UNDERSTANDING FILTER INDUCED STAR HALOS

By Jim Thompson, P.Eng

Astronomical filters can improve the quality of our observing or imaging efforts. They increase the contrast of the object we are trying to observe, and correspondingly increase the signal-to-noise ratio (SNR) of our images. These qualities I have documented numerous times in the test reports authored up to this point.

One characteristic of filters I have not discussed is their undesirable tendency to generate optical artefacts. By adding a filter to our telescope setups, we are adding two new surfaces for dirt and dust to collect upon, or for a reflection to occur off of. The later phenomenon is what is discussed in this article, reflections off of filters. More specifically this article summarizes my investigation into the origin and nature of halos around bright stars caused by the presence of a filter.

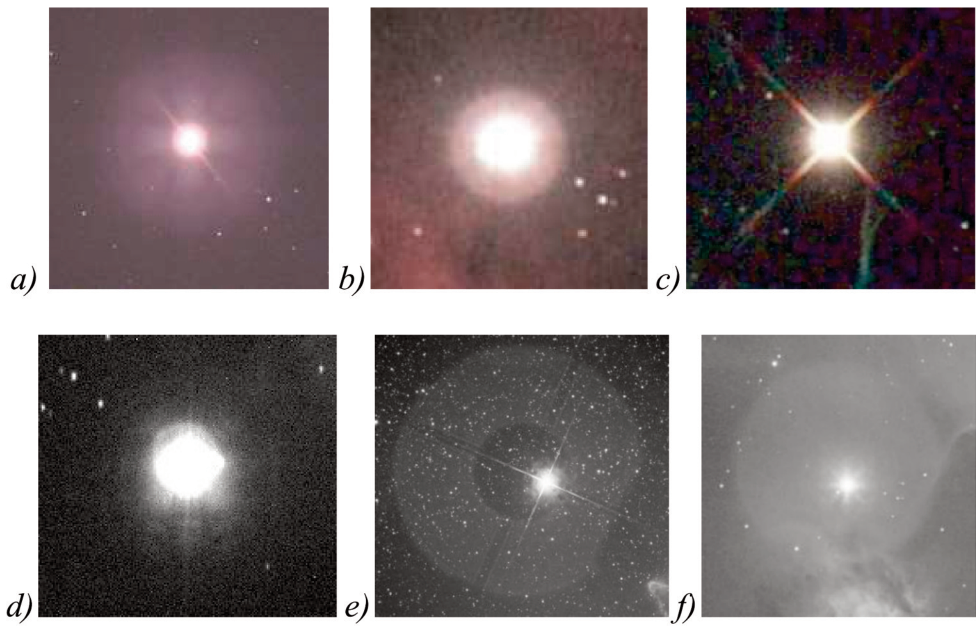

Figure 1: Star Images from Various Sources Illustrating Artefacts

Background

Prior to the effort documented here, I had not paid much attention to star halos. From the perspective of someone who observes through the use of Electronically Assisted Astronomy (EAA), the presence of halos around bright stars is just one of several image artefacts that have come to be accepted as part of the EAA process.

Through my recent comparison testing of very narrowband filters it has come to my attention that halos, or rather their absence, can sometimes be the deciding factor for astrophotographers on whether to purchase one filter over another. For this reason I decided to have a more thorough look at the problem.

To start, it is important to come to a consensus on what people are calling a "halo". **Figure 1** presents several images of bright stars with different types of artefacts around them. In many cases there are more than one type of artefact present in the images.

Halos are defined as clearly delineated disks, relatively small in angular size, around bright stars. They are typically centered on the star but can be offset slightly when the star is at the edge of the field of view. Depending on the star brightness and other factors, there may be multiple concentric halos that both increase in diameter and decrease in brightness by a regular interval.

