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About color correction in astrophotography

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Abstract

Color correction in standard images is mainly based on controlling the interaction of illuminant and reflectance and often results in a compensation of actual chromatic casts with respect to a chosen reference illuminant. Primary reference illuminants come from our reference star, the sun, whose color characteristics are of G2V star class. Visually, color correction in standard images allows us to obtain scene colors more pleasant and closer to our everyday experience. Quality of color is usually intended to please the vision system of the observer, that looks at the picture using the powerful mechanisms of visual color and contrast adjustment (color constancy), a very different tool with respect to a camera. In astrophotography this basic principle does not apply: the illuminants of the many different stars or emission nebulae are the only information we detect, while the only reflectance involved (not considering Solar System planets) is originated by dust particles producing the so called reflection nebulae. Thus, what is the meaning and the goal of color correction in astrophotography? In this paper, we try to present to the reader some points of discussion about this broad question.

Introduction

In astrophotography it is necessary to assume a notion of color that differs from the traditional concept. When rendering an astrophotography the main purpose is not to provide ”nice picture”, or try to find the ”natural” color of stars or nebulae. There is nothing natural (as in common photographic sense) in observing the deep sky with the help of a telescope or with a long exposure time photograph. Our visual system did not evolve to observe night sky, but to help us to live on the earth. First of all, the sensitivity of human cones is too low to observe the weak illumination of stars at naked eye. In night-time, mainly the rods are active, so almost no color stimuli reach our brain. Second, if we observe with the help of a telescope or a large focus length, the light amplification can be larger than the sensitivity threshold for high magnitude stars (between -1 to 2) [1] and we can have a hint of the spectral emission producing a sensation of blue, orange or reddish color. Anyway we are far from effectively exploit the cones activity.

On the other hand, the purpose of sky observation is mainly scientific, so color balancing has the objective of preserving the relevant information. Stars as light sources are characterized by luminosity and color temperature, these two parameters need somehow to be preserved and effectively rendered.

In the following, we introduce the reader about the star color characterization, then we present a range of methods to render the colors of the sky, grouped according to three different goals: to create pleasant images, to produce the same sensation as observing the sky using the human visual system and to enhance the contrast and others visual features. Finally, we summarize our conclusions.

Star color characterization

In astrophysics the color of stars is an important parameter to understand and classify stars (Figure 1). Indeed the star classification is based on the star color temperature and its luminosity, normalized with respect to the Sun's temperature.

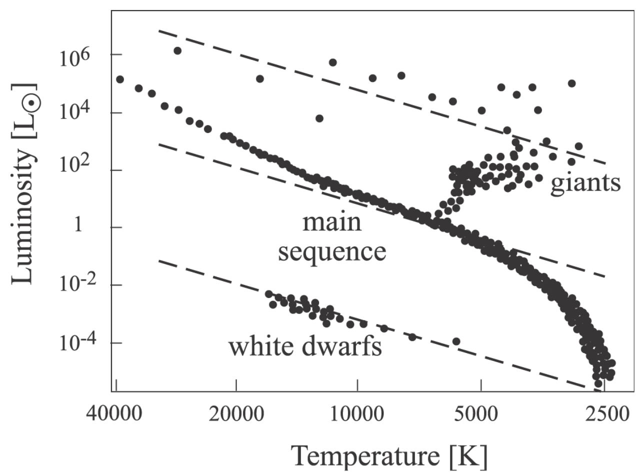


Figure 1. *Graph representing star taxonomy according to the color temperature and the luminosity.*

Color temperature is the temperature of a black body Planck emission, the intensity of radiation emitted in a given wavelength and direction as a function of temperature.

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} * \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} \tag{1}$$

From this viewpoint the notion of color is purely physical. It can be measured in the UBVRI (Ultraviolet, Blue, Visual - green -, Red, Infrared) photometric system proposed by Johnson and Morgan [2] and further improved by Cousins [3]. The UBVRI filters proposed by Johnson and Cousins, have central pass band and width values are (FWHM is the Full Width at half Maximum of the response curve): U: 365.6 nm, FWHM 34.0 nm; B: 435,3 nm, FWHM 78.1 nm; V: 547.7 nm, FWHM 99.1; R: 634.9 nm, FWHM 106.6 nm; I: 879.7 nm, FWHM 289.2 nm (Figure 2).

To compute the color temperature many methods have been proposed; a simple approximation equation used in Astrophysics [4] is:

$$T = 466 * \left(\frac{1}{0.92(B-V)+1.7} + \frac{1}{0.92(B-V)+0.62} \right) \tag{2}$$

The color index is therefore the difference of intensities in the B and V bands, (B-V).

