CCD vs CMOS for Video Astronomy
by Jim Thompson, P.Eng
Test Report – November 20th, 2017

Introduction:
Video Astronomy (VA), the method of observing the night sky through a video camera instead of an eyepiece, has come a long way in the past 20 to 30 years. For a long time VA was a mostly homegrown practice, with technically inclined tinkerers adapting security cameras or webcams to allow them to be used with a telescope to see deepsky objects. Over the years a small number of these tinkerers have developed their ideas into a commercially available product, the longest lived of these grassroots outfits being the Canadian company Mallincam. The field of Video Astronomy has changed a lot however in the past two or three years. The numbers and types of camera models that are being used has grown quickly, and the way in which these cameras are used has also evolved with the continuing development of dedicated software. Video Astronomy now sits under a larger umbrella called Electronically Assisted Astronomy or EAA, which includes a wide spectrum of techniques from Fast Imaging to Near Real-time Viewing to photo-multiplier technology (ie. Night Vision). The biggest change to the EAA field has been the recent availability of high performance and affordably priced CMOS based cameras. Traditionally a CCD type sensor has been the preferred choice for applications requiring high sensitivity, but CMOS sensors are catching up due to more development dollars being spent on this less expensive technology. The question then is: "As of today which is better for VA, CCD or CMOS?"

Objectives:
I have had an opportunity over the past couple of years to use a large variety of EAA cameras, some CCD based and some CMOS based. I have also paid attention to a number of different online user groups, noting the various trends in camera types and methodologies. I have the impression that users are moving away from CCD based cameras because they are "old technology" and there are more camera choices now that are CMOS based. In my opinion CCD based cameras are still much more sensitive than CMOS cameras and therefore provide a more immediate observing experience. In this test report my objective is to illustrate why I believe this to be true through the side-by-side comparison of two different cameras: one CCD based and the other CMOS based. My comparison is performed from the perspective of someone who wants to observe in near real time, so an emphasis has been put on the ability of the camera to present a usable image in a reasonably short period of time. The term "usable image" is rather subjective, but in my opinion is a valid means of assessing the performance of each camera for the purposes of observing (not imaging). Well depth, signal-to-noise ratio, quantum efficiency, and other technical terms often used to quantify camera performance may be important to an astrophotographer, but they mean very little to a person who just wants a nice low noise image of a deepsky object in 20 to 30 seconds.

Methodology:
Although I have performed a large variety of tests over the past two months, this report will concentrate on the results of the most recent tests which were performed on the evening of October 20th, 2017 using a StarlightXpress Lodestar X2C (CCD based) and a ZWO ASI290MM (CMOS based). Figure 1 provides an image of each of the cameras for reference. The two cameras were installed side-by-side on my Atlas EQ/G mount, and images captured simultaneously on the same targets. The pairing of camera to telescope resulted in roughly the same field of view and focal ratio between the two cameras (see below).

- Setup #1: Lodestar X2C (bin 1x1, dark frame subtraction off) with William Optics FLT98, long-half Mallincam MFR5 focal reducer (effective f/ratio ~ 4.7), Meade O-III light pollution filter;
- Setup #2: ASI290MM (bin 2x2, gain 400 out of 600, dark frame subtraction on or off as noted in results) with William Optics ZS66, long-half Mallincam MFR5 focal reducer (effective f/ratio ~ 4.4), Meade O-III light pollution filter.

Lodestar X2C ASI290MM

Figure 1 Images of the Two Test Cameras

The Lodestar X2C uses probably the most sensitive CCD sensor currently available for use in EAA cameras, the Sony ICX828/829. I also have analog video cameras using this same sensor (MC Xterminator, AVS APU-1), but I decided to use the Lodestar camera in order to have as similar a workflow to the ZWO camera as possible, thus minimizing the impact of software on the results. The ASI290MM uses one of the more sensitive CMOS sensors currently available for EAA, the Sony IMX290. This sensor is smaller in size than the ICX828/829, but I was able to achieve a similar field of view by using it on a shorter focal length telescope. The ASI290 camera had an added advantage over the Lodestar in that it is a monochrome camera. The Lodestar camera I used is a one-shot colour (OSC) camera, which with its CMYG Bayer matrix is roughly 50% as sensitive as the monochrome version of the same sensor.

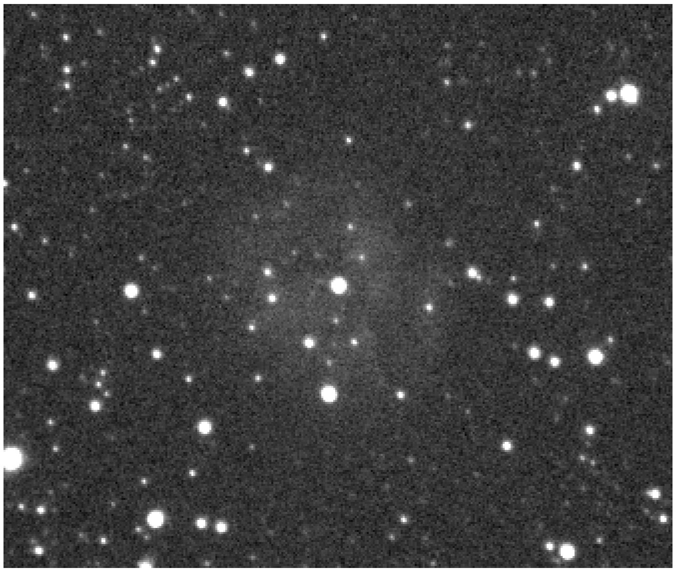
The test consisted of observing a variety of deepsky objects over the course of an evening from my backyard in Ottawa, Canada. The limiting visual magnitude at zenith from my location is typically around +3.5. Images were captured as PNG's directly from each camera's software: Starlight Live 3.3 for the Lodestar, and SharpCap 3.1 for the ASI290. On each target images were captured for a range of total exposure times for later side-by-side visual comparison. Captures from the Lodestar were accomplished using a single exposure for times up to 90 sec, after which longer total exposures were achieved through stacking since mount tracking was not reliable enough above 90 sec. Captures from the ASI290 were all accomplished using stacks of 10 sec exposures. This is the most common mode of use for these new CMOS cameras, their low read noise allowing for good SNR using fairly short sub-exposure times. Using short exposure times is also touted as a benefit when using these cameras on less capable mounts such as basic Alt-Az Goto mounts, although that was not an issue for my test as I used a GEM.