Images a), b) and d) in Figure 1 show

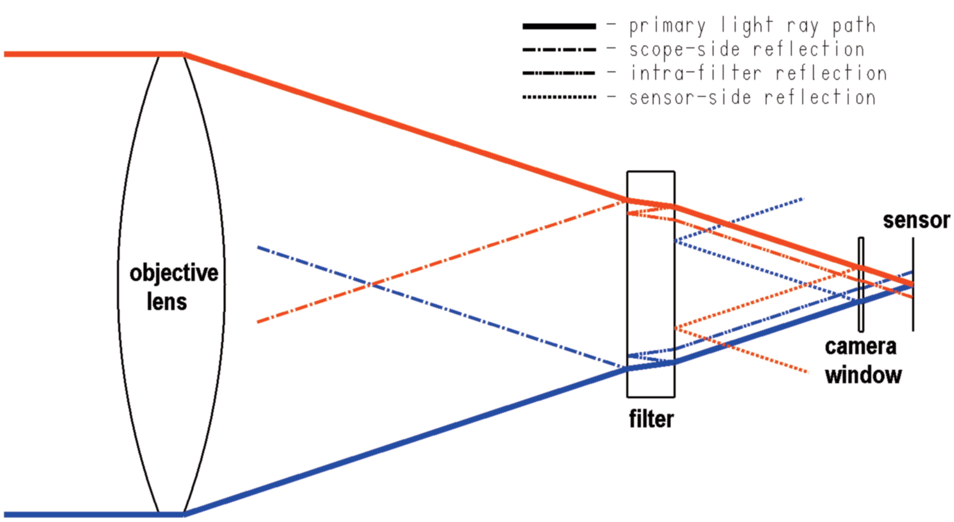

Figure 2: Schematic View of Typical Telescope-Filter-Camera Arrangement

evidence of a halo. The randomly distributed spikes around the star in images b) and d) are a result of small imperfections in the primary optics of the scope used to capture the image and are unrelated to the presence of a filter.

The bright symmetrical spikes in images c), e), and f) are diffraction spikes caused by the scope's secondary mirror supports, and in image a) is caused by a spider's web spanning across the inside of the optical tube. Images a), d), and f) all show a diffuse symmetrical 4-lobbed pattern around the bright star which is another artefact caused by the primary optics, not related to the filter.

Finally, images e) and f) both show a large disk or donut that is off center from the bright star. These are ghost images; reflections between the scope optics and the camera that the filter may also play a role in.

Based on the information I could find online, halos are believed to be due to a reflection involving the filter. **Figure 2** illustrates schematically the components of a typical optical train, and how each component might contribute to the generation of a reflection. Reflections from the scope side of the filter, if they are able to somehow make their way back to the sensor, are responsible for large ghost images like those in images e) and f) in Figure 1. Reflections from the sensor side of the filter are also able to generate

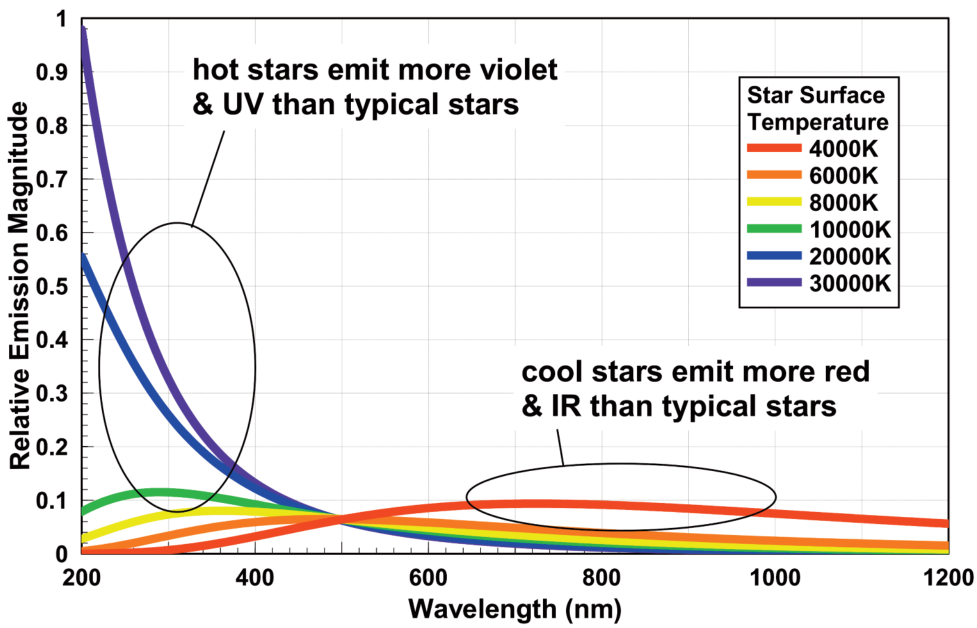

Figure 3: Comparison of Star Emission Spectra – Stars w/ Equal Visual Brightness

ghosts depending on scope focal ratio, how close the filter is to the sensor, and whether there is additional optics in the path between filter and sensor.

