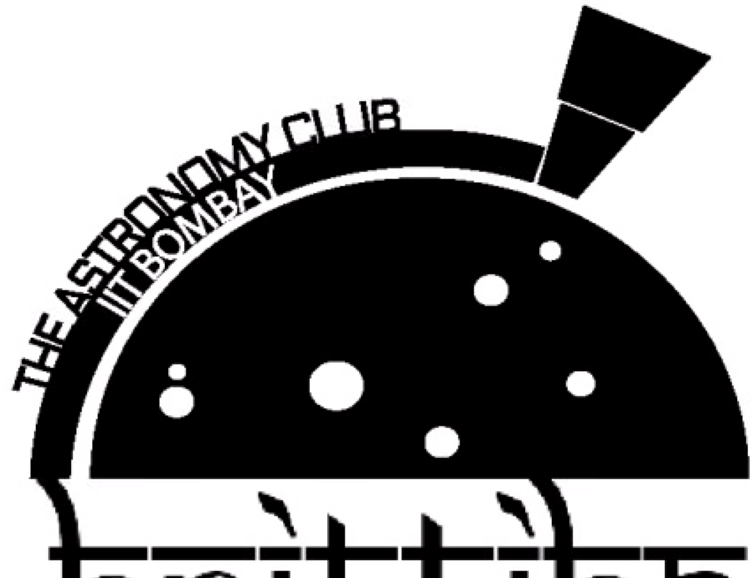
Stacking and Filters

Learners' Space Astronomy



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Stacking and the Use of Filters : Module 4

Krittika

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1 Introduction

The process of combining multiple frames into a single image is called stacking. This process requires significant computational resources and is performed by dedicated software. Usually three different types of image are required for the stacking process: Light frames, Dark frames and Flat frames. The images containing the astronomical motive are called Light frames. Dark frames are images obtained by taking images with a closed lens cap. They do not contain any real image information but merely consist of sensor noise. These images provide important information on the electrical and thermal state of the imaging sensor. The third type of image are Flat frames. They are usually taken against a synthetic white background and help to eliminate effects caused by dust on the sensor and vignetting.

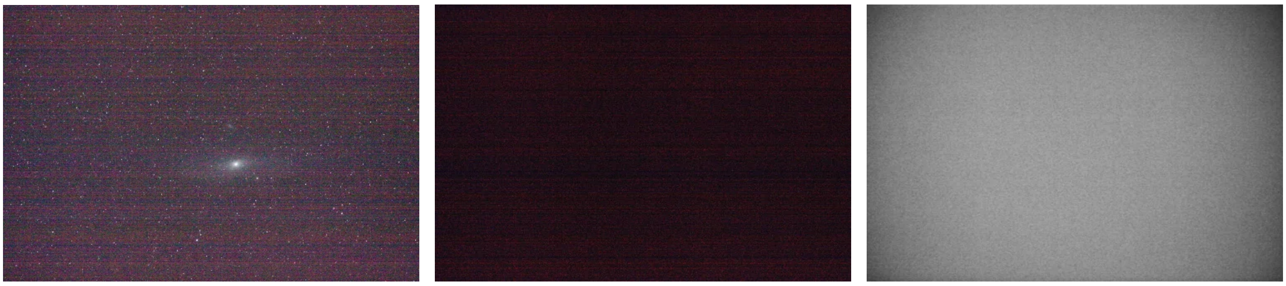


Figure 1: (Respectively, light frame, dark frame, flat frame) Illustrated on a sample image of the Andromeda Galaxy. The Light frame was obtained with 2 seconds exposure time at 200 mm focal length (ISO 12800) The brightness of the darkframe was artificially increased to better show the sensor noise. (In reality it would look almost entirely black) Source

2 Why Process?

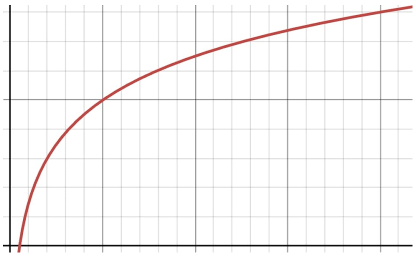


Figure 2: This is what the graph of SNR (measured in dB on y axis) versus number of frames (on x axis) would look like. The nature of the graph is logarithmic. The SNR in non logarithmic units is in general expected to be proportional to the square root of the number of frames

The main problem with stars and things you want to photograph is that they're so dim. Very little light reaches the earth from a dim star, so just pointing one's camera at the sky and clicking the shutter will only capture a few of the brightest stars. Ideally, one wants to leave his/her shutter open for as long as possible, but there are problems with this.

