

## PHILOSOPHY FOR THE CREATION OF ASTRONOMICAL IMAGES

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### ABSTRACT

The quality of modern astronomical data, the power of modern computers and the agility of current image-processing software enable the creation of high-quality images in a purely digital form. The combination of these technological advancements has created a new ability to make colour astronomical images. These programs use a layering metaphor that allows for an unlimited number of astronomical datasets to be combined in any desired colour scheme, creating an immense parameter space to be explored. A philosophy is presented on how to use scaling, colour and composition to create images that simultaneously highlight scientific detail and are aesthetically appealing. This philosophy is necessary because most datasets do not correspond to the wavelength range of sensitivity of the human eye. The use of visual grammar, defined as the elements that affect the interpretation of an image, can maximize the richness and detail in an image while maintaining scientific accuracy. By properly using visual grammar, one can imply qualities that a two-dimensional image cannot show intrinsically, such as depth, motion and energy. In addition, composition can be used to engage viewers and keep them interested for a longer period of time. The use of these techniques can result in a striking image that will effectively convey the science within the image to scientists and to the public. Details of the pictorial examples used are presented in the conference web-proceedings and webcast.

### INTRODUCTION

For many decades astronomical colour images have been generated using large-format photographic plates and traditional darkroom techniques, (e.g. Malin, D. Royal Astron.Soc.Quart.Jrn. 33, 321, 1992). In the early 1980s, charge-coupled device (CCD) detectors began to replace photographic plates as the instrument of choice for astronomical research. However CCD arrays lacked the number of pixels necessary until recently to compete with the fine grain of photographic plate emulsion. In

recent years CCD detectors have grown in size, the physical size of pixels has decreased and mosaics of CCD arrays have been implemented in many instruments. The large numbers of pixels in these cameras now allow high-quality optical images to be generated in a purely digital form.

Furthermore, the continuous improvement of imaging capability in non-optical windows of the electromagnetic spectrum has enabled the creation of high-quality images at other wavelengths as well. Historically, astronomical images have been made by combining greyscale images taken through red, green and blue optical filters. But often images are made from datasets that are either outside the optical window or do not match the characteristics of the colour-detecting cones in the human eye.

The development of advanced astronomical instrumentation has been contemporaneous with the advancement of computing power and, in particular, digital image-processing (IP) software for commercial applications. These IP programs, e.g., Adobe Photoshop, Photoshop Elements and The GIMP, offer unprecedented power, flexibility and agility in digital image generation and manipulation. The combination of these technological advancements has led to a new ability to make colour astronomical images. And in many ways, it has generated a new philosophy in the creation of these images. No illustration of this is more apparent than the “Pillars of Creation” image of the central region of the Eagle Nebula (M16), with the *Hubble Space Telescope* (HST) [Hester, J. & Scowen, P. 1995 “Embryonic Stars Emerge from Interstellar ‘EGGs,’” STScI Press Release 1995-44.]. This image demonstrated the tremendous resolution of the HST Wide-Field Planetary Camera 2 (WFPC2) camera. It also showed how narrow-band imaging can change our view of an object. It also demonstrated how colour schemes can be used to imply depth, motion and texture in an astronomical image. Just as importantly, it illustrated how effectively such images can inspire the public and generate enthusiasm for astronomy in general.

Generating a colour image can be distilled into the following steps: (1) intensity scaling and projection of each dataset into greyscale images; (2) importing the datasets as layers into an IP software package; (3) assigning a colour and intensity rescaling to each layer; (4) fine tuning the image, which includes overall colour balance, the cleaning of cosmetic defects, and orientation and framing; and (5) preparing the image for electronic distribution and print production. Prior to image generation, it is also very important that your monitor is colour calibrated and a colour management workflow is established. These techniques are described in detail in Rector et al. (<http://arxiv.org/abs/astro-ph/0412138>).