Intra-filter reflections result in relatively small sized artefacts around stars, their angular size dependant only on the focal ratio of the scope and the thickness of the filter glass. Based on the geometric arrangement described in Figure 2, the size and brightness of the intra-filter reflection does not depend on how far the filter is from the camera. This is an important property that will come up again later in this article.

The rest of this article presents the results of a series of experiments I have performed, each one meant to garner some understanding of a particular aspect of the halo problem. The following summaries are presented in the order in which the experiments were performed. For more details on my experiments and the associated results, a copy of the summary report is available upon request.

Impact of Star Type

The first investigation I performed was to comb through my library of past image captures in search of images with star halos and determine the properties

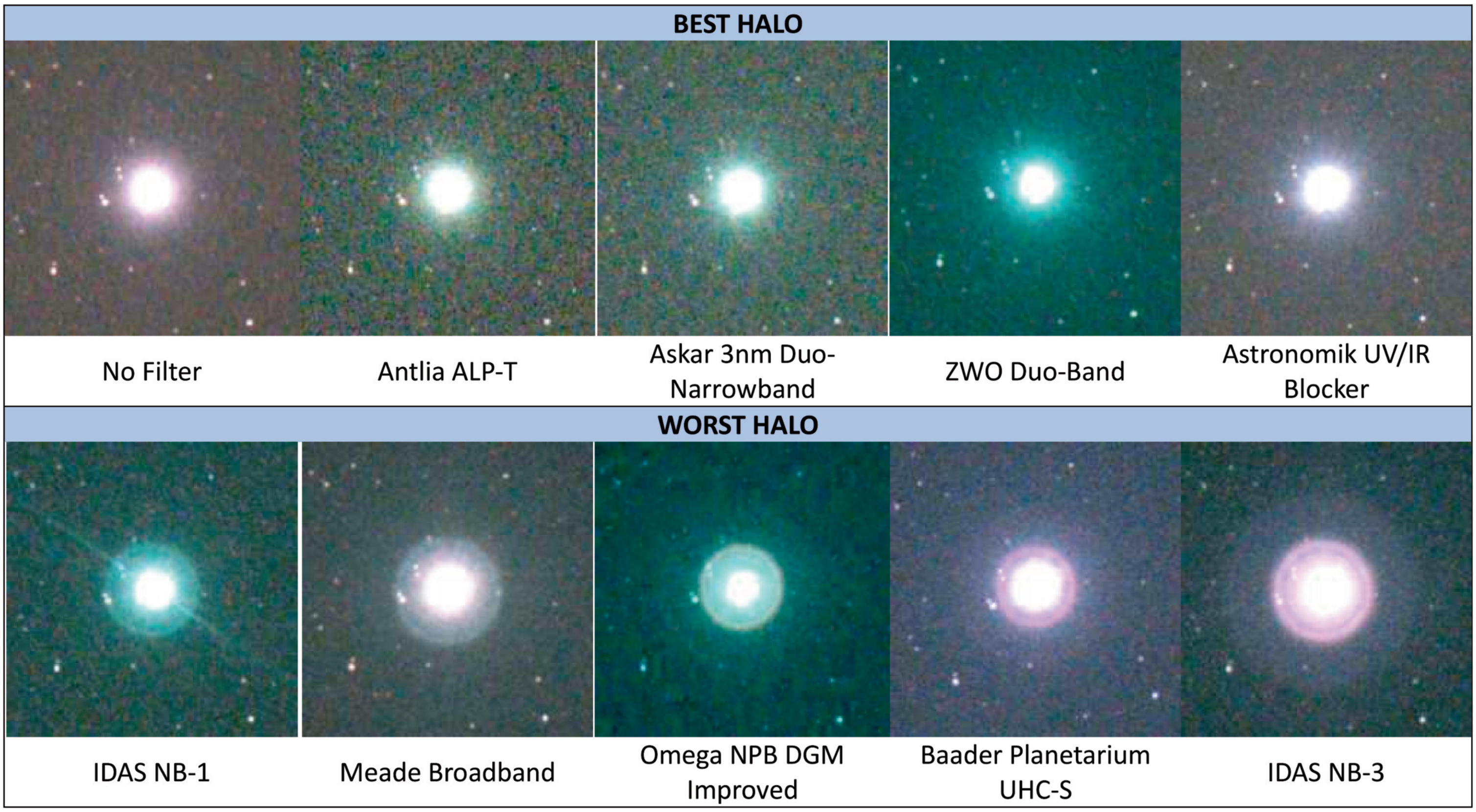

Figure 4: Sample of Best & Worst Survey Filter Halos

of the particular stars that displayed the halos.