Results:

Fifteen different deepsky objects were observed during the observing session. All of the images collected have been posted to an album on my Flickr account: https://flic.kr/s/aHsm9X8NZD. I have made a selection from the images collected for presentation and further discussion within this test report. Note that the images below are crops from the full images, compared at the same image scale. The first object to be compared is the Cocoon Nebula, IC5146. Crops from these images are compared side-by-side in Figure 2 below.

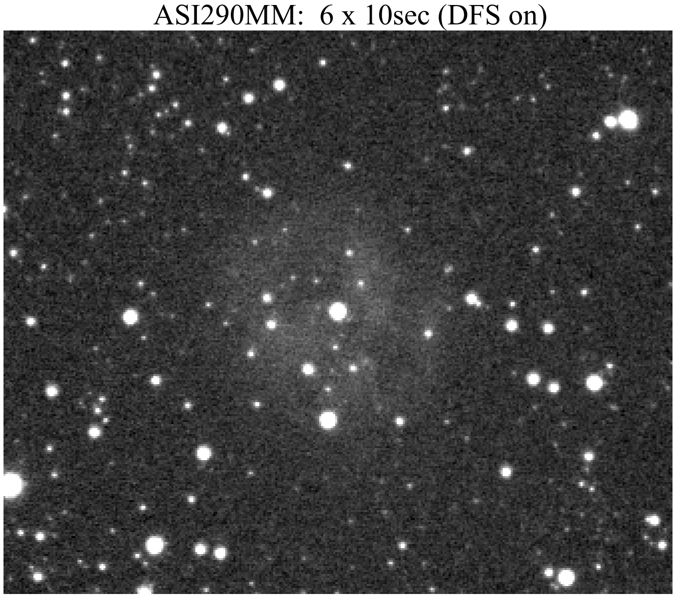
Figure 2 Cocoon Nebula (IC5146) Comparison Images

ASI290MM: 3 x 10sec (DFS on) | Lodestar X2C: 1 x 30sec

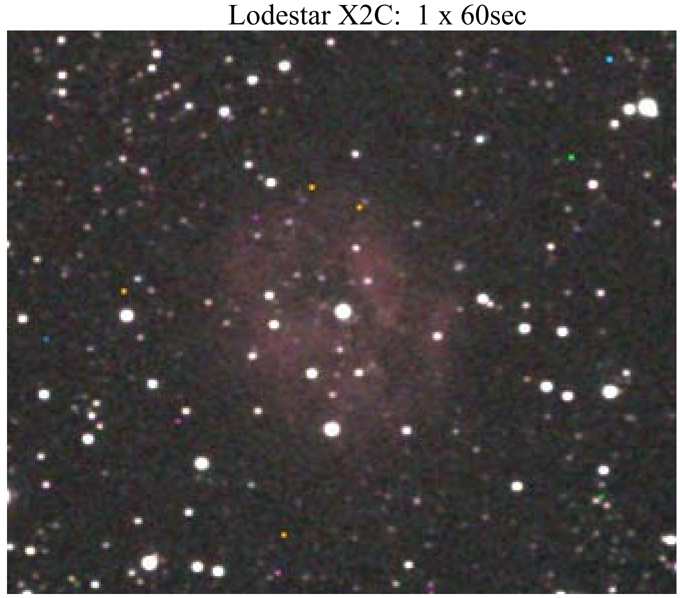


ASI290MM: 6 x 10sec (DFS on)

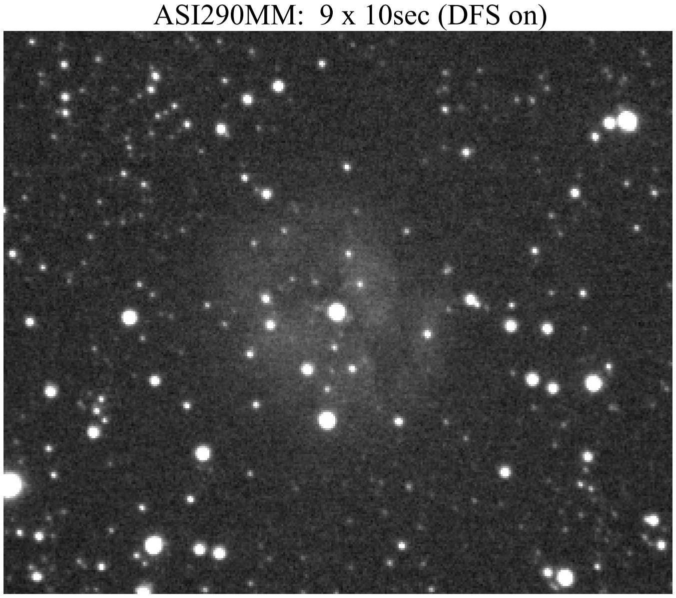
Lodestar X2C: 1 x 60sec



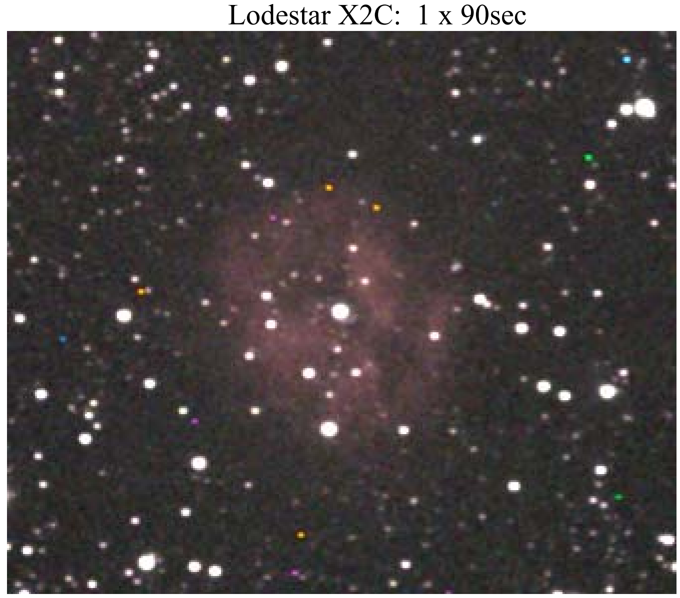
ASI290MM: 9 x 10sec (DFS on)