## PROCEDURE

More than one dataset, and preferably at least three, should be combined to produce a colour image. A dataset is defined as a two dimensional image of a particular waveband, polarization or other distinct characteristic; e.g., an optical image through a single filter, or a radio image at or in a particular waveband and/or polarization. These techniques are designed to take advantage of the distinct structural information in each dataset for which they were obtained. For comparison, a popular technique among amateur astronomers is known as the LRGB method, (e.g., Gendler, R. "Astro Imaging—Creating High-Resolution Colour CCD Mosaics with Photoshop," *Sky & Telescope*, August 2003, pp. 130-134 2003), wherein an image is first generated in the traditional "natural colour" scheme from datasets obtained through red, green and blue filters. To improve the image quality, an unfiltered, "luminosity" image is added that lacks colour information but has a higher signal to noise ratio. This technique is well suited for small aperture telescopes because most objects are limited by relatively poor signal to noise. The LRGB method is effective for decreasing the noise in an image, but results in a loss of wavelength-specific structural information. This method is not well suited for use with scientific data, which is rarely obtained unfiltered. Indeed, narrow-band observations are obtained specifically to increase the contrast between emission-line and continuum-emission regions of an object. Thus the quality of an image can actually be improved by the exclusion of particular wavebands.

## PHILOSOPHY OF IMAGE CREATION

Historically, a small percentage of telescope time has been used to create public outreach photographs to appear in the news, textbooks and magazines. However photography is now rarely used; and currently two other sources for outreach images dominate. One source is images from research data that are directly provided by individual astronomers or by image-making teams. These images are created with the specific intention of being released to the public. In the other case, institutional news and public relations teams appropriate images and figures that were created by scientists with the sole intention of communicating to their colleagues. These images are often released to the public stripped of their captions and therefore lack a guide as to how to understand them. It is particularly this latter case that makes the issue of how images are constructed, and subsequently interpreted by the non-expert, of relevance to astronomers.

In general, the lay person has little understanding of how astronomical images are made. And inevitably astronomers and image processors are asked about the authenticity of the representation, with such questions as, "is that what it really looks like?" and, "is this what I would see if I were standing right next to it?" It is beyond the scope of this paper to discuss the physiological and psychological response of the human eye to the intensity and colour of light, however it is worth noting that the

answer to the above questions is always “no,” regardless of how the image was generated. Images can be generated that do render the “intrinsic” colours of an object as closely as possible by using a set of filters that cover a wavelength range similar to the human colour-vision range and by photometrically calibrating the filters relative to each other. And yet these images also differ from human perception for several reasons, including the eye’s poor sensitivity to red light and its inability to detect colour from faint light. Additionally, contemporary astronomical images tend to display observations in selected, limited-wavelength ranges; and these ranges are distributed throughout the entire electromagnetic spectrum, not just the optical. Thus, an image serves as an illustration of the physical properties of interest rather than as a direct portrayal of reality as defined by human vision. After all, the reason for using a telescope is to show what the human eye cannot see.

This is not to argue that one is free to perform any image manipulation, as the intention is to retain scientific accuracy. To move, modify or delete structure within the data for aesthetic reasons is not allowable if the goal is to portray the true nature of the object. What manipulations are then allowable, and even desirable? Colour and intensity scaling schemes that maximize the richness and detail within the object should be used to convey the most information about the source while retaining the visual qualities that make it naturally intriguing. In particular, “visual grammar,” defined as the collection of elements that affect the interpretation of an image, can be used as a guide for finding a composition and colour scheme that highlights aspects of the astronomical object while retaining scientific accuracy.

The employment of visual grammar when choosing the intensity scalings, colour scheme and composition is crucial for producing an image that is clear without a legend, thereby making it legible to the public, and sufficiently engaging. The process is similar to that used by 19th-century painters who portrayed the newly-explored American West for a public that was as unfamiliar with it then as they are now with the far reaches of space (Kessler, E., Ph.D. dissertation, University of Chicago 2004). The challenge is to create an image that accurately conveys the nature of an unknown world in a way that is both exotic and inviting. While this may appear to be a conflict between art and science, it is the contention of the authors that it is possible, and indeed worthwhile, to address the aesthetics of the image while simultaneously articulating the scientific content of the data. The use of colour and composition to achieve these goals is discussed below.