Not all stars generate visible halos, and some stars are worse than others. In general, the stars with halos are bright, often the brightest star in the frame, but that is not always the case. A consistent property of stars that tend to have halos is that they are hot. For example: the star Alnitak in Orion has a surface temperature of 29,000K and is notorious for causing halos.

In more than half of the examples I found in my image library the halo bearing stars are very hot, 10,000K or higher. Curiously though I also found that 1/3 of the examples were from very cool stars, less than 5000K.

The implication of this observation is that the emission spectrum of the star, which is defined by its surface temperature, has an effect on the extent to which a filter generates a halo. **Figure 3** illustrates how the emission spectrum of a star changes with its temperature. The spectra in the figure are scaled so that the overall visual brightness of the stars is the same. The figure shows that hot stars have their emissions biased towards the violet end of the spectrum, and cool stars are biased towards the red end. It stands to reason then that a filter designed to minimize halos around the majority of stars might not perform well on very hot or very cool stars.

Impact of Filter Position:

The next investigation I performed was an experiment to determine how the appearance of a star halo changes with the position of the filter relative to the camera. This experiment was performed by placing a filter known to cause halos at different distances from the sensor and recording images of the resulting halo. Halo size, in pixels, was measured from the images as the primary output of the experiment.

When the filter alone was placed on the scope, the filter-sensor distance made no significant difference in the size of the halo. This observation is consistent with the comment made earlier, and confirms that the halo is most likely due to intra-filter reflections. Some additional testing involving the addition of a focal reducer showed that the behaviour of the resulting halos and ghost images became much more complex.

Comprehensive Filter Halo Survey

There is a large amount of anecdotal evidence available online regarding the prevalence of halos when using particular filters. I was not however able