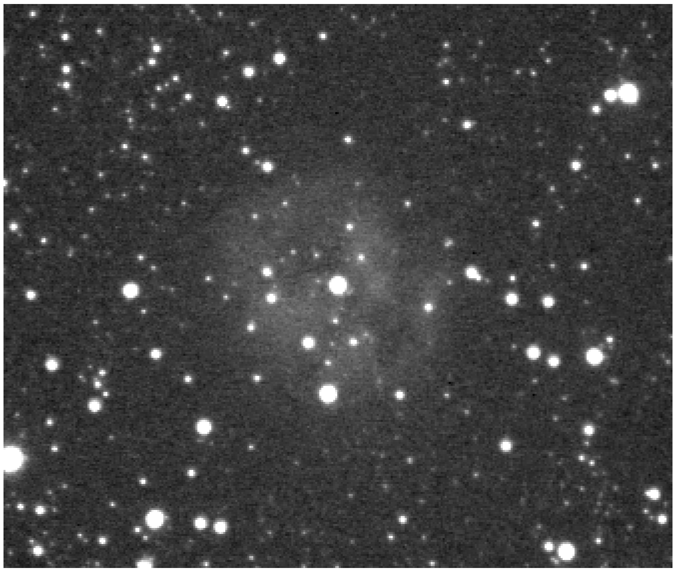
Lodestar X2C: 1 x 90sec



ASI290MM: 18 x 10sec (DFS on)

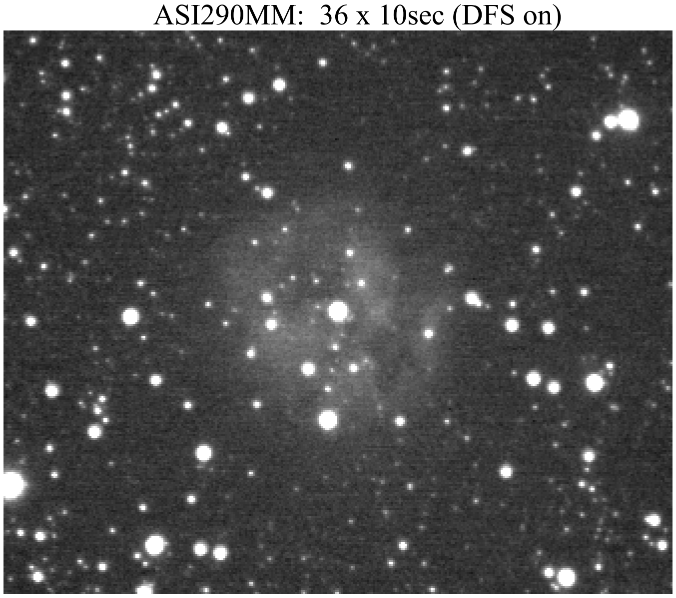


Lodestar X2C: 2 x 90sec

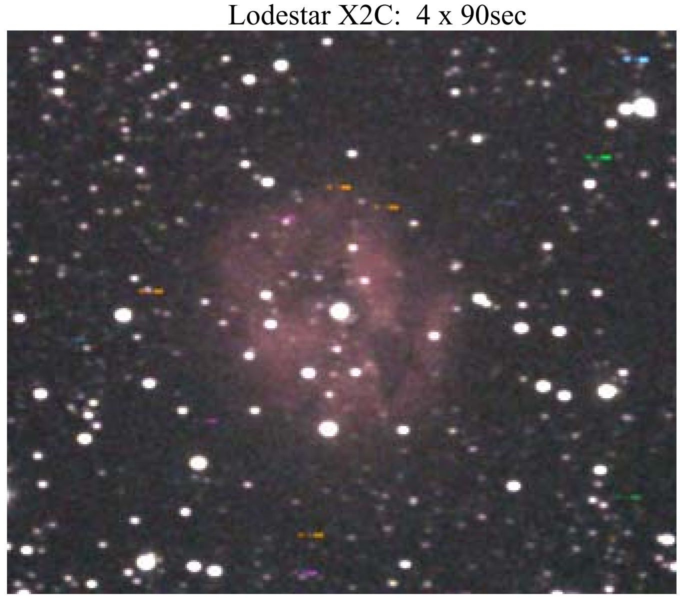


ASI290MM: 36 x 10sec (DFS on)

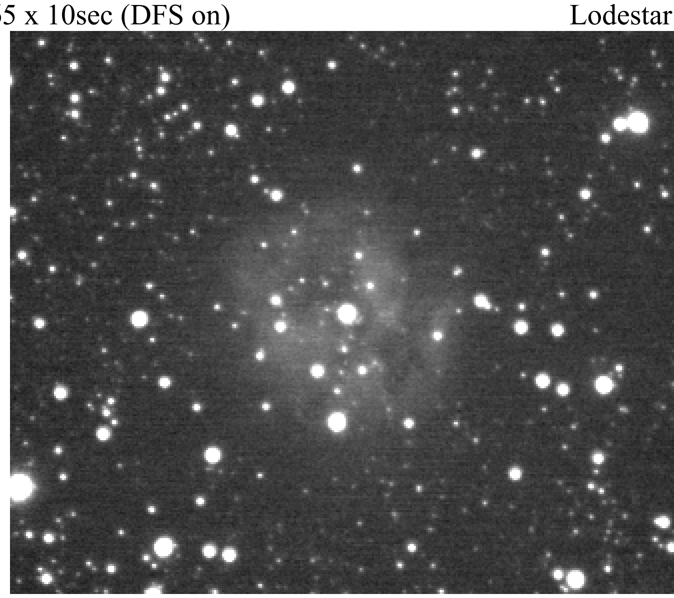
Lodestar X2C: 4 x 90sec



ASI290MM: 65 x 10sec (DFS on)



