Color Astronomical Imaging Using Polarizing Filters

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Many types of astronomical objects can be imaged using amateur telescopes and cameras offering nearly limitless opportunities for exploring celestial wonders from a suburban backyard. Most commonly images are taken using standard RGB filters and the resulting images are deemed "true color". These images feature colors that would be similar to what would be obtained using color film in a conventional film camera. An example of a true color image taken by the author can be seen in Figure 1.

Over the past five years the author has concentrated on the use of emission line filters for imaging nebulae and this activity has produced a number of images that have a very different appearance than those taken using traditional true color techniques. Additionally the filters actually provide a means to "deconstruct" the nebula revealing individual spectral lines of the constituent elements comprising the nebula. Such images can provide insight into ionization potentials within the nebulae.

One of the properties of narrowband emission line filters is that only light of a small wavelength range will pass through the filters, while all other light is blocked. This characteristic behavior of the filters mitigates the effect of light pollution; be it man made or natural (such as The Moon). This offers an important benefit to astronomers operating in less than optimal dark sky conditions. An example
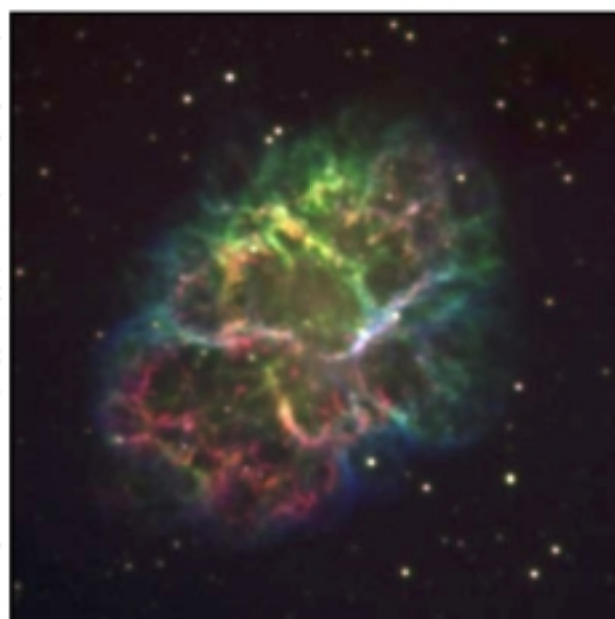

Figure 1- The Crab Nebula in LRGB

Figure 2 - The Crab in SII, Halpha, O-III
SII=Red, Halpha=Green, O-III=Blue

of an emission line image of the Crab Nebula taken by the author from a relatively bright suburban backyard is seen in Figure 2.

The out of band blocking of the emission line filter will also block broadband radiation emanating from the core region of the Crab Nebula. The effect of the blocked broadband radiation can be seen by comparing Figure 1 to Figure 2: the "fog" is missing in the emission line image. As a result a significant proportion of the radiation emanating from the Crab Nebula is lost when using emission line filters.

At the moment the most common ways for amateurs to make an image of the Crab Nebula have been to take RGB/LRGB (aka "true color") images or emission line images.

A goal of this paper is to introduce to amateurs an alternate method, the use of linear polarizing filters, for such imaging of the Crab Nebula and other objects. Before doing so, it is appropriate to discuss the nature of the Crab Nebula in order to better understand why the proposed alternate method works as it does.

Thermal and Non-Thermal Radiation

The light radiated by most astronomical objects is thermal radiation. Thermal radiation is generated when heat from the random movement of subatomic particles within atoms is converted to electromagnetic radiation. The wavelength range and spectral intensity of the emitted radiation is strictly a function of the temperature of the object and obeys Planck's Law for blackbody radiators.

The broadband light in the core of

the Crab, however is non-thermal and is created in an entirely different way. When a charged particle passes through a magnetic field it will travel in a spiral path. Because the path is curved, the particle undergoes acceleration.

