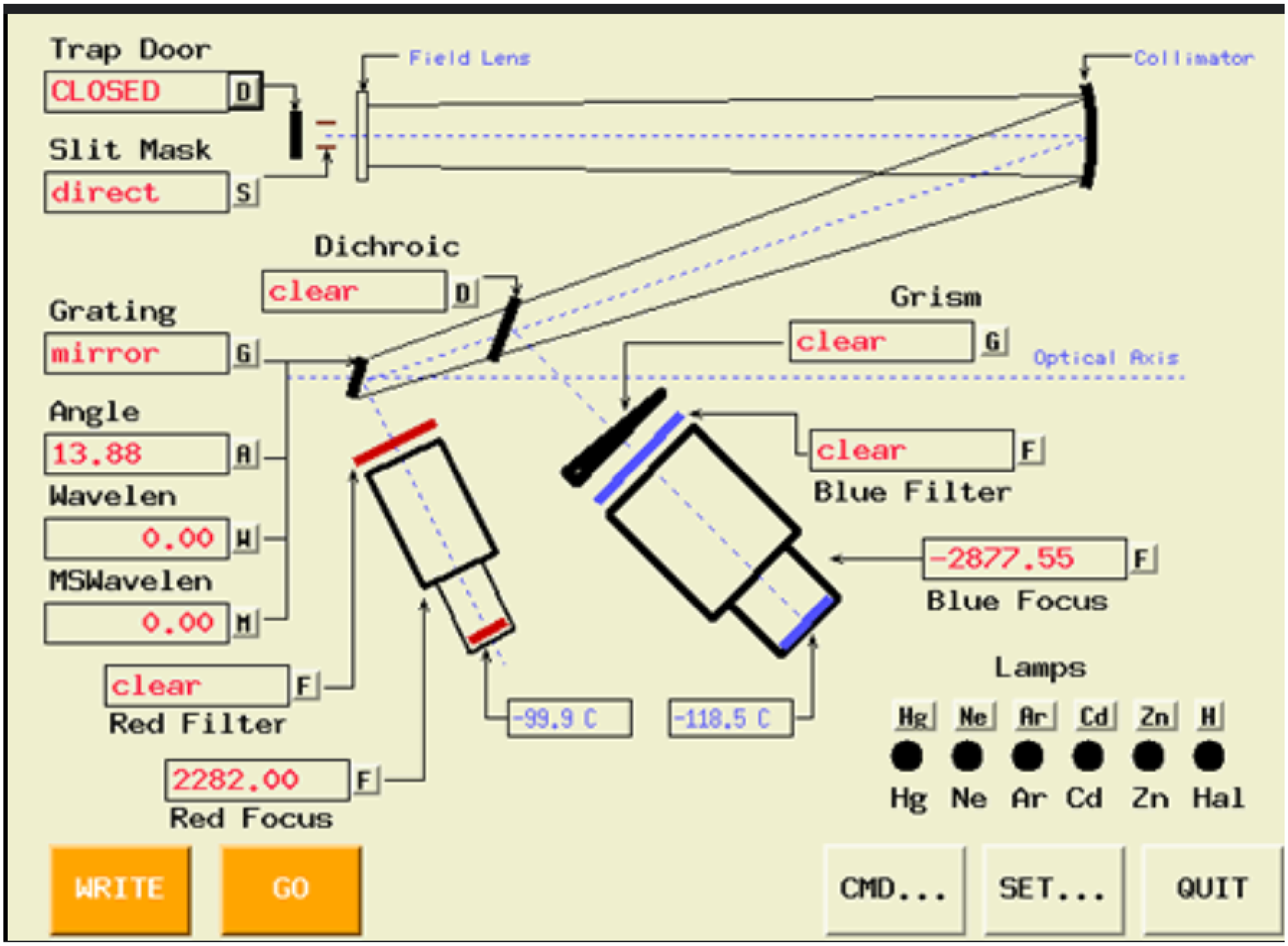
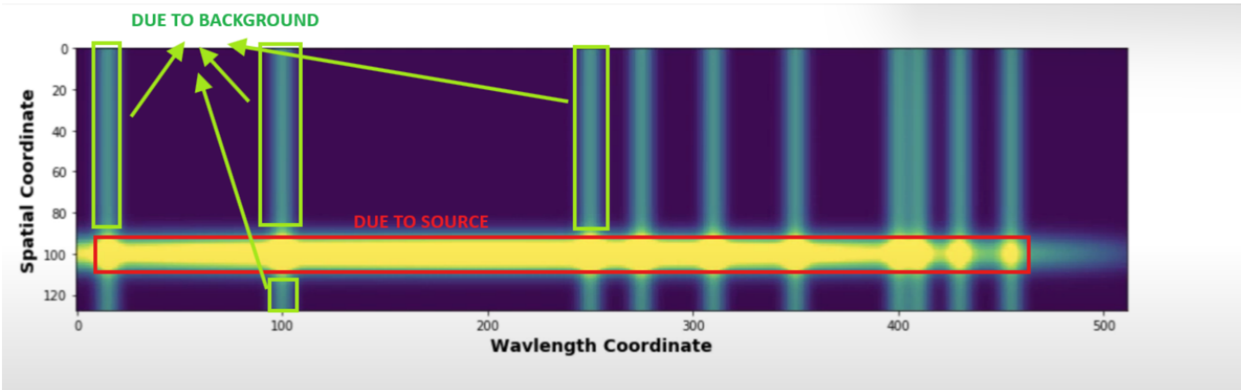


Figure 2.1: LRIS

2.3 Extraction

- Filtering

  The data received from spectrometers is 2-D dataset of intensities vs wavelength and position.



  The background noise can be filtered in Python. First, get the sum of the along column for the region near the source, in our case, near 100 of wdth, suppose 40, and then reduce the noise of width 40 from the region where there is no source.

```
source_and_noise = image.sum[80:120]  #we took width 40
noise=image.sum[20:60]  #we took width 40
source= (source_and_noise - noise).sum(axis=0) # this is a 1-D array of
    intensity vs wavelength
```

- Calibration

  The next step in the process is the calibration of our filtered data. It is done in two steps:

  – Calibration of flux density or intensity:
    The Spectra of a standard star is used to calibrate the the units of intensity of our data.

  – Calibration of wavelength:
    The spectra of lamps of known wavelength are used to calibrate the column index of our data with the wavelength of appropriate unit.