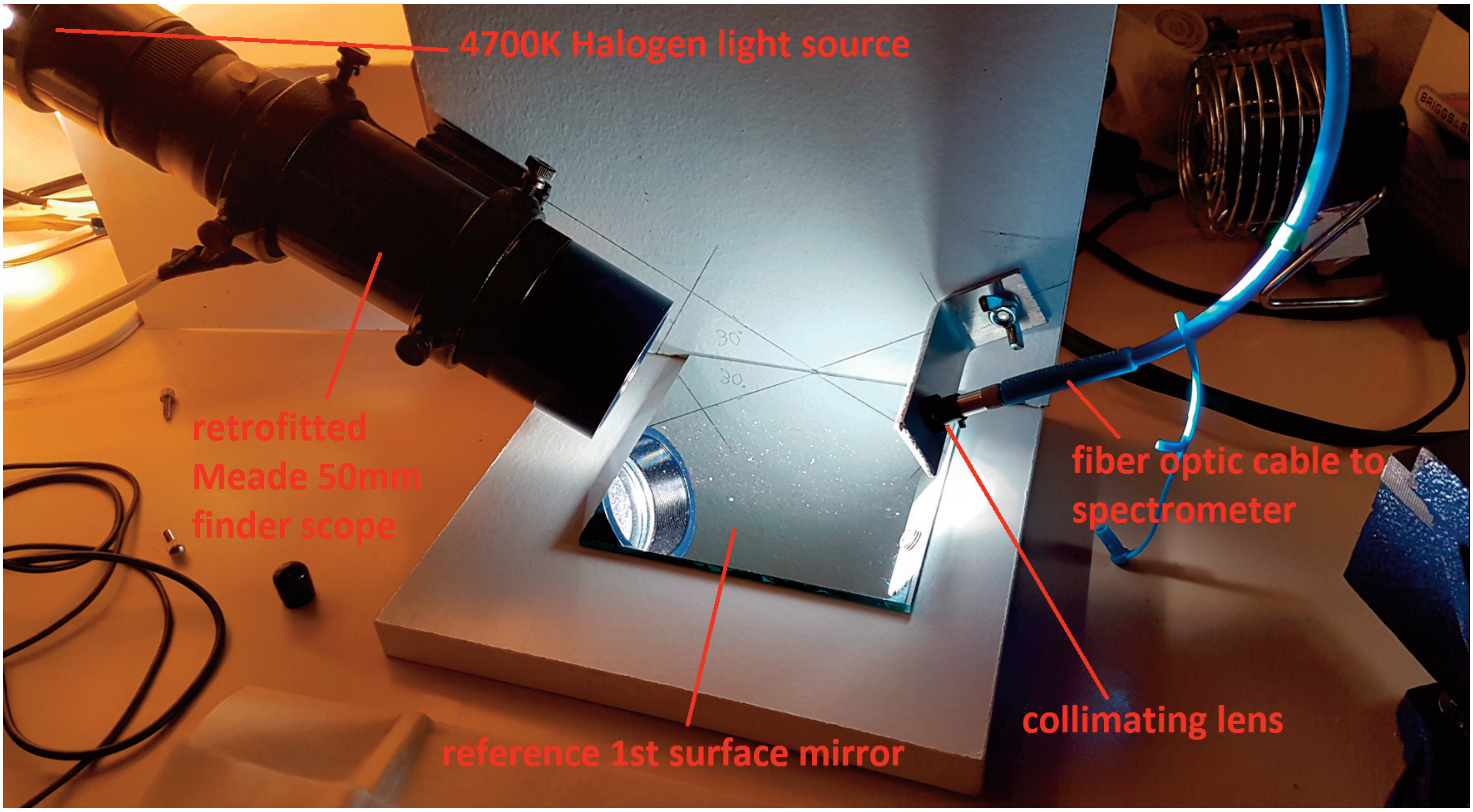

Figure 5: Home-Built Reflectometer

to find any prior test results involving more than one or two filters. My researching of filters over the past ten years has resulted in my accumulating a large variety of filters, offering an opportunity to perform a reasonably comprehensive survey of filters to determine their propensity for generating halos.

I assembled a library of 45 different filters and collected image data using all of them on the same star on the same night. The result was a rather large range of observed halo severity, from practically none to extremely bright multiple halos.

Examples of the best and worst observed halos are provided in **Figure 4**. Perhaps not surprisingly, the worst halos were generated by filters that were either inexpensive or meant for visual observing. Halo sizes varied also, but in a way that was consistent with the manufacturer stated filter glass thickness; thicker glass produced larger halos.

To enable a more quantitative comparison between filters, each image was analysed in AstroImageJ to extract the contrast between halo and background in each colour channel. The green colour channel was found to be the one making the largest contribution to overall halo contrast for most filters, however there were a fair number of filters with blue channel dominated halos as well.

With a quantitative measurement of each filter's halo brightness in hand, the next step was to measure the physical properties of each filter with the hopes of finding a property that correlated with the halo contrast data.

Filter Reflectivity

When I started this research project, the easily accessible reference material I found online gave me the impression that halos are primarily caused by reflections between the filter and the camera sensor window.

I have since come to understand that is not the case, but at the time this initial impression led me in the direction of measuring filter spectral reflectivity. To be able to measure the spectral reflectivity of a filter I had to construct a rudimentary reflectometer.

This is a fairly simple instrument consisting of a collimated light source pointed at the filter at a fixed angle, and a sensor positioned over the filter at an appropriate location to receive the light that has been reflected off of it. In my case I used a halogen spot bulb jerry-rigged to the eyepiece end of a Meade 50mm finder scope as my collimated light source. The reflected light was gathered by a collimating lens attached to the end of a fibre optic cable, with an Ocean Insight USB4000 spectrometer on the other end.

A photo of the apparatus I constructed is shown in **Figure 5**. I constructed the back plate to allow for two different test angles: 60°, and 20° off axis from the filter.

Using my test rig I measured the reflectivity of all 45 filters in my survey library, at both 60° and 20° off axis, and on both sides of the filter. I found that a number of filters very clearly have anti-reflective coatings on their camera-facing side. Although it is assumed that the anti-reflective coatings help to reduce halos, I did not observe a clear connection between halo visibility and the presence of an anti-reflective coating. Some other filter property must also be involved in halo production.

Filter Off-Band Blocking

When I found that camera-side reflectivity did not strongly indicate as the cause of halos I went back to the manufacturer provided data to see if there was some other physical parameter that might be responsible. I noticed that the off-band blocking reported by the manufacturers did correlate to some extent with my measured halo data. **Figure 6** summarizes the manufacturer provided data that I based my observation on. From this small sampling of filters, it seemed that off-band blocking might be a significant factor in halo generation. To be sure I needed to measure this property from my library of 45 survey filters.

Before getting into my measurement, it is important to first provide a clear definition of what "off-band blocking" means. The purpose of a filter is to pass light from objects we want to observe while blocking as much unwanted light as possible. Wavelengths of light the filter is designed to pass are considered to be "in-band", and wavelengths the filter is designed to block are "off-band".