When a charged particle is accelerated a photon is emitted or absorbed.
An ultra-relativistic electron (one traveling close to the speed of light) travelling through a magnetic field travels in a spiral path and will emit electromagnetic radiation called Synchrotron Radiation. Synchrotron radiation is broadband and doesn't follow Planck's Law for blackbody radiators in terms of intensity versus wavelength. At the heart of the Crab Nebula is a pulsar that emits synchrotron radiation.

One of the properties of Synchrotron radiation is that it is highly polarized. In the case of the Crab nebula it is strongly linearly polarized and its discovery played a key role in the process of explaining the operating mechanism of the Crab Nebula in the late 1960s.

Imaging with a Polarizing Filter

Using a polarizing filter, an image of the Crab Nebula was taken by the author. Three different polarization angles were used: Vertical, Horizontal and 45 degrees. The data from the filter when oriented vertically was assigned to the Red channel, the 45 degree orientation assigned to Green and the Horizontal orientation was assigned to Blue. The resulting image, referred to by the author as a **Simple Polarigram**, is shown in Figure 3.

Changing the palette by assigning R= 135 degrees, G= Vertical and B= Horizontal but otherwise processed in the same way as Figure 3, the image in Figure 4 was created by the author. The simple polarigram method described above offers an alternate way to image

Figure 3: Simple Polarigram of Crab Nebula
Polarizer orientations:
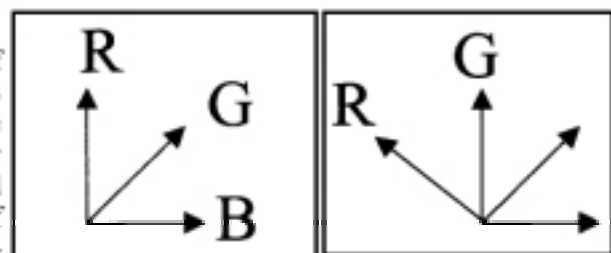*Red = Vertical, Green = 45 degrees, Blue = Horizontal*

Figure 4: Simple Polarigram of Crab Nebula
Polarizer orientations:
Red = 135 degrees, Green = Vertical, Blue = Horizontal

the Crab Nebula and in so doing, reveals otherwise latent structural details of the nebula. In this case,

instead of revealing a core unobstructed by the fog such as the emission line image reveals, the polarization of the broadband synchrotron radiation is revealed, exposing one of the key signatures of such synchrotron radiation.

A technical Issue and a solution

Since non-polarized light includes all angles of polarization an unpolarized source will pass some amount of light through a polarizer, albeit attenuated. Additionally every filter will have some "leakage" of signal that should be rejected but passes through the filter in an attenuated state.

The filaments surrounding the core of the Crab Nebula are classic emission line sources and do not exhibit polarization. However they do appear in the simple polarigrams shown in Figures 3 and 4 above but muted compared to the emission line image of Figure 2.

Other regions of the Crab Nebula also emit unpolarized light mixed with the polarized synchrotron radiation. The output of the polarizers will include this undesired "common mode" signal. A schematic view of this mixing of the desired and undesired common mode signal contained in the output of the polarizers is shown in **Figure 5**.

If the image from one polarizer orientation is subtracted from the image from another orientation, the unpolarized common mode signal is eliminated. For example if the image from the Horizontal polarizer is subtracted from the Vertical polarizer's image, the result contains only the polarized signal of interest with none of the undesired common mode signal.