It is important to generate an image that focuses on the astronomical content and not on the method of data acquisition or image construction. In this regard, it is important to note that the public does have expectations based upon past experience;

## CHOOSING A COLOUR SCHEME

e.g., spiral galaxies are expected to have bluish disks because most images of spiral galaxies are that colour. From prior experience the public has developed a mental link between the colour and morphology of spiral galaxies. Thus, an image of a green spiral galaxy can be distracting. In contrast, the public does not necessarily expect nebulae to have a particular colour because each nebula has a unique morphology. And few nebulae are well known to the public, although notable exceptions do exist, e.g., the Horsehead Nebula. Therefore, if the public is not likely to be familiar with previous images of a nebula, one is allowed greater freedom in choosing the colour scheme, scaling and framing. Datasets outside of the visual regime, e.g., radio, IR and X-ray, are also cases where colour schemes are less constrained.

When working with optical data, a traditional approach to colour assignment, often referred to as natural colour, is to assign to each dataset the “visible” colour of its filter. The visible colour is essentially the passband of the filter as perceived by the human eye; i.e., what one would see if one looked through the filter against a bright, white light. For this approach to work well, several filters that cover most of the visible range of light must be used (Wainscoat, R. J. & Kormendy J., *PASP* 109, 279, 1997). However, datasets in enough filters may not be available. And the overall colour of the image can become skewed if the colours of the filters aren’t balanced; e.g., an image that is created from V, R, I and H-alpha datasets would contain too much red because the three of the four datasets would be assigned a reddish colour. Furthermore, modern images often include data from wavelengths outside the visible regime. Thus, there is a need to define a more generalized methodology for colour selection.

Choosing a colour assignment will depend on the datasets to be combined, the science to be illustrated, and personal aesthetic. When choosing colours it is also important to consider the fact that our eyes, and indeed our senses in general, function by detecting relative differences; e.g., a line appears to be long only when a shorter line is present for comparison. Colour in an image is similarly intensified or weakened by the contrast of a colour’s properties with other colours in the image (Itten, J. *The Elements of Colour*, John Wiley & Sons 1970). Thus, contrasts between colours can be used to highlight or de-emphasize elements of the image. Black and white images have only one contrast scheme, that of light to dark. However, there are seven contrasts in colour images. To produce a striking image, attention to these contrasts is strongly encouraged.

In this section, the different colour contrasts are noted as recommended colour assignment schemes are described. When assembling an image, notice which contrasts can result after the initial colour assignment. And then adjust the colour

scheme, either by choosing different colours or by swapping the colour assignments amongst datasets, to achieve these contrasts. The next section describes examples of colour schemes and their resultant contrasts in astronomy images.

In general a good starting strategy when assigning colour is to space the colour assignments evenly around the colour wheel; e.g., if creating an image with three datasets, assign undiluted colours that are  $120^\circ$  apart on the colour wheel. This is known as a triadic colour scheme and is the simplest example of hue contrast. The traditional RGB colour scheme falls into this category because the primary colours red, green and blue are separated by  $120^\circ$ . This selection represents the extreme instance of the hue contrast in the same way that white-black represents the extremes of the light-dark contrast. Similarly, the secondary colours cyan, yellow and magenta are also separated by  $120^\circ$  and may be used. However, one is free to use any colours that are separated by  $120^\circ$ . Similarly, if there are four datasets, space them at  $90^\circ$  intervals around the colour-wheel, which is known as a tetradic colour scheme. Note that white and black can be included as colours in the contrast of hue scheme, so any pure whites and blacks that appear in the final image will strengthen this contrast. Three or more adjacent colours, i.e., within  $30^\circ$  of each other on the colour wheel, also create a contrast of hue, although the effect is subtle.