Firstly, the stars move around the sky, so on any exposure above about 15 seconds (depending on the focal length, it can be completely fine as well) the stars will stretch out into curved streaks. This is a cool effect if it's what you're after, but if you want a picture of the sky as it appears to your eyes it's not helpful. The second problem is that digital cameras pick up stray radio signals, cosmic rays, thermal vibrations, aircraft and satellite trails, and all sorts of other things which aren't starlight.

Fortunately, stacking images can get rid of all of these problems and increase the amount of detail visible in return for a little effort.

Roll a dice once and you might get any result from 1 to 6. Roll it a thousand times, and you can be pretty sure the results will average out to about 3.5. If the results average to a different value, you can be fairly sure your dice is loaded. There's no way you could know that from a single roll, but by taking the average of lots of rolls you can see the pattern of behaviour. Your camera works the same way. If you take a single photo in the dark, it will look speckly.

This is because of the random signals, or noise, the sensor picks up. This noise obscures the actual subject of your photo and means you can't tell what is a speckle and what is a dim star.
Taking lots of photos is the equivalent of rolling a dice a lot of times- you are taking a lot of samples of each individual piece of sky and taking the average brightness to eliminate random variations. The average value of a pixel that was pointing at a star will tend to be slightly brighter than a pixel that was pointing at dark sky, but this difference might be smaller than the random variations on any single photo.

In general, the more photos you take, the more uniform the background noise becomes after averaging and the more detail you can pick out. A statistician would say that the averaged photo contains more information than a single exposure- there's more meaningful detail. This is embodied in SNR (signal to noise ratio)

3 More on Frames

3.1 Light Frames

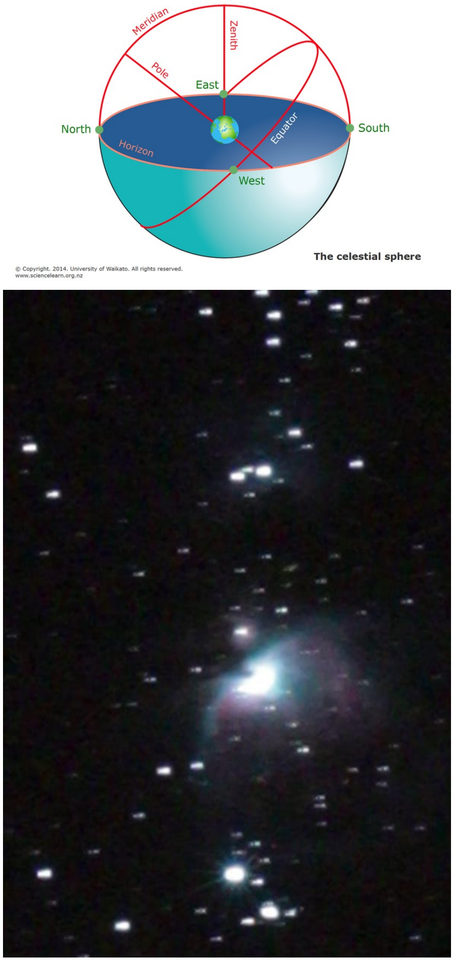


Figure 3: The first image shows the celestial sphere, it can be used to visualise why the angular velocity (as sutended on our eyes) of stars is proportional to the cosine of declination. The latter image shows the streaking that can occur with too high exposure time in untracked AP.

The most important image type are the light frames. Whilst other frame types are used for improving the overall image quality, light frames carry the primary image information. The final image is composed by averaging the light frames. When doing untracked astrophotography you are forced to use high ISO settings. Naturally this comes with a significant increase in image noise. The noise can be so strong that you might not be able to make out the galaxy you wanted to image at all. However, another common type is tracked astrophotography, in which the camera is automatically rotated so that the relative position of the stars on the frame remains the same. This allows for higher exposure times, though the upper limit of exposure times often comes from the fact that the pixels can get saturated if the part of the sky is very bright due to light pollution or otherwise when subjected to a higher exposure time. Why this is better is because more exposure time increases the SNR and for the same final SNR we need lesser frames, which implies a lesser computational cost.