The work of Sir George Gabriel Stokes in 1852 taught a convenient mathematical method for describing the polarization
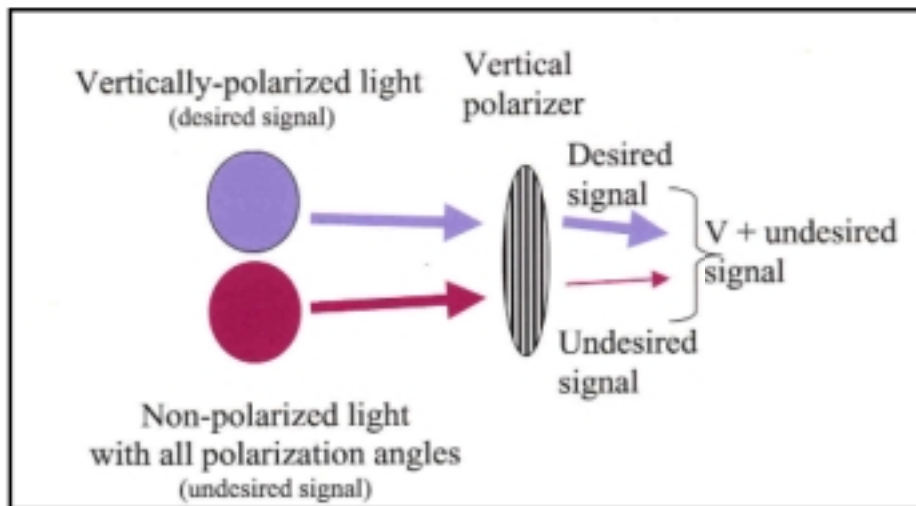
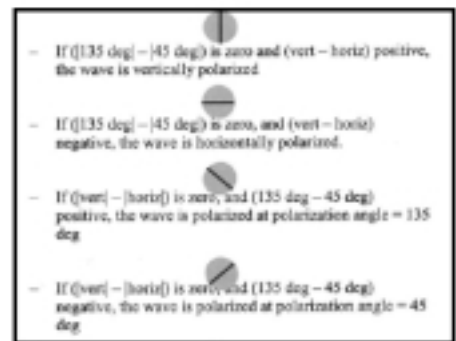Figure 5: Undesired common mode signal mixed with the desired polarized signal

- If (|135 deg| − |45 deg|) is zero and (vert − horiz) positive, the wave is vertically polarized

- If (|135 deg| − |45 deg|) is zero, and (vert − horiz) negative, the wave is horizontally polarized.

- If (|vert| − |horiz|) is zero, and (135 deg − 45 deg) positive, the wave is polarized at polarization angle = 135 deg

- If (|vert| − |horiz|) is zero, and (135 deg − 45 deg) negative, the wave is polarized at polarization angle = 45 deg

Figure 8: polarization angle determination

ing other angular combinations can be used to make a color image as shown below.

Figure 6 is such an image. In this case the data from the 135 and 45 degree filters were subtracted and the difference was used for the red channel of a color image. The green channel's data is the difference between the horizontal polarizer's data and the vertical polarizer's data. The blue channel's data is the difference between the data from the 45 degree and horizontal polarizers.

As Figure 6 shows, the Crab Nebula has significant polarization with virtually every region showing different angular orientation of the polarization and has a rather unusual appearance when so displayed. Other polarizer angle differences and color channel assignments can be chosen to make color images of differing colors. The structural delineations don't fundamentally change in these alternate renditions typically although the colors and contrast do. One such example is seen in **Figure 7**.

In Figure 7 the polarization gradients are not as pronounced as in Figure 6. Note that the angles are all referenced to 135 degrees in Figure 7 versus in Figure 6 which has two of the three angles being orthogonal and being offset by 45 degrees relative to each other.

This affects the contrast observed in these images. For that reason and another explained below, the author prefers and recommends the angle pairs used in Figure 6 over those used in Figure 7.

If the images from two orthogonal polarizers are subtracted and the result is zero, it implies that either there is no polarized signal or the polarized signal
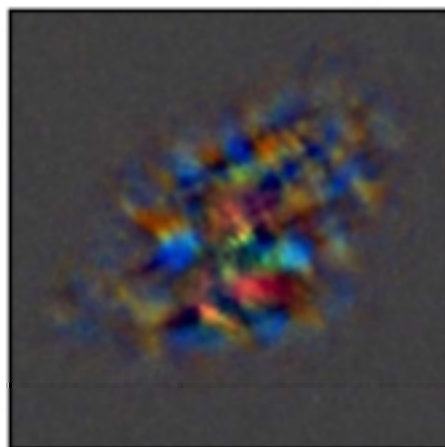