By choosing colours that are evenly spaced on a colour wheel, the sampling of the colour space is improved; i.e., there will be a wider range of colours within the image. Also, for this reason, it is important to assign fully-saturated colours to each layer, because only fully-saturated colours can combine to produce all of the colours available in the colour wheel. Unfortunately it is impossible to produce an image that fully samples the colour space with only two datasets. However, this limitation can be overcome by creating a third dataset that is the intensity average of the existing two. This technique has been successfully used in several images, including an HST/NOAO image of the Helix Nebula (Hubble Heritage 2003).

Alternatively, if there are only two datasets one can assign colours that are separated by  $180^\circ$ , which is known as a complementary colour scheme. The complements are used in two contrasts: complementary and simultaneous. It is worth noting that selecting exact complementary colours and mixing them together, creates what are called compensating tones. When combined, they will produce neutral grey in the CMY subtractive system or pure white in the RGB additive system. Two or more colours are defined as mutually harmonious if their mixture yields a neutral grey. However if the colours are not exact complements then a brown is produced; this defines the case which is considered non-harmonious. A harmonious combination of three colours can be made by splitting the complement. For example, if yellow is chosen

then its complement, blue, can be split by instead selecting two blues, one that is more purple and one that is more cyan.

The simultaneous contrast is particularly important since colours are affected by their surrounding hues. When a colour is viewed, our physiology produces its complement as an afterimage. One can experience this phenomenon by staring directly at a colour for several seconds. After looking away one will see an after image of the complementary colour. Hence if there are two non-complementary colours, physiologically four colours are seen, two of which are after images. If there is a sharp common border between the two actual colours, it becomes ill-defined and appears to “vibrate”. The same physiological colour mixing also occurs if daubs of colour are adjacent, rather than mixed. Although the resultant hue will be the same, it will appear more luminous. This method was used by the Pointilist school of art.

Therefore, based upon the number of available datasets, one should attempt to distribute the hues assigned to the images in a manner that maximizes the usage of the colour space. And, of course, the effect should be pleasing. If, after the initial assignments, the overall colour of the image is unattractive, try swapping the colour assignments given to the layers. Also, try changing the initially assigned hues overall; e.g., instead of starting with red, green and blue (RGB) assignments, try using cyan, magenta and yellow (CMY). Once approaching a scheme that appears to be close to attractive, adjust the hues for the individual layers separately. Even changes of only a few degrees in hue can have a significant impact on the appearance of the image. Choosing the colour assignments for each layer is perhaps the most important step of the process, so attempt multiple schemes and weigh decisions carefully.

Aside from its aesthetic aspect, colour can be used to imply physical characteristics, such as depth, temperature and motion. For example, our minds perceive hues that contain blue, collectively known as cool colours, to fall into the background while hues that contain red, known as warm colours, jump towards the viewer. This is a result of our everyday experience, wherein distant objects, such as mountains, appear to be bluer because of scattered light from the foreground air mass (see Lynch, D.K. & Livingston, W., “Colour and Light in Nature” Cambridge University Press, 2001 for examples). Thus, the warm-cool contrast can be used to create an image that has a three-dimensional feel by selecting colours for data layers which, when combined, produce warm colours for the objects that should come forward and appear closer, and cool colours for those that should fall into the background and thus appear farther away. In addition, our mind perceives cool colours to be literally colder than hues which contain warm colours. This is a result of our experience with reddish flames and bluish ice. Of course it is in contrast to the Planck spectrum, where-

in redder objects are cooler and bluer objects are hotter.

Note that a given contrast can be supplemented using other contrasts. For example, if an image contains the colours of orange-red and cyan, it has the complementary contrast as well as a warm-cool contrast wherein the orange will appear in the foreground. Since dark colours in a light background also jump forward, one can use the light-dark contrast to further create depth by darkening the red-orange and surrounding it by a light cyan. Both colours should be equidistant in value from neutral grey to maintain a harmonious relationship.