By averaging many light frames the stacking process drastically reduces image noise. The simple rule is: The more light frames, the better the quality of the final image. If you are into signal theory you might know that in an ideal case the signal to noise ratio increases with the square root of the number of images. Unfortunately this also means that to further improve the final image you'll need ever more light frames. In practical terms it means that when doing untracked astrophotography no fewer than 100 light frames should be taken.

The exposure time depends on the objective being used as well as the position of the motive in the night sky. The position is important because at locations closer to the celestial pole longer exposure times are possible due to the less detrimental effect of the apparent motion of the stars. Using exposure times that are too long can cause problems in the stacking process because star trails might prevent proper star detection. This will make light frame position matching impossible thus preventing the stacking at all. **This problem does not arise with tracked photography**

3.2 Dark Frames

Dark frames are images obtained with a closed lens cap. They owe their name to the fact that they are are almost entirely black. Even in the absence of light thermal and electrical effects inside the camera will cause minor signals to be detected by the sensor. Those signals do not carry light information but provide data on the state of the sensor such as a noise fingerprint and hot pixel detection. Hot pixels are pixel defects on the sensor that lead to single pixels always being on (hot). Dark frames are subtracted from the light frames in order to eliminate those effects from the resulting image.

Figure 4: The Rosette Nebula in hydrogen-alpha, before dark frame calibration (left) and with reduced thermal noise after it has been applied (right). Credit: Steve Richards. Source

Dark frames must be obtained with the same camera settings used for getting the light frames (ISO, exposure time). They should also be taken under the same environmental conditions (temperature). To minimize statistic effects a master dark is computed by adding up all dark frames and computing the mean value of each pixel. Due to the high ISO number used for untracked astrophotography the darkframe noise is usually high. Therefore the number of dark frames should also be high in order to compensate for this.

Modern digital cameras are capable of performing an internal dark frame subtraction. This feature is called ICNR (internal camera noise reduction). If this mode is active the camera will automatically take a darkframe after the lightframe and subtract it immediately. On DSLR type cameras this feature can be disabled whilst other cameras may not allow disabling it (i.e. Panasonic Lumix FZ 200). If ICNR is enabled there is no need for obtaining additional dark frames. Although this does simplify the post-processing it comes at the price of doubling the time necessary to obtain the light frames. Whether your camera supports ICNR can be determined from the manual. If you do not have a manual you can detect the presence of ICNR by taking a test image with closed lens cap. If the time necessary for taking the image is double the exposure time ICNR is used by the camera.

3.3 Flat frames

Figure 5: The use of flat frames. Light frames before flat correction having dust motes all across the image and vignetting at the edges have been used. Source

Flat frames help to compensate an inhomogeneous brightness distribution caused by vignetting of many camera lenses. They also help to eliminate the negative effect of dust that collects on a camera sensor over time. When obtaining flat frames the camera should be in the same orientation as it was when obtaining the light frames. Camera focus and ISO settings should also be identical and the ”AV” mode should be used in order to avoid over- or underexposed image parts. The most basic method for obtaining flat frames are so called ”T-Shirt Flats”. The Lens opening is covered with a simple white T-Shirt. The camera is then pointed at a bright white object and a series of images is taken (10-20). A suitable background could for instance be an illuminated wall, the daylight sky or a computer monitor showing an entirely white image. The result is an image which contains mostly information caused by vignetting and dust particles on the sensor. Flat frames are usually a good way to judge the amount of dust on a camera sensor. Flat frame compensation is especially important when using a tracking mechanism and working with industrial cameras (C-Mount). The sensors of those cameras are exposed to dust when not being attached to a telescope. Unlike modern DSLRS they not have additional means to clean their sensor.