Lodestar X2C: 6 x 90sec



ASI290MM: 106 x 10sec (DFS on)

To compare the images side-by-side I have adjusted their histograms how I would if I were observing, which usually consists of adjusting the white point until the object is bright but not too noisy, and adjusting the black point so that the background is almost black but still visible. I have made an effort to adjust the ASI290 images to have the same overall brightness as the Lodestar images. The result is that when images of the same total exposure time are compared side-by-side, the images from the ASI290 are clearly noisier. To more clearly illustrate the relative noisiness of the images I have used the image analysis freeware Fiji to extract luminance values along a line across the middle of each image. Figure 3 shows the location of the profile line in the image, right through the middle of the central star in IC5146. The resulting data has been plotted in Figure 4. I find the results very interesting in that the magnitude of the noise is very evident, being quite large with the ASI290 with 30sec total exposure, a variation on the mean luminance value of roughly ±6000. For the single 30sec exposure using the Lodestar the variation on mean luminance is only approximately ±1200, a pretty significant difference.

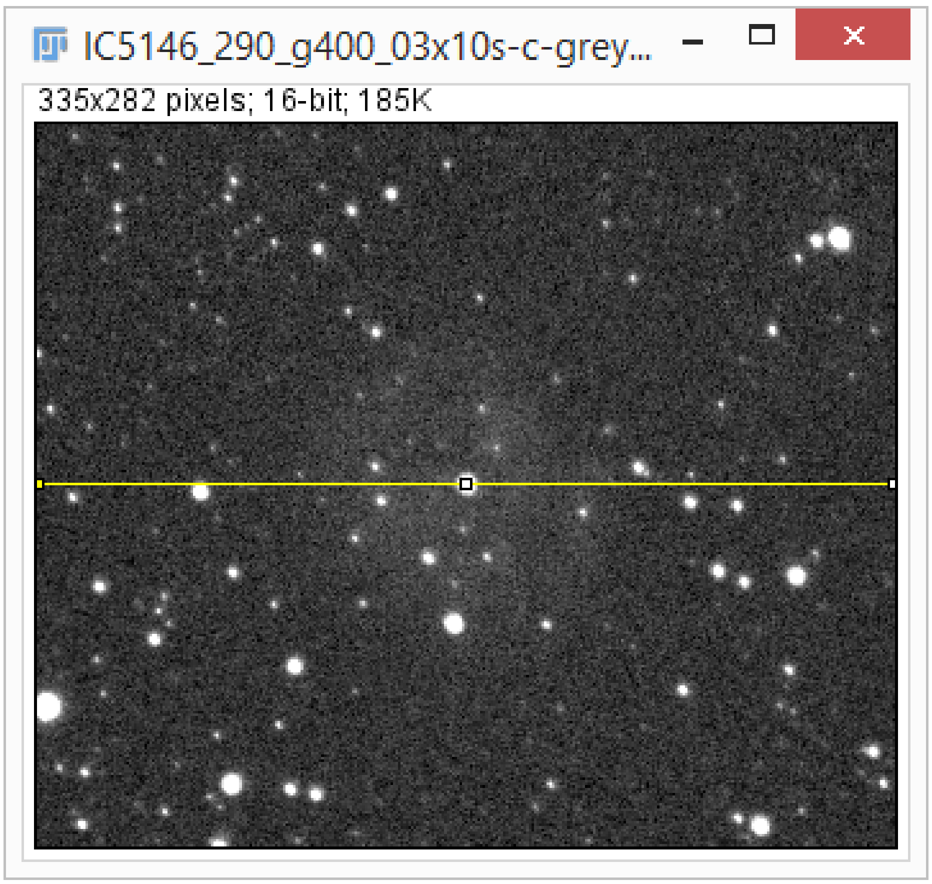


Figure 3 Line Location in FIJI for Profile Analysis

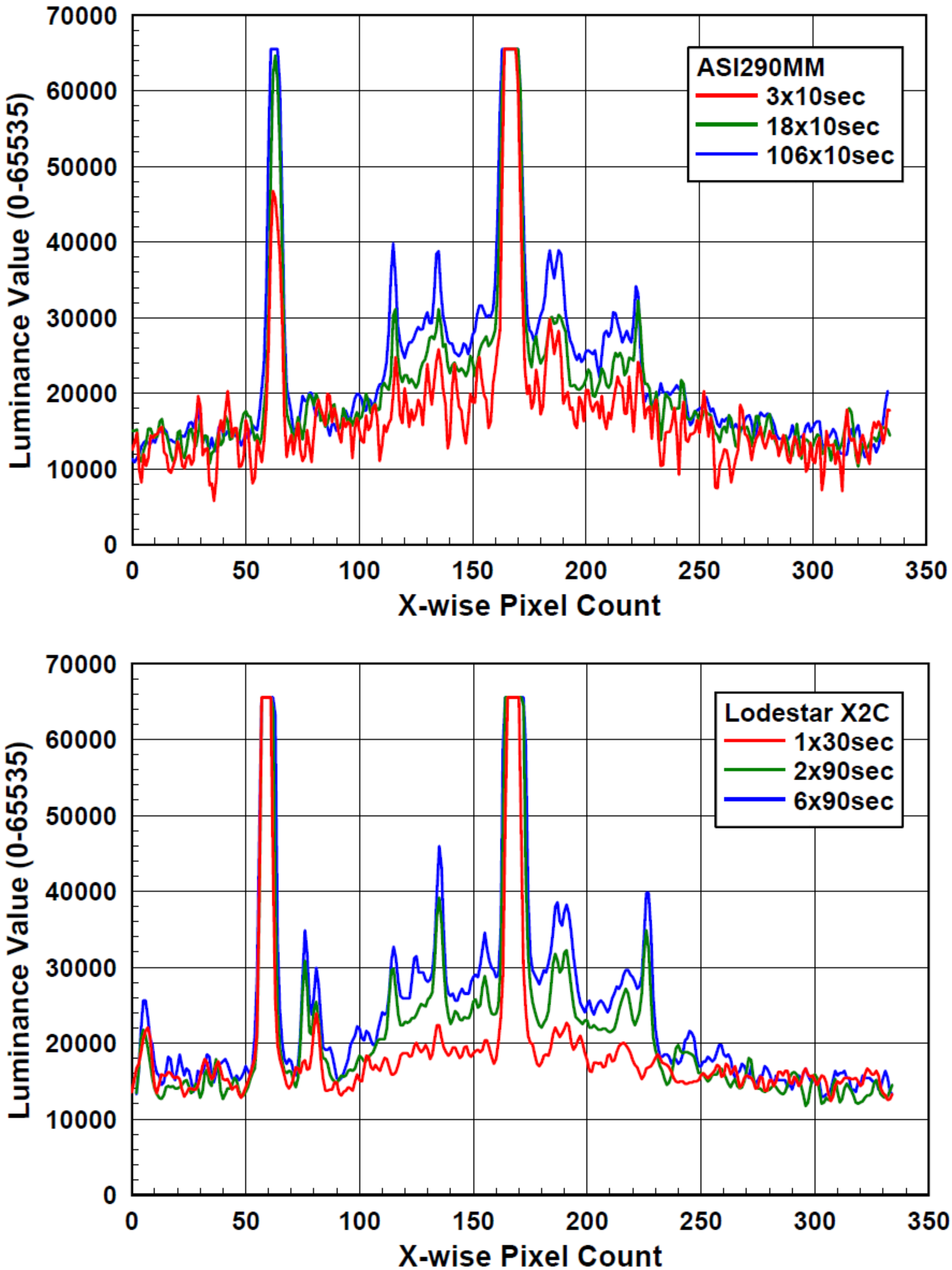


Figure 4 Line Luminance Profile Comparison

As the number of stacked frames increases with the ASI290 there is an obvious decrease in the magnitude of the noise in addition to the increase in total exposure time. This is the expected result of stacking, and is the basis of the "stack many short exposures" methodology many people use today with their CMOS cameras. Interestingly stacking does not seem to have as big an impact on the noise level in the Lodestar images. There is a small decrease in noise with number of stacks, but for my particular data set the main advantage of stacking images from the Lodestar is a longer total exposure. If I had not adjusted the image histogram during capture to be brighter with increasing total exposure time, the decrease in noise level with stacking may have been more obvious. This is true for both the ASI290 and Lodestar.

Another way of comparing the relative noisiness of the images is to look at the image histograms. Using the Fiji software again I selected the same rectangular region in the images that is mostly just background sky and compared their histograms. Figure 5 illustrates the region I selected, and Figure 6 shows the resulting histograms. Again the impact of stacking on the ASI290 images is very evident with the histogram getting taller and narrower, ie. progressively more and more pixels are close to the mean background luminance as you stack more images. Similar to the line profile data, the Lodestar images show very little change in the histograms with stacking, in fact I would argue that there is no change at all.