Reducing the transmissivity of a filter to off-band wavelengths is desirable for good filter performance, but it comes at a cost as more coating layers are required to achieve this result. The extent of off-band blocking that is provided by different filter manufacturers varies widely and is correlated closely with filter price.

The common way of expressing the magnitude of off-band blocking is to use a property called Optical Density (OD). OD is related to transmissivity by the following equation: OD = - LOG10(transmissivity), where transmissivity is expressed as a fraction not as a percentage.

To be able to measure OD required me to come up with

Filter	OEM Quoted Off-Band Blocking		Measured Halo Contrast		
	Transmission	OD	Red	Green	Blue
Optolong L-eNhance	< 1%	> OD2	0.33	1.15	0.48
IDAS NBZ	< 0.1%	> OD3	0.01	0.74	0.08
Optolong L-uLtimate	< 0.01%	> OD4	0.08	0.69	0.14
Antlia ALP-T	< 0.003%	> OD4.5	0.08	0.51	0.06
Askar 3nm Dual Narrowband	< 0.001%	> OD5	-0.16	0.57	-0.02

Figure 6: Filter Manufacturer Quoted Blocking vs. Measured Halo Contrast

an apparatus capable of high sensitivity and accuracy. My past filter transmissivity measurements have been made to within ±1%, but to measure blocking I needed accuracy three orders of magnitude better, an accuracy of ±0.001%.

To achieve this level of accuracy required me to use my spectrometer with a variable exposure time. The reference light intensity was measured with no filter in place at a short exposure time, on the order of 0.1ms. When the filter was added, the exposure time was increased as required to get a light intensity reading that was well above the instrument noise level.

Noting both the exposure time and the light intensity reading allowed me to calculate the resulting OD. The maximum practical exposure time used was 10,000ms (10sec), giving me sufficient instrument sensitivity to measure filter blocking down to OD 5. The collimated halogen light source from my reflectometer apparatus was reused for this measurement setup.

Between the light source and the filter under test was placed a band pass filter that allowed me to work with a limited part of the spectrum at one time. This was necessary to keep the spectrometer's CCD sensor from saturating and giving erroneous results. A photo of the test apparatus is provided in **Figure** 7.