4 What exactly happens during processing?

4.1 Bayer Matrix and Debayering

Colour CMOS camera sensors usually have four colour channels (two greens, one red and one blue). The sensor has a sensitive layer of pixels which measure the "intensity" of light only, and converts it to numbers. This sensitive surface can be considered "monochrome" or black and white only. It does not record colour information. However, just above this sensitive layer of pixels is a grid of tiny filters, one for each pixel. These filters selectively allow allow red, green or blue light through. So a "green" pixel is the same as a "red" pixel – but the filter above it is red or green. This is referred to as the Bayer Matrix or Bayer Filter. The order or sequence in which these tiny filters appear is usually different for each sensor, for example RGGB, GRBG, GBRG, BGGR…
When the image comes from the sensor into the computer, it is composed of one big monochrome image (it has white, black and all the levels of grey inbetween). The computer displaying the image (and your image processing software) does not know which pixels have, say, a red filter above them, or which have a blue or green filter above them. It's just a big mono image. Therefore, when imaging and creating an RGB image from a .FITS Image File or .SER Video file in RAW mode, we need to tell the computer which of these black, grey and white pixels have red, green and blue filters associated with them. Only then can they form a meaningful "RGB" colour image, with the usual RGB (Red Green Blue) colour channels. Lucky for us, this information is described as the "Bayer Matrix" for that particular sensor, which just a formula describing the pixel filter sequence, e.g. for example RGGB or GBRG, GBBR.

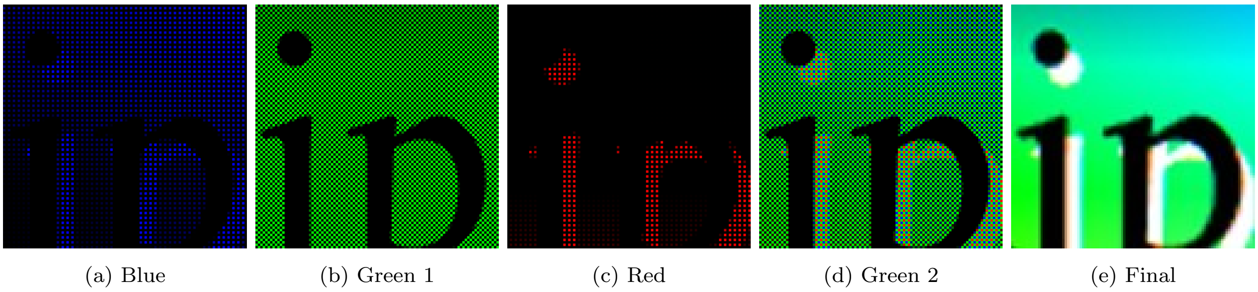

(a) Blue (b) Green 1 (c) Red (d) Green 2 (e) Final

Figure 6: The corresponding images for each colour filter and the image constructed using these. Source

We must first apply a "Debayer Matrix" to the sub-frame images. Only then we can stack it with other sub-frames and finally process it to bring out the details. Why? Because, when we take sub-frames, there is usually a little drift or variation between each frame. A star or small detail for example, will never land on the exact same pixel every time. The pixels are too small. A breath of wind, or a wobble in the atmosphere (heat haze or Seeing), vibrations from the tracking drive, or minute variations in the tracking of your mount (Periodic error) will cause that star to move a few pixels to one side and a few to the other (sometimes a lot!). Stacking software compensates for these changes and tries to drop a star in frame 1 on top of the same star in frame 2, but there is always unavoidable variation between sub-frames, and no two subs are exactly alike. So if we did not Debayer the images before stacking them, the star or feature would land on several adjacent pixels, and when stacked, it would be composed of many different (and wrong) colours. You would get a strange rainbow effect across the image, and it would make no sense.

4.2 What next?

The software is doing a few tasks that you can do by hand, but it's incredibly tedious. First it aligns all the photos so that the stars are in the same place. Good stacking software will save copies of your photos once it's aligned them so you can reject frames based on inaccurate tracking, star trails, obstructions.

Next, it does dark field subtraction. Sensor noise isn't entirely random- your camera's sensor will have a pattern to where the compensation. Your stacking software will work our your camera's noise profile from the dark photos you took with the lens cap on. Subtracting this from the image means that whatever is left should be truly random noise distributed evenly over the image, so your end photo won't have brighter and darker regions.