Colours and colour combinations can also evoke emotional responses (e.g., Whelan, B.M. "Colour Harmony 2", Rockport Publishers: Rockport, Mass. 1994); e.g., red is synonymous with the powerful emotions of love and hate. Thus, colour combinations with red are often powerful and forceful. The colour yellow, associated with the Sun, often implies life and motion. Blue is often associated with calmness; and violet is often synonymous with magic, mysticism and the extraterrestrial world. Trendy colours, such as the pastels that were popular during the 1980s, give a contemporary feel but may appear dated in the future. Colour schemes which include conservative colours such as dark green and royal blue convey a sense of strength and stability which may allow the image to age better. The contrasts of saturation and extension may be used to balance or enhance emotional responses. For example, surrounding red by dull colours causes the red to saturate and hence dominate. If a large area contains greenish colours this area may be balanced by a small area of red or pink using the contrast of extension.

It is important to emphasize that this approach does not advocate hard and fast rules of colour assignment. Indeed, it is recommended that a favourite colour scheme is used as a starting point. Then by using colour contrasts and the other factors discussed above, produce a harmonious and powerful composition. The next section discusses some of the different colour schemes commonly used and indicates in more detail how colourizing a layer can produce a colour contrast.

Unfortunately terminology is not used consistently when describing the different colour schemes used in astronomical imaging. A traditional colour scheme, often called "natural colour" or "true colour," is a specific colour scheme intended to match the three colour photoreceptors in the human eye. In the natural colour scheme, data are obtained in broadband optical red, green and blue filters (e.g., Johnson R, V and B) and are assigned red, green and blue colours respectively. In addition, the datasets are scaled photometrically, i.e., with calibrated data, identical transform functions and maximum and minimum values that reflect the transmission and sensitivity

## DEFINITION OF COLOUR SCHEMES

functions of the filters and telescope. Note that if the datasets in an image are subsequently rescaled the resulting image is not technically a natural colour image. In the natural colour scheme, emission nebulae tend to appear as a deep red due to the strong H-alpha emission line at  $16563\text{\AA}$ , a wavelength of light which is perceived as a deep red by the human eye. It is worth noting that the natural colour scheme does *not* accurately match the eye's sensitivity to colour; e.g., the Orion Nebula (M42) is a deep red in most natural colour images due to its strong H-alpha emission. However, M42 actually looks greenish when seen through a telescope due to the human eye's poor sensitivity to faint red light.

By deduction, the term "false colour" therefore applies to all images which are not made with the above colour scheme. In this paper the term "representative colour" is used when describing images assembled from multiple datasets of different wavebands, but in a manner that does not meet the criteria of natural colour. This term is used because each dataset encodes properties of a physical phenomenon and colours are assigned to properly represent it. Most astronomical images generated from professional data fall into this category because the datasets are not necessarily obtained through broadband optical red, green and blue filters. And these datasets are usually scaled and projected to maximize detail. A representative-colour scheme is said to be in "chromatic order" if the filters are assigned colour based upon the wavelength of their passbands. If the datasets are not assigned colour in order of wavelength, it is known as "composite order."

Here the term pseudo-colour is used to refer to a distinct technique wherein a monochromatic image is converted into a colour image by mapping grey levels into colours according to a previously-defined colour lookup table (LUT). In a pseudo-colour image, the colour changes as a function of the value of a single physical property represented in the image, e.g., polarization, velocity or monochromatic flux density, thereby creating a multicoloured image. Note that the pseudo-colour image itself is not monochromatic unless all of the colours in the LUT are of the same hue; e.g., the popular "heat" pseudocolour scheme is not monochromatic because the LUT contains red, yellow and colours of intermediate hue. Images generated from natural, chromatic and composite colour schemes are fundamentally different than pseudo-colour images. Examples of different kinds of images may be found in Rector et al. (2005).