OD was measured in three bands

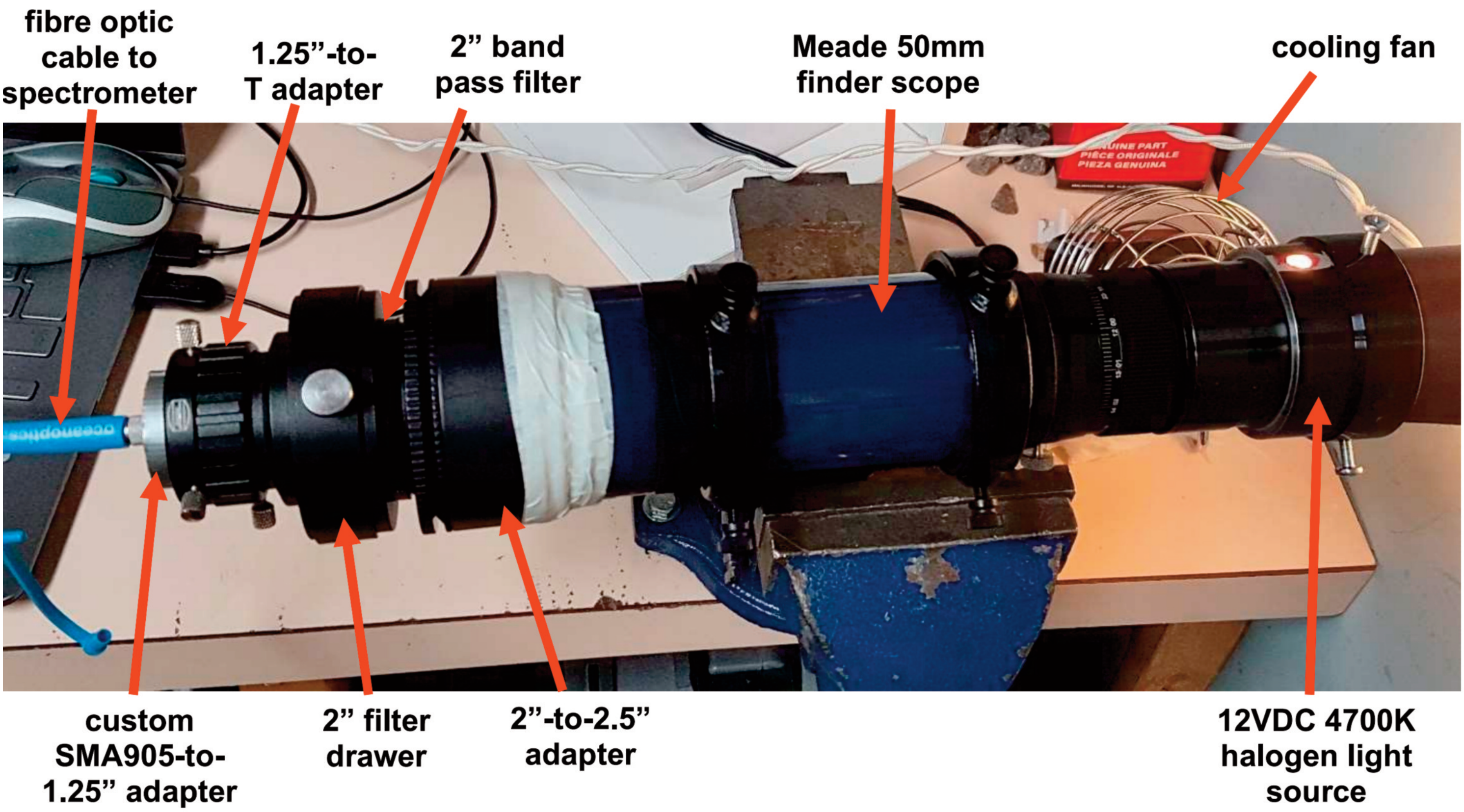

Figure 7: Home-Built OD Measurement Apparatus

(red, green, blue) for all 45 filters in my list. It was a labour-intensive activity, taking just under eight hours to complete. I was surprised to find a large variation in blocking, some filters having blocking less than OD2 in each band while others were over OD5.

In general, filters with low blocking values were either lower priced filters or filters intended for visual use only. Comparing my OD measurements to my halo contrast results, it was evident that there is some level of correlation present.

The extent of this correlation is visualized in **Figure 8**. This plot shows the measured reflectivity and OD of each filter tested, as well as the measured halo contrast, in this particular case for the green colour channel. I produced similar plots for the blue and red channels as well.

In general, the data suggests that filters with high levels of off-band blocking, OD values >4, have little or no discernable halos. Filters with off-band blocking less than OD4 may or may not present significant halos, there is too much scatter in the data below OD4 to make a more definitive observation. Filters having the brightest halos tended to have both low off-band blocking and high reflectivity. Filters with moderate reflectivity, in the 30-60% range, have generally less halo contrast than filters with higher reflectivity, even when their off-band blocking is low.

Conclusions

I have drawn the following conclusions from my experiments and analyses on the topic of filter induced star halos:

1: Filter induced artefacts are caused by reflections both from the exterior surfaces of the filter, and reflections occurring within the filter. Artefacts commonly identified as halos are primarily due to intra-filter reflections. Ghost images are due to reflections between the filter and other surfaces such as the camera sensor window or a nearby focal reducer/field flattener. Filter manufacturers can do little if anything to reduce reflections from surfaces ahead of the filter in your optical train.

2: The distance of the filter from the sensor does not impact the appearance of the halo. Its size is dependant only on the thickness of the filter glass and the scope focal ratio. Thicker glass or faster focal ratio both result in larger halos.

3: The extent to which a halo is produced depends on the surface temperature of the star. Comparing stars with the same visual magnitude, very hot stars (>10,000K) and very cool stars (<5000K)