Lastly it stacks all the photos up and takes the average of each pixel. This is the statistical wizardry that finds stars too dim to make out in any single exposure by reducing background noise. It may also save an image showing the brightest value seen for each pixel- this is usually a compromise, more speckly than the averaged image but with more faint stars visible.

At this point you have an averaged image which contains as much detail as you are going to get from your raw photos. After this we want to tweak the light levels of your stack (stretch the image) to show faint details hidden in the image. We should adjust the levels so that the background grey in the image is just darkened to black, and all levels above that are lightened to make the stars more visible.

5 Case Study

This section will be written with the example of what the popular software DeepSkyStacker does. There will be a lot of aspects of what DeepSkyStacker does that will not be talked about in this module, to read that you can refer to this.

5.1 Registration

Registration roughly means identifying stars to help in alignment and adjustment before stacking. For each picture DeepSkyStacker will attempt to automatically detect the stars. In simple terms, DeepSkyStacker considers that a star is a round object whose luminance decreases regularly is every direction, and whose radius is no more than 50 pixels. Note that DeepSkyStacker will reject elongated star images which might occur if your mount isn't tracking correctly. Once the star is detected its exact center is computed by fitting a Gaussian curve to the luminance.

DeepSkyStacker will only stack images that contain at least eight stars that are common between all light frames. In practice this means that you should set the Star Detection Threshold in the Settings.../Register Settings or Register checked pictures/Register Settings/Advanced dialogue so that DeepSkyStacker detects 20 or more stars to stand a good chance of finding eight stars in common between all light frames.

The star detection threshold is 10% by default (10% of the maximum luminance). Reducing the Star Detection Threshold will result in DeepSkyStacker finding more (fainter) stars, on the other hand if you increase the threshold, then only brighter stars will be detected and so this will reduce the number found.

Setting the threshold so low that many hundreds of star are found will be counter-productive as there will be much more data to process for star registration and if too many stars are detected there is a greater chance of mis-registration. You should probably aim for over 20-25 stars and no more than a couple of hundred or so. If you have set the detection threshold low and DeepSkyStacker is still not finding enough stars because the image is underexposed, you can increase the image brightness by using the ”Brightness” adjustment in the Raw/FITS DDP Settings.

DeepSkyStacker can chain registering and stacking processes. You just have to give the percentage of the pictures that you wish to keep at the end of the registering process to start the stacking process. Only the best pictures will be used in the stacking process.

5.2 Alignment

During the alignment process the best picture (the picture with the best score) will be used as the reference frame unless you choose another reference frame using the context menu. All the offsets and rotation angles are computed relative to this reference frame.

The offsets are rotation angles are computed by identifying patterns of stars in the frames. To put it simply the algorithm is looking for the largest triangles of which the side distances (and so the angles between the sides) are the closest. When a sufficient number of such triangles is detected between the reference frame and the frame to be aligned the offsets and rotation are computed and validated using the least square method. Depending of the number of stars a bisquared of bilinear transformation is used.

5.3 Stacking

Stacking starts off with something called Background Calibration which consists of normalizing the background value of each picture before stacking it. The background value is defined as the median value of all the pixels of the picture. One of the options in proceeding further adjusts the background of each picture to match the reference frame.

Then it goes for the detection of hot pixels. The goal of the automatic detection and removal of hot pixels is to replace hot pixels with a value computed from neighbor pixels.

First the very hot pixels are identified by an analysis of the dark frames (or the master dark frame if available). Every pixel which value is greater than [median] + 16 x [standard deviation] (sigma) is marked as a hot pixel.

For all those pixels the value in the calibrated image (after offset/bias subtraction, dark subtraction and flat division) is interpolated from the neighbor pixels.