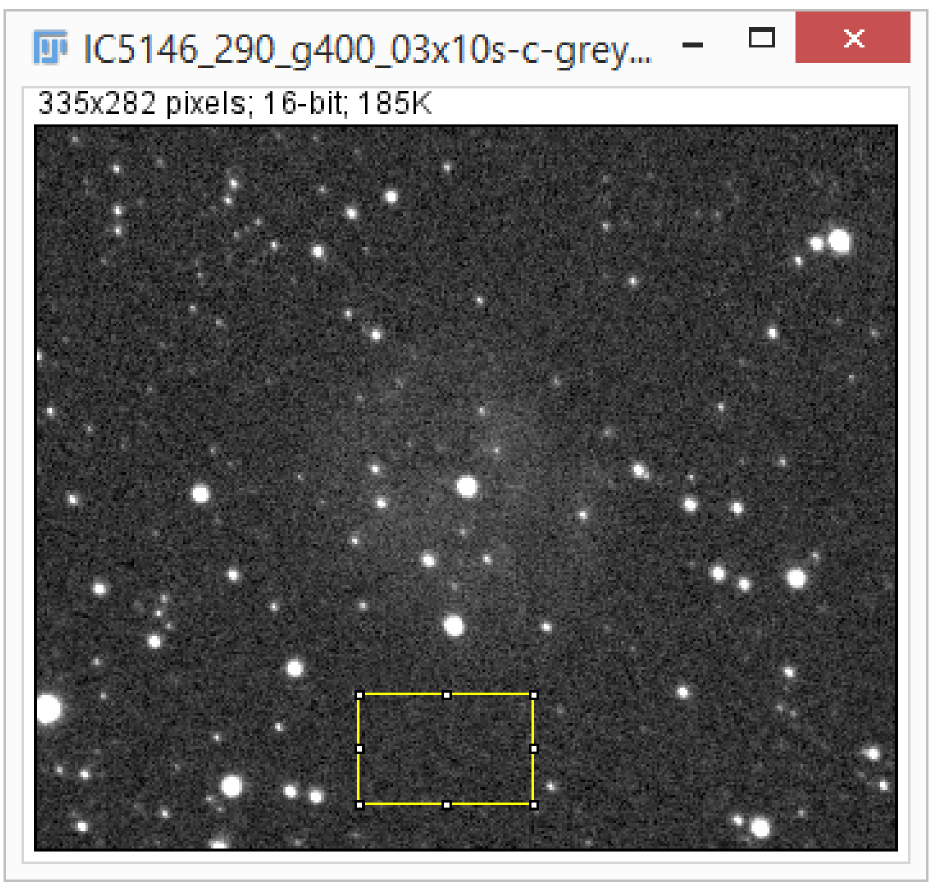


Figure 5 Rectangle Location in FIJI for Histogram Analysis

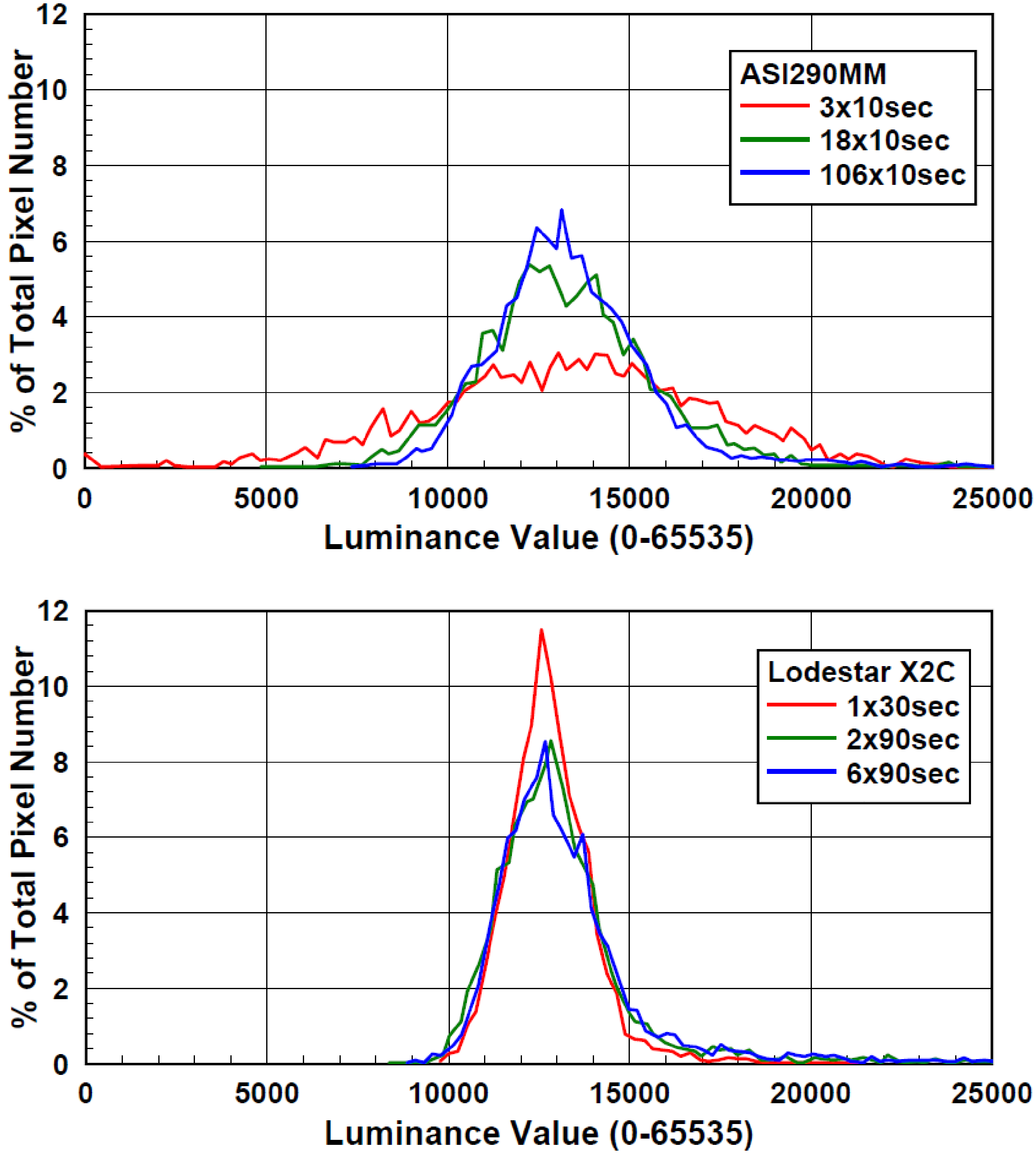


Figure 6 Image Background Histogram Comparison

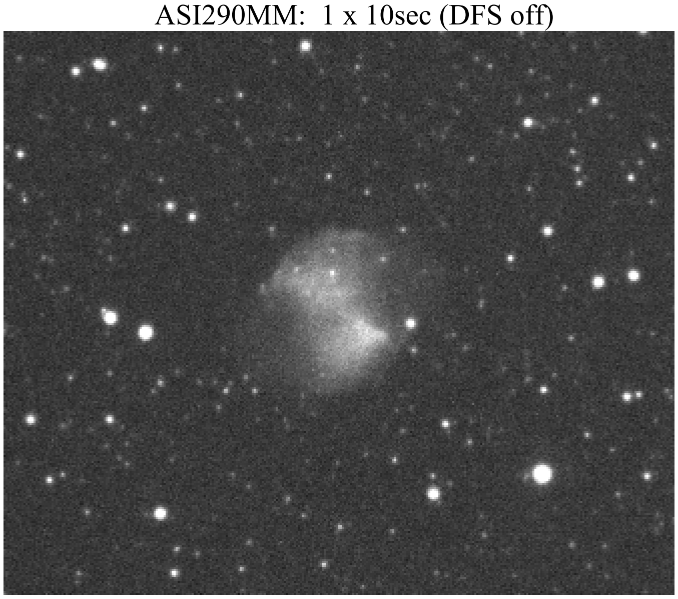
Comparing between the two cameras it would seem that the ASI290 needed more stacks to produce a background histogram as tight (tall and narrow) as the Lodestar. Even the 106x10sec image from the ASI290 does not have as tight a histogram as the 1x30sec Lodestar image. So how many stacks then would it take for the ASI290 to be equal? How many before the ASI290 is better?

The image sequence captured on IC5146 was the most complete of those collected. I have included images from some of the other objects I observed in the figures below, but have not performed any line profile or histogram analysis on them. They are presented for visual comparison only, to further support the findings from the IC5146 images. As mentioned above, all of the images captured during my testing session have been posted to an album on my Flickr account (see link above).