Figure 6: Stokes Parameter polarigram of Crab Nebula Polarizer Differences: 135deg- 45 deg = Red, V − H = Green, 45 deg − H = Blue
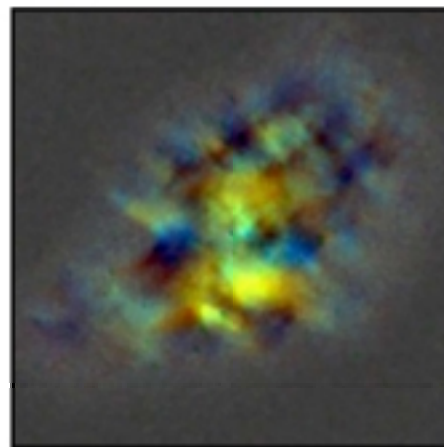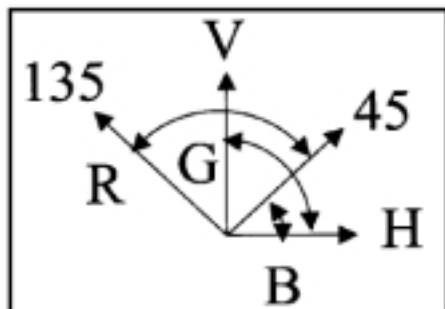

Figure 7: Alternate Palette Rendition Polarizer differences: 135deg - V = Red, 135deg − 45 = Green, 135 deg − H = Blue

state of electromagnetic radiation.

From a simple perspective, Stokes defined four parameters, S0, S1, S2 and S3 that completely described the polarization state of an electromagnetic wave, including light. In Stokes' work, the 90 degree and 0 degree oriented polarizers were summed and called S0, this amounts to luminance in the world of amateur ccd imaging. The second Stokes parameter, S1 is computed by subtracting the 0 degree from the 90
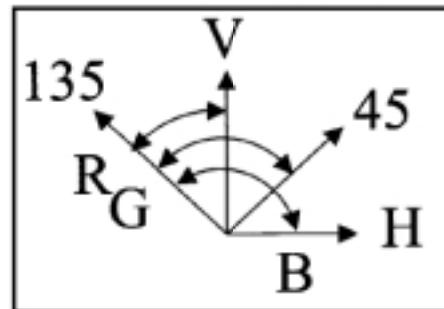
degree polarizer data.

Likewise the S2 parameter is the difference between the data from the 135 degree and 45 degree polarizers. Stokes also decomposed a circular polarization component, named S3 that is the difference between a right –hand and left-hand circular polarizer, but we will ignore that parameter for this work.

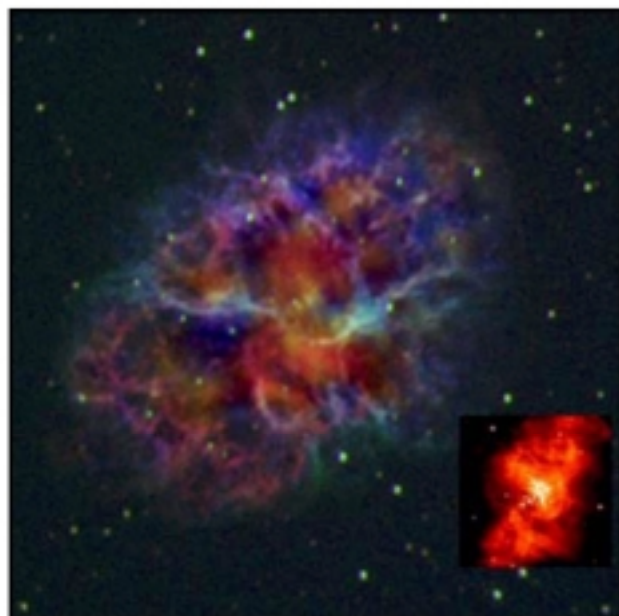The various Stokes parameters or modifications of them such as subtract-

Figure 9: Stokes polarigram rendition combined with Emission Line Image a Hubble Space Telescope Image is inset for reference

is equally strong in each polarizer orientation. The latter case results when the target light's polarization angle lies halfway between the angles of the polarizers or any 90 degree rotation from that halfway angle. For example if the difference signal from the 135 and 45 degree polarizers is zero then the target polarized wave's angle is at 0 degrees or 90 degrees if there is any polarization in the signal.