One of the goals of a composition is to keep the viewer engaged with an image. That is, the goal is to keep the eye trained within the borders of the image. Human perception of images is complex but includes seeing "bilaterally," that is, dividing the page into left and right halves, and perceiving the bottom part of an image as closer than

## THE COMPOSITION OF AN IMAGE

the top part, e.g. Bloomer, C.M., Principles of Visual Perception, 2nd Edition, Design Press. 1990. Simplifying this, for 95% of those in western cultures the eye will enter from the left edge of the image, roughly one-quarter of the way up from the bottom. Travelling horizontally for a short distance, the eye then moves along a diagonal up to the right and exits close to the upper right corner. If a picture doesn't redirect this travel onto a different path, that is, onto a trail that winds within the frame, then the viewer spends little time apprehending the content and the picture is neither memorable nor engaging.

A visit to an art gallery will illuminate the tactics used by artists to redirect the eye towards the centre of the image plane. For example, they use vertical structures and upper-left-to-lower-right diagonals to block the eye's default path. Additionally, they will redirect the eye back towards the point of entry, close to the left edge, by using a spot of high contrast either in terms of brightness or of colour.

Cropping can be used to remove high contrast spots, like stars, that would drag the viewer's eye quickly out of the picture plane. It can also be used to place naturally occurring diagonals and verticals in the correct position in the picture plane for slowing down the eye's motion and to change its trajectory. Care should also be taken in selecting the picture's centre. If the midpoint of the target of interest is placed dead centre, then the target will appear to be sliding down when the image is viewed vertically, e.g. on a monitor or on a wall. Instead, the target midpoint should be placed above the horizontal centreline of the image to keep it from appearing as if it is about to fall out the bottom of the image plane. The target's midpoint should also be offset from the vertical centreline in order to ensure that the image appears dynamic rather than static. A static image risks allowing the eye to follow the default path in from the lower left of the image and then rapidly out via top right corner.

The quality of modern astronomical data, and the technologies now available to manipulate them, allows high-quality images to be created in a purely digital form. Many groups are now exploiting this fact to create attractive images intended for scientific illustration and outreach. The success of these images in public outreach is responsible for much of the popularity that astronomy currently enjoys.

A practical guide is presented in Rector et al. (<http://arxiv.org/abs/astro-ph/0412138>) as to how to generate astronomical images from research data by using powerful image-processing programs such as Photoshop and The GIMP. These programs use a layering metaphor that allows an unlimited number of astronomical datasets to be combined; and each dataset can be assigned any colour. This is an improvement over traditional methods, wherein only three datasets can be combined, and

## SUMMARY

only with the primary colours of the colour space, usually red, green and blue. In the layering metaphor, each dataset can be individually scaled and coloured, creating an immense parameter space to be explored. These IP programs offer excellent flexibility and agility in the creation of images, allowing easy exploration of this parameter space.

A philosophy is presented here on how to use colour and composition to create images that simultaneously highlight the scientific detail within an image and that are aesthetically appealing. Because of the limitations of the human eye, it is fundamentally impossible to create an image of an astronomical object which shows “how an object truly appears”. This is particularly true for datasets outside of the optical window and for datasets with limited-wavelength coverage, e.g., emission-line optical filters. Indeed, the goal of many of these images is to show what the human eye cannot see.

Thus, by properly using visual grammar, i.e., the elements that affect the interpretation of an image, it is possible to maximize the richness and detail in an image while maintaining scientific accuracy. With visual grammar one can imply qualities that a two-dimensional image intrinsically cannot show, such as depth, motion and energy. A basic primer has been included on some elements of visual grammar, such as the seven colour contrasts, including examples of these contrasts in astronomical images. In addition, composition can be used to engage and keep the viewer interested for a longer period of time. The effective use of these techniques can result in an appealing image that will effectively convey the science within the image, to scientists and the public alike.