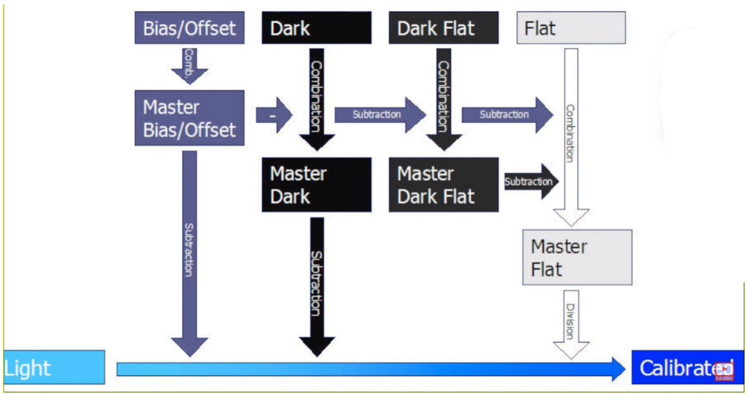


Figure 7: A flowchart to explain the processing

The actual stacking process takes place in the following order:

- Creation of the master dark from all the dark frames (with the selected method).
- Creation of the master flat from all the flat frames (with the selected method).
- Computing of all offsets and rotations for all the light frames that will be stacked.
- Creation of the final picture by adding all the light frames with the selected method. The master dark is automatically subtracted from each light frame and the result is divided by the calibrated master flat, then if the option is enabled the hot pixels detected in the dark frame are removed and the value is interpolated from neighbors.
- These light frames are then stacked.

Above, we have mentioned ”using the chosen method”, the possible methods are:

- **Average** : This is the simplest method. The mean of all the pixels in the stack is computed for each pixel.
- **Median** : This is the default method used when creating the masters dark, flat and offset/bias. The median value of the pixels in the stack is computed for each pixel.
- **Kappa-Sigma Clipping** : This method is used to reject deviant pixels iteratively. Two parameters are used: the number of iterations and the standard deviation multiplier used (Kappa). For each iteration, the mean and standard deviation (Sigma) of the pixels in the stack are computed. Each pixel which value is farthest from the mean than more than Kappa * Sigma is rejected. The mean of the remaining pixels in the stack is computed for each pixel.
- **Median Kappa-Sigma Clipping** : This method is similar to the Kappa-Sigma Clipping method but instead of rejected the pixel values, they are replaced by the median value. It is the most popular method used for stacking. There are also some more sophisticated algorithms that can be found in the link mentioned above.

In a nutshell, these can also be described by two equations:

$$CalibratedFrames = (Lights - MasterDark)/MasterFlats \tag{1}$$

$$StackedImage = F(CalibratedFrames) \tag{2}$$

Where F is the stacking algorithm used.

6 Filters

6.1 Introduction

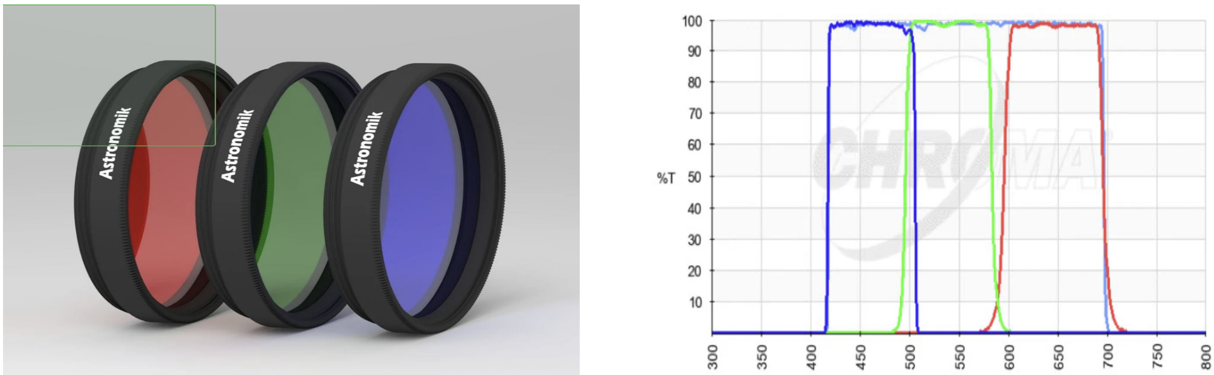
In astrophotography, a filter is a device which allows only the desired light to pass through and rejects the undesired light. Depending on what kind of light is desired and undesired, there are various types of filters, each with its own set of applications.

6.2 Types of Filters

6.2.1 Broadband Filters

They allow a band (around 100 nm) of wavelengths to pass through and reject other wavelengths.