The latter question is answered by taking the difference between the vertical and horizontal polarizer signals. If there's a
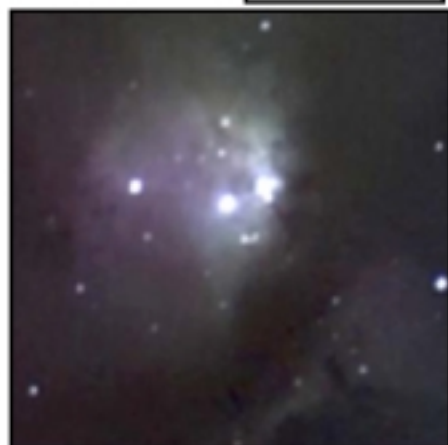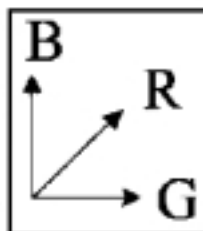

positive difference while the 135-45 delta was zero, then the target light's polarization is vertical (90 degrees). If the resulting signal is negative when the vertical and horizontal polarizer signals are subtracted, then the target light's polarization is horizontal. Four such special cases are illustrated in **Figure 8**.

Composite Images using Stokes Parameter Images

While the Crab Nebula's Stokes Parameter renditions may have an interesting and bizarre appearance when compared to conventional images, images so made can be effectively used in a composite image to highlight the pulsar region in the core. For example using emission line data blended with the Stokes Polarigram data, a composite image can be created that has a unique appear-

ance. The Stokes polarigram data greatly assist in visually enhancing the pulsar region. Additionally the colors are modulated by the polarization of the inner structure which provides a visualization of such polarization.

A composite image made from the data used to make Figures 2 and 6 yields the image in **Figure 9**.

Note that the pulsar region in the composite image is rather prominent and is readily identified by comparing with the image taken of the embedded pulsar by the Hubble Space Telescope shown as an inset to Figure 9.

Other Objects for exploration with Polarigraphy The Crab Nebula is unique in the skies of the Northern Hemisphere. There's really no other large pulsar of similar brightness with optical polarization so readily observed. However Synchrotron radiation is not the only optical radiation that exhibits polarization that can be imaged using the polarigraphic techniques described above.

Polarization can result from nonpolarized light reflecting off a surface. One example is the sun reflecting off water. In that case the reflected light from the water surface is horizontally polarized. In an analogous manner starlight can be reflected off dust particles.

Dusty star forming regions often have large circumstellar discs that influence the collimation of stellar jets, the formation of cometary/bipolar reflection nebulae and large scale cold molecular outflows (1). These discs may contain magnetically aligned microscopic grains which can create a polarizing region of reflection nebulosity.

As of early February 2007, the author has photographed two objects exhibiting such polarization from star forming regions that have significant reflection nebulosity, M78 (NGC2068) and Hubble's Variable Nebula (NGC2261). The first is from M78 and both the simple polarigram and the Stokes polarigram are shown below as Figures 10 and 11 respectively.
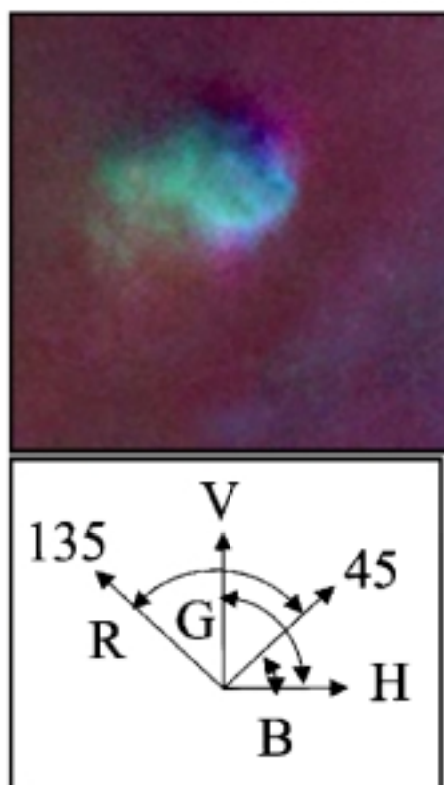