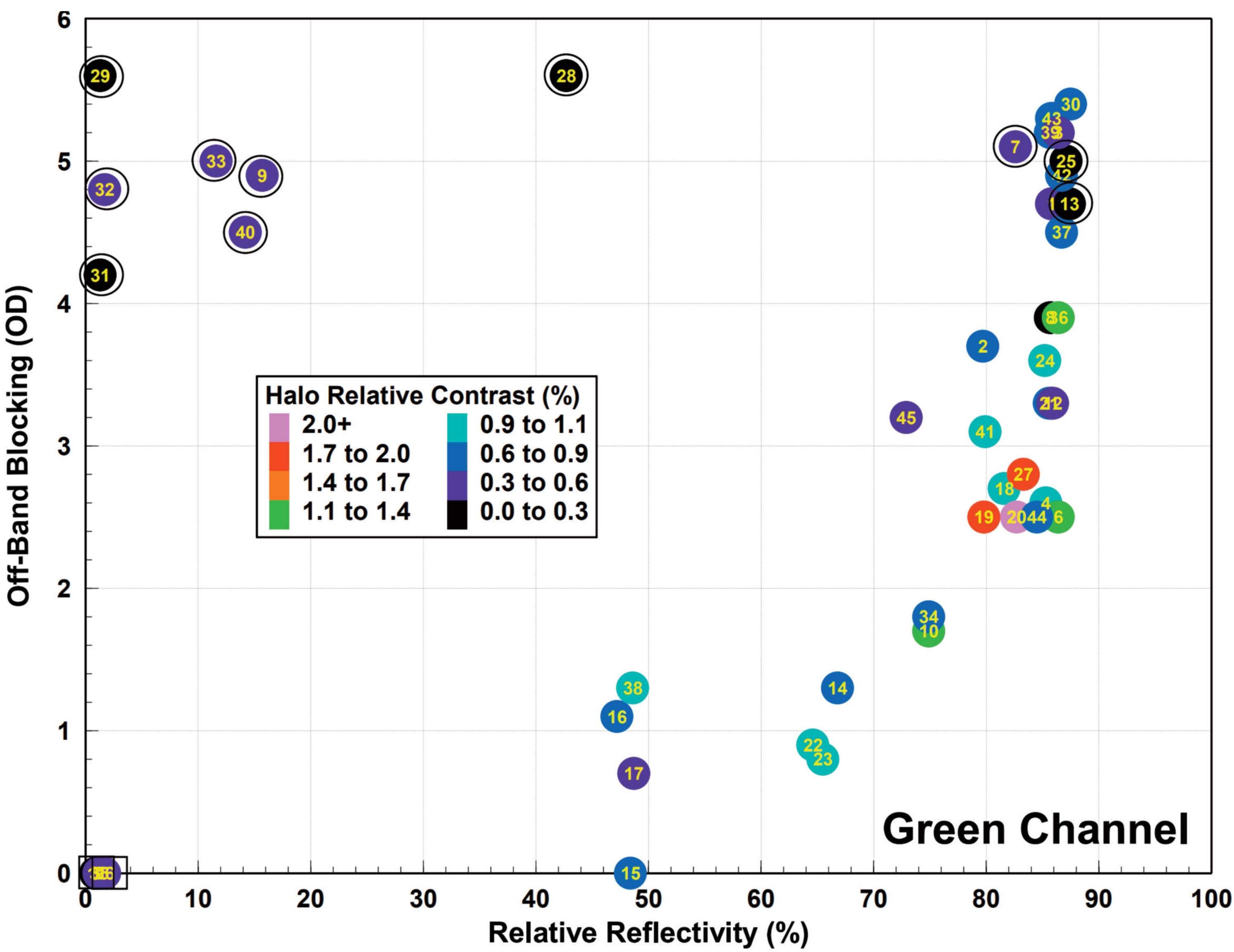

Figure 8: Measured Filter Off-Band OD vs Relative Reflectivity, Green Channel

will produce brighter halos than moderate temperature stars. Since filters are commonly used for imaging emission nebulae in star forming regions, there is likely an observing bias in the astrophotography community towards scenes containing young stars that are both hot and bright.

4: A filter's tendency to produce halos is highly dependant on its off-band blocking performance. From the 45 filters tested, all those with off-band blocking >OD4 had little or no discernable halo. For filters with blocking below OD4, secondary effects like filter reflectivity become more important.

5: Application of an anti-reflective coating on the camera side of the filter can help to reduce the appearance of halos, although the magnitude of the impact is less than increasing off-band blocking. An anti-reflective coating designed to operate in the blue part of the spectrum is most effective at reducing halo brightness, especially for very hot stars.

6: Narrowband or multi-narrowband filters are more prone to halos because by design they are reflecting a large amount of off-band light. Application of high off-band blocking and anti-reflective coatings on the camera side of the filter are very important design requirements for these types of filters. They are especially prone to halos on fast optics like RASA or Hyperstar systems because of the fast f-ratio, but they are also prone to ghost images off of the corrective optics that sit immediately in front of the filter. This is not the fault of the filter manufacturer, it is a result of the reflectiveness of the scope optics. ATT