1. RGB Filters - Used to separately capture the red, green and blue components of light coming from an object. These images are then combined in image processing software to produce a single RGB coloured image.



(a) How they look

(b) Transmission vs Wavelength plot

Figure 8: RGB Filters

2. UBV Filters - They are used in photometry for classifying stars based on their colour. A star's brightness (radiative flux, to be precise) is measured in the three wavelength bands - U (ultraviolet), B (blue) and V (visual). The ratios of U to B and B to V are related to the star's U-B and B-V color index. These can be used to calculate the star's temperature by comparing with the blackbody radiation curve (Planck's law). Loosely, the larger the ratio of U to B (or B to V), the hotter the star, because, hotter objects radiate more light energy at shorter wavelengths and less at longer wavelengths.

3. Light Pollution filters - These filters are used to capture (almost) true color images of deep sky objects while effectively blocking out the parts of the visible light spectrum that contribute the most to light pollution. Figure 8 shows the transmission vs wavelength plots (the red curves) of two popular light pollution filters. The orange spikes represent wavelengths corresponding to various common sources of light pollution. The green spikes represent common wavelengths found in the light received from deep sky objects. The Optolong L-Pro filter (Figure 10a) blocks light at four specific ranges: near 425 nm, where LED lights contribute significant blue light pollution; around 535 nm, corresponding to green light emitted by mercury lights; and two dips at 575 nm and 620 nm, blocking most of the yellow and orange light emitted by low and high-pressure sodium lights. However, the filter still allows some light in the yellow and orange range, as demonstrated by the peaks between 540 nm and 625 nm on the graph. The Optolong UHC filter (Figure 10b), on the other hand, blocks all light in the yellow and orange wavelengths.

6.2.2 Narrowband Filters

They allow a narrow band (around 3 nm to 30 nm) centred around some particular wavelength to pass through and reject everything else. They are used especially for imaging emission nebulae, which emit a large portion of their light at very specific wavelengths. Some of the common narrowband filters correspond to emission lines like $H\alpha$, $H\beta$, S-II and O-III. These can be combined later to produce false-colour images of deep sky objects with each colour corresponding to a different element. A great advantage of using narrowband filters in astrophotography is that they remove the effects of light pollution almost completely.

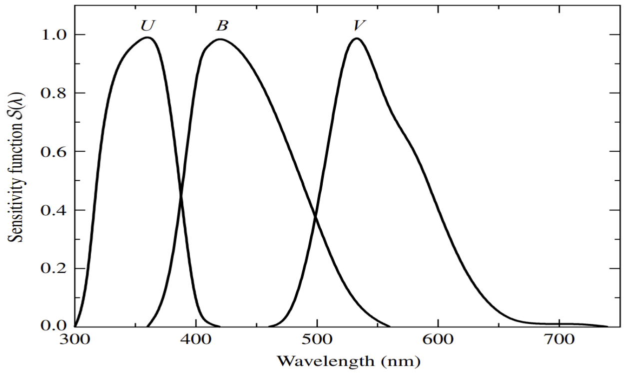
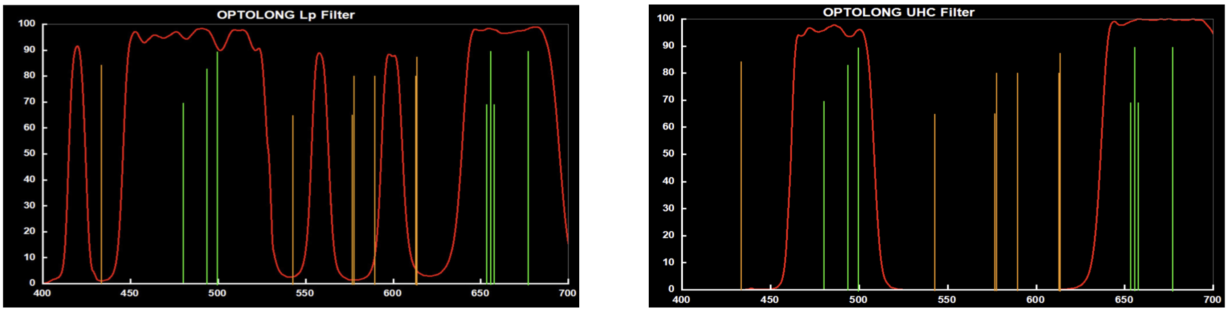


Figure 9: Transmission vs Wavelength for UBV filters



(a) OPTOLONG L-Pro Filter

(b) OPTOLONG UHC Filter

Figure 10: Broadband Light Pollution Filters

6.2.3 Polarizing Filters

They are used to reduce glare and enhance contrast while observing the Moon and planets. They consist of two polarizing layers, which changes the amount of transmission of the filter by rotating them.