Figure 10. Simple Polarigram of M78 Polarizer orientations:Red = 45 degrees, Blue = Vertical, Green = Horizontal

Figure 11. Stokes Polarigram of M78 Polarizer differences:135deg- 45 deg = Red, V – H = Green, 45 deg – H = Blue

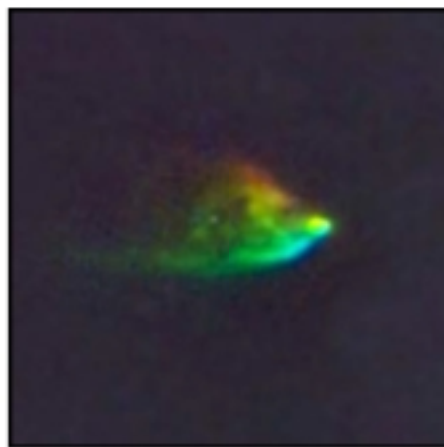Figure 12: Hubble's Variable Nebula
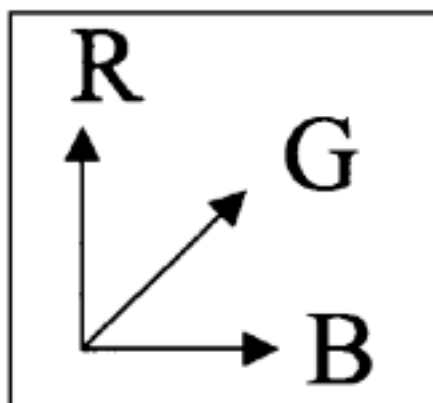(NGC2261) in RGB

Figure 14: Stokes polarigram of
NGC2261 Polarizer differences:
135deg- 45 deg = Red, V – H = Green,
45 deg – H = Blue

Figure 15: Stokes Polarigram
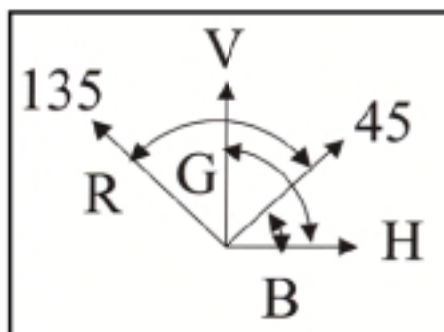combined with RGB Image

Figure 13: Simple Polarigram of
NGC2261 Polarizer OrientationsRed =
Vertical, Green = 45 degrees, Blue =
Horizontal

In Figure 12 is an RGB image of Hubble's Variable Nebula, also known as NGC2261. In Figure 13 is a simple polarigram of it while in Figure 14 is a Stokes polarigram of the same object. Finally in Figure 15 is a composite image made from the RGB image and the Stokes polarigram.

Image Processing

There are numerous practical considerations when processing the image data using the concepts described in this paper. Areas needing attention include raw data calibration, photometric normalization and the loss of numerical precision that can present a hazard when subtracting numbers of similar magnitude. Specific methods that have been developed are unfortunately beyond the scope of this article but are planned for a future work.

Discussion and Conclusion

This work has shown that the use of polarizing filters are effective at revealing optical polarization in the Crab Nebula, M78 and Hubble's Variable Nebula. Two different data reduction methods were used to process the images: direct mapping of polarizer outputs to color channels and the mapping of differences between pairs of polarizer outputs so as to eliminate the non-polarized common mode signal.

Strong linear polarization is observed in the simple and Stokes polarigrams of the Crab Nebula published in this paper. Additionally, a composite image of the Crab Nebula was made, combining the Stokes polarigram with an emission line image. The resulting image showed enhanced visualization of the pulsar region, yet is comprised solely of visible light images.