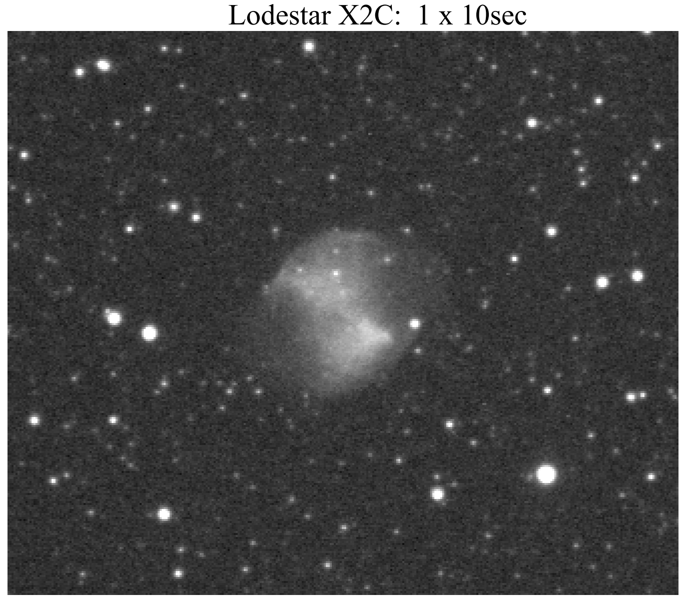
Figure 7 Dumbbell Nebula (M27) Comparison Images

ASI290MM: 1 x 10sec (DFS off)

Lodestar X2C: 1 x 10sec

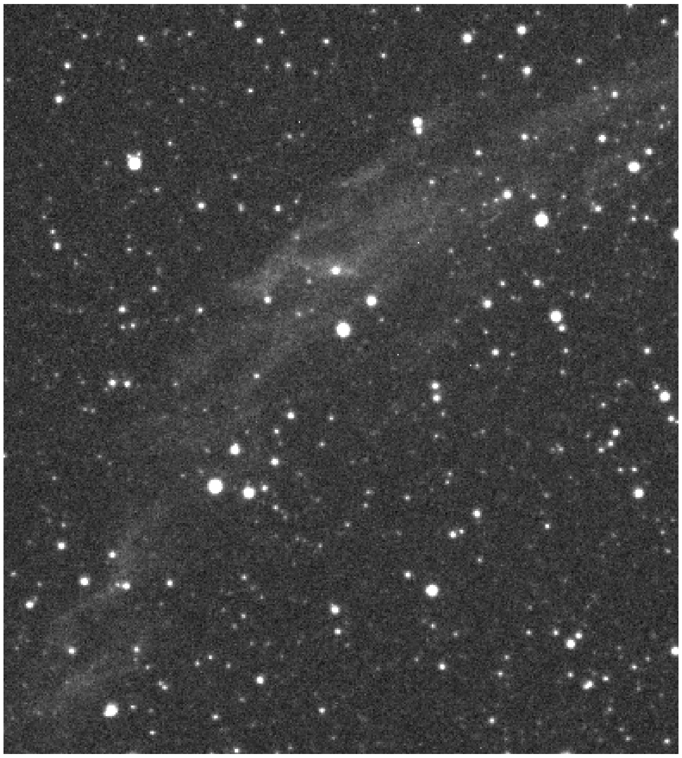


ASI290MM: 2 x 10sec (DFS off)

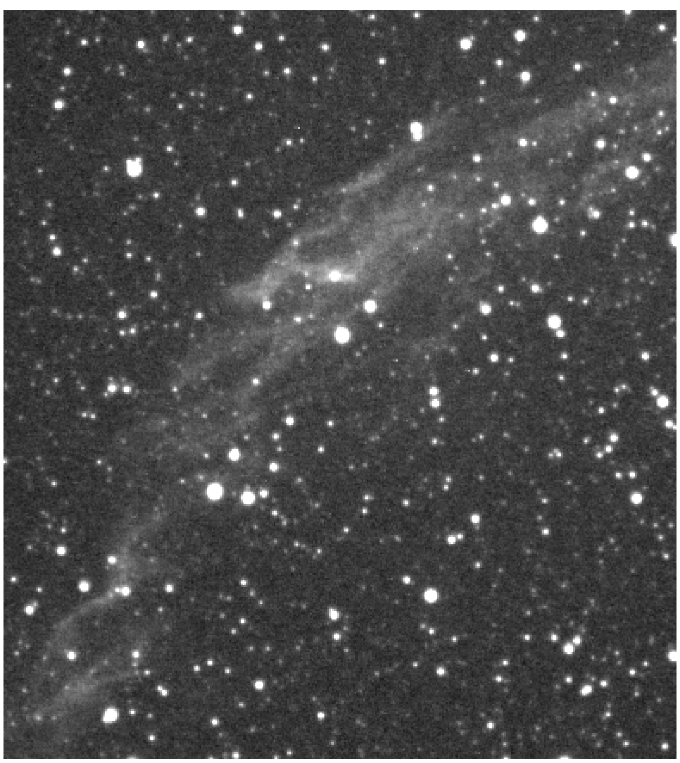


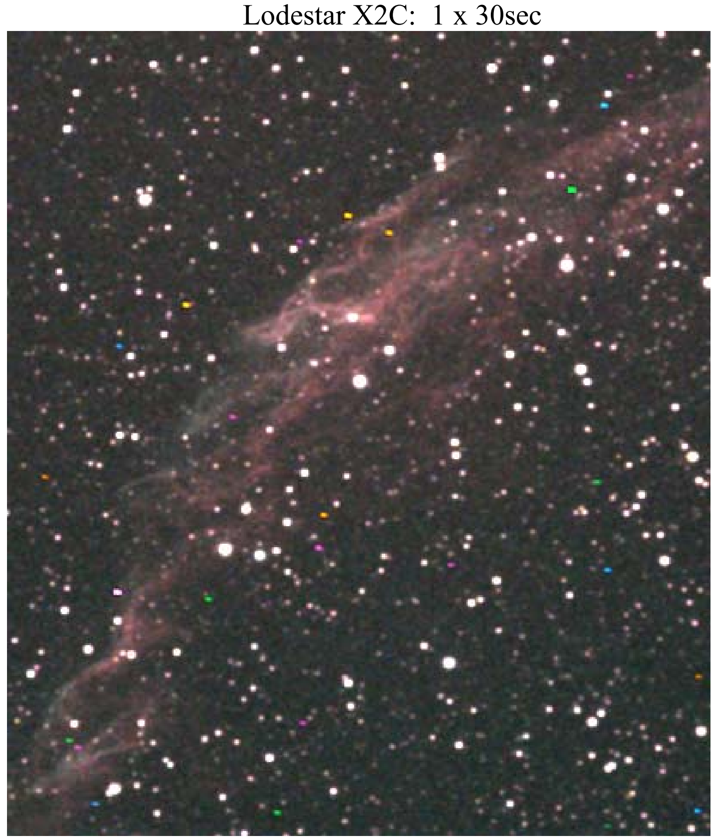
ASI290MM: 3 x 10sec (DFS off)