6.2.4 Moon Filters

Also called neutral density filters, they reduce the intensity of all wavelengths of light equally (their opacity is fixed and cannot be varied like polarizing filters). They are mainly used to reduce glare and enhance contrast while observing the Moon, hence the name.

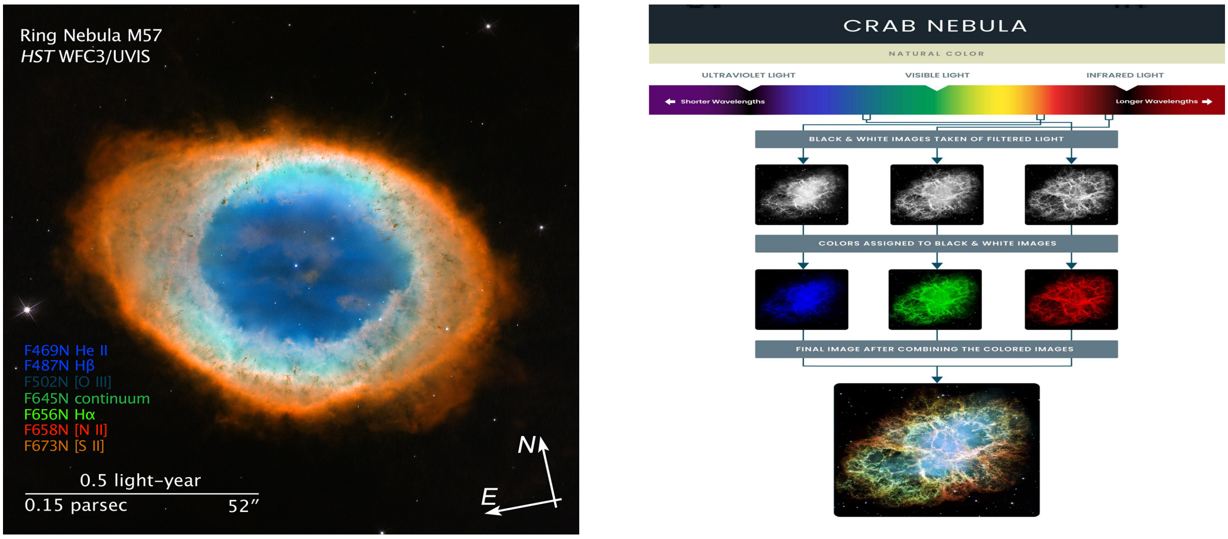
6.2.5 Solar Filters

They are used for safely observing the Sun through a telescope. They transmit only about 0.00001% of the incident light. Directly observing the Sun without a solar filter will cause irreversible eye damage and can also damage the telescope parts due to overheating.

Figure 11: Solar Filter Mounted on a Telescope

6.3 Filters used in Hubble Space Telescope

Did you know that Hubble does not have any colour cameras on it? It uses filters to allow only a certain range of light wavelengths to pass through at a time. Their grayscale intensities are recorded using electronic sensors (CCDs, etc.). As a result, every image Hubble sends to Earth is in black and white. Hubble scientists and image processors create Hubble's beautiful false-color images by adding an individual color to each separate black-and-white filtered image. These single-color images are then combined to make the final picture. For example, consider the HST image of Ring Nebula (M57) taken on September 19, 2011. Narrowband filters corresponding to emission lines of elements like He, H, O, S and N were used to capture the nebula at multiple wavelengths. Each of those were assigned a different colour and they were combined to get the final image (Figure 12a)



(a) Ring Nebula (M57)

(b) Crab Nebula (M1)

Figure 12: Some false-colour images taken by Hubble Space Telescope (HST)