Previous work by Malin and Pasachoff* used a photographic technique for performing the differencing of the polarizer channels. While an ingenious process, practical considerations involving the film medium made the process somewhat difficult in comparison with today's digital methods. In this work the all-digital technique used by the author permitted complete freedom in selecting the channels to subtract so that many more combinations could be tried in search of some of the more interesting combinations of data.

The primary consideration used by the author for selecting the channel pairs to be differenced was the noted simplicity of computing the polarization angles by using pairs of orthogonal channels offset by 45 degrees for the differencing as illustrated in Figure 8.

Coincidentally the image produced using the channel pairs in this configuration yielded a more detailed image than the previous work by Malin and Pasachoff.

The Crab Nebula Stokes polarigram of Figure 6 is the most highly detailed Stokes polarigram thus far published to the best knowledge of the author. Furthermore the composite image of the Crab Nebula (Figure 9) is the first such image published that is known to

the author. The composite image provided a novel way to enhance the visualization of the pulsar region's magnetic field while using only optical data taken with a conventional ground-based amateur telescope and ccd camera.

An additional difference in this work and the previous work were the simple polarigrams that accompanied the images. While a simple concept with noted scientific deficiencies, the technique has potential in artistic renderings of astronomical objects, which is a major goal of this work.Finally Malin and Pasachoff's work focused solely on the Crab Nebula, while this work has used the Crab merely as a departure point to begin a larger survey. This work also included M78 and NGC2261.

Reflection nebulae M78 and NGC2261 exhibited significant linear polarization in the simple and Stokes polarigrams introduced in this paper. To the best knowledge of the author, these polarigram images of M78 and Hubble's Variable nebulae are the first such images published of these objects.

As reported previously by Scarrott et al(1), and Aspin et al(2), NGC2261 exhibits linear polarization around R Mon. Aspin's work reports the source of this polarization to be a circumstellar disk comprised of magnetically aligned particles, consistent with the speculation of the author when the target object was selected.

Likewise, the M78 region (NGC2068) is another star forming region that shows linear polarization due to magnetically aligned dust grains. Such polarization is observed in both polarigrams of the object reported in this work.
Considering the vast number of star forming regions with significant reflection nebulosity, the author expects to find many more objects exhibiting linear polarization using the techniques described in this paper.

Equipment

With the exception of the Emission Line image shown in Figure 2, all images were taken using a 450cm f/12.6 home built classical cassegrain

telescope equipped with a focal reducer providing a final 3366mm focal length, or approximately f/7.46. The CCD image sensor used was a Kodak KAF3200ME 3.1 megapixel CCD without coverslip mounted in a Finger Lakes CM10 Maxcam. The image scale was 0.42 arc-sec/pixel.

The Emission Line image of Figure 2 was taken using a Celestron C14 telescope at f/12.46 with a Tektronix TK1024 Back Illuminated 1 megapixel CCD mounted in a Finger Lakes IMG1024S Dream Machine camera.The image scale was 1.12 arc-sec/ pixel.

The polarizer used was an all glass polarizer made by Edmund Optics Corp. The emission line filters used were Custom Scientific 3nm FWHM AR-Coated amateur grade and the RGB filters used were Optec IR-blocking RGB filters.

This work will be described in more detail in late September 2007 at the East Coast Conference for Astronomical Imaging (ECCAI 2007).

References:
* The Malin and Pasachoff image can be found at:
http://www.aao.gov.au/images/captions/crab_pol.html

(1) S.M Scarrott, P.W. Draper and R.F. Warren-Smith "The origin of the 'polarization disc' in NGC2261 / R.Mon", Mon. Not. R. astr. Soc (1989) 237, 621-634

(2) C. Aspin, I.S. McLean, and G.V. Coyne, "CCD observations of bipolar nebulae III. R.Mon / NGC2261", Astron. Astrophys. 149, 158-166 (1985)

Editor's Note
Richard's work holds scientific interest, and even in grayscale (our print subscribers), the variations in the narrowband and phase shifted images hold intrigue, and reveal fascinating information about the structural detail of the object. But to receive the full impact of Richard's work, and his art, please visit our web site for the full color supplemental material. A link is available on the main page, from the article summary, or directly from the supplemental material page.