Figure 8 Western Veil Nebula (NGC6992) Comparison Images

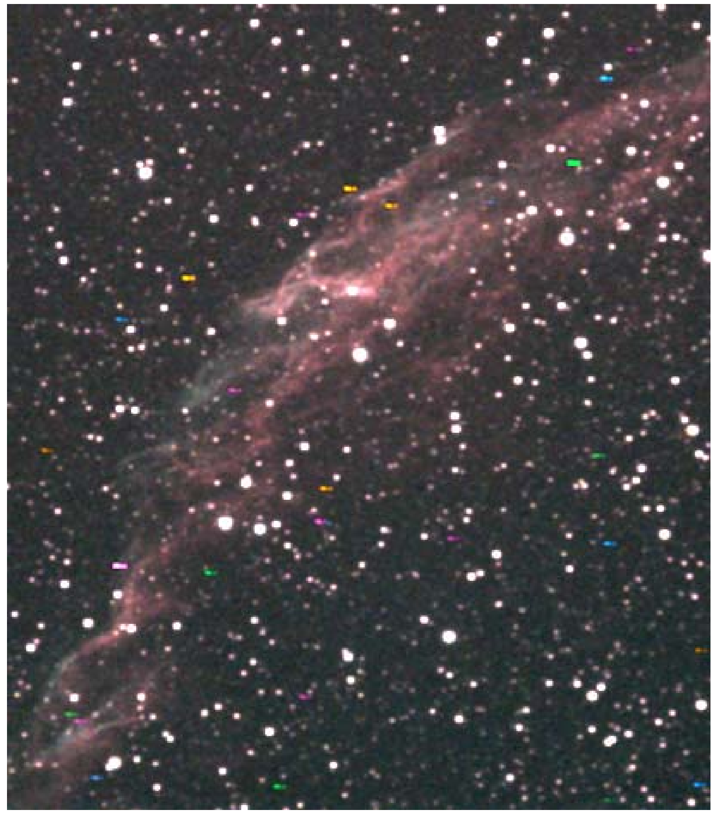

ASI290MM: 3 x 10sec (DFS off)


Lodestar X2C: 1 x 30sec


ASI290MM: 19 x 10sec (DFS off)


Lodestar X2C: 4 x 30sec

ASI290MM: 97 x 10sec (DFS off)



Lodestar X2C: 8 x 30sec

ASI290MM: 120 x 10sec (DFS off)

Conclusions:

Over the years using all my various cameras I have formed an opinion about CCD versus CMOS cameras for VA. The October 20th testing performed as part of this report, as well as a week-long session of observing back in September 2017 that I have not mentioned yet (see images on Flickr at: https://flic.kr/s/aHsm4TPyAF) have only served to reinforce my position. Based on my experience and the results presented in this test report I have drawn the following conclusions:

1. Despite the technical data and marketing information published on the latest cameras and the CMOS sensors upon which they are based, CMOS cameras are still not as sensitive as CCD cameras by a wide margin. By "sensitive" I mean that CMOS cameras are not able to deliver an image of similar quality (noise level, brightness of object) in the same length of time. The disparity of total exposure time would seem to be on the order of 6 to 10 times longer with CMOS, and that is with the CMOS sensor binned 2x2 (N.B. that from the images presented in this test report the difference is on the order of 3 to 5 times, but that is when comparing a monochrome CMOS to a CMYG colour CCD which incurs another factor of ~2x).
2. If provided enough time to stack sub-frames, a CMOS camera can produce an image of similar quality to that from a CCD. If that time is extended long enough the CMOS camera can even produce an image that is of better quality than the CCD. The CMOS based cameras that are in use today have higher resolutions and better dynamic range than the older CCD cameras used for EAA, so they have the potential to produce a nicer image if provided enough time.
3. Based on their relative performance, CCD and CMOS based cameras fit into two different categories of usage:
    a. Useful image in less than 1 or 2 minutes = CCD camera, best suited to live observing and public outreach;
    b. Useful image in 5 to 10 or more minutes = CMOS camera, best suited to detail observing of deepsky objects and low cost astrophotography.

So if you are looking to skip along through a list of objects in an observing session and don't want to be limited by the magnitude of the object or the length of time available, use a CCD based camera. If you want to focus on a couple interesting objects an evening and study/image them in more detail over the course of a few hours, use a CMOS camera. If you are observing relatively bright deepsky objects only (eg. Messier objects) or if you have access to very fast optics (eg. Hyperstar), the length of time to a useful image is much shorter, but this would be equally true for a CCD camera as for a CMOS camera. CCD cameras based on the ICX825 sensor sit somewhere in between the two categories of usage mentioned above. They retain a good percentage of a CCD's sensitivity advantage but also have higher than SD resolution. For many they provide a good compromise between time and image quality.

Next steps for me include further investigation into the relative performance of different CMOS based cameras. I have already posted some results on Cloudy Nights from a four camera (ASI185, ASI290, ASI294, & ASI385) comparison I have started, but I intend to do more testing to confirm what their performance is compared to each other as well as with a CCD camera. Another thing I would like to test is using the ASI290 in a way that is not like what most people are doing, which is short exposure times and high gains combined with many stacked frames. I want to try longer exposures with lower gains and many stacked frames, and long exposures with high gains but a very small number of stacked frames similar to how the Lodestar was used during this test.

I hope my work is useful to the EAA community. If you have any questions, please feel free to contact me at: karmalimbo@yahoo.ca

Cheers,

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