Stars are classified into seven main classes of temperature/luminosity: O, B, A , F, G, K, M; further subdivided into

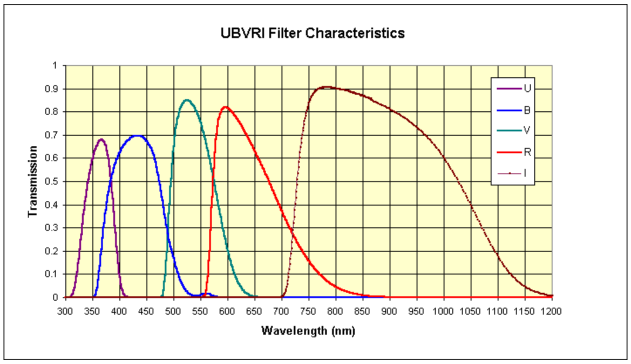


Figure 2. *Graph showing the characteristics of UBVRI filters.*

finer temperature classes and into 5 sub classes for decreasing luminosity. Our Sun in particular belongs to class G2V (V stands for roman numeral 5).

Goals of rendering

As stated in the introduction, our visual system did not evolve to see colors in low-light conditions typical of astronomic observations. Therefore, looking to the sky during the night would produce in our brain only gray levels or a dark greenish gray image, as only scotopic vision is involved. In general, when making astronomical color images, the aim is to show the colors of the celestial objects as how they would appear if the light level were sufficient to stimulate the three types of cones. However, this is not the only possibility. In the following sessions, we discuss about different rendering goals of astronomical images. We grouped a range of methods according to three different intents: i) rendering astronomical images to create pleasant images, ii) rendering to produce the same sensation as observing the sky using the human visual system and iii) rendering to enhance the contrast and others visual features.

Rendering pleasant images

The first goal of rendering is to create pleasant images (see figure 3). Even if there are many methods to achieve this goal, each one with clear point of views, there is no common ground truth to judge the results. Decreasing the costs of telescopes and cameras and increasing the possibility of spreading the images, lead a huge number of amateur astronomers to take pictures of celestial objects, processing them in order to create fabulous images. For instance, it is common to render with saturated blue the color of the milky way or of other galaxies, even if the blue component is very low. This approach also affects how we believe the colors of the Universe should be.

The G2V method

An important key to success in recreating a color images, is the choice of the bassband filters: they have to isolate only the correct spectrum wavelengths. This is especially true for nebulae pictures, as we observe an emission spectrum that consists of emission lines of few elements: a rough filter can introduce big error in the final color image. Other factors to consider are: the effects of filter passbands and transmittance, the CCD quantum efficiency, the effect of atmospheric attenuation and the back-

Figure 3. *A rendering of M31, the Andromeda Galaxy, to obtain a pleasant image, taken from [22]*

ground sky light. These effects have to be discarded: the signal that reach the camera sensor should be proportional only to the flux coming from the celestial objects. For this reason a method to color balance an image is to capture (with the same devices and tools) filtered images of a reference color temperature, in order to estimate, and therefore remove, the factors that compromise the signals [1]. The reference commonly used are stars belonging to the spectral class G2V, to which our Sun belongs, with a color temperature of 5.770 K and color index $B-V$ equal to 0.625. These methods are based on the idea that human visual system is calibrated for the light emitted by the Sun. In this way colors should appear naturals.
This method is implemented and explained from a practical point of view by Hubl [5]. On his website, an Excel file composed by four worksheets, is available to help to create step by step, a color image.
An image obtained with this method is shown in figure 4b.

The average field stars method

Another method [1] to color balance the image is based on the assumption that the average color of the stars in the image is white or close to it. In this case, the colors of brightest stars are used as color reference (instead of using a G2V star). In most of the cases, this method works well. In specific situations, like in bright emission nebulae where objects are strongly colored, this assumption is not verified, and the color balance is not accurate.

The $B-V$ method

On Hubl website [5], another method called $B-V$ Color calibration is described. The idea comes from [6] and tries to overcome the problem of bad transparency of the sky, a situation that introduces a color shift that cannot be compensated with the G2V method. When taking pictures of stars, the long exposure time leads to saturate all the G2 stars, making their use to color calibrate impossible. A possible solution is to use the measured brightness of faint stars, available on many internet database. Using UBVRI filter system, proposed by Johnson [2]. The B and V (Blue and "Visual", that stands for green) originate the $B-V$ color index indicating the star color. The difference between V and R is another color index. A third index is given combining the Johnson UBV filters with the Cousins RI filters ($V-R_C$). A G2 star has

(a) (b) (c)

Figure 4. *Three different rendering of M31, the Andromeda Galaxy. a) A rendering obtained with ACE [17], a SCA algorithm, b) A rendering with a G2V method, obtained with eXcalibrator [21], c) Photometric elaboration, using arcsinh function in Pixinsight. Images by D.L.R.Marini*

a B-V index of 0.65, a $V-R$ index of 0.52 and a $V-R_C$ index of 0.36. To use the $B-V$ method to color correct the image, it is necessary to look for unsaturated stars with a $B-V$ index between 0.6 and 0.7, and a $V-R_C$ index in the range between 0.2 and 0.6. This means looking for stars that should be white. Considering now the measured red, green and blue ADU (analogue-to-digital units, the digital number representing the voltage, output of the camera CCD. This is also referred to as *counts*) of such stars, it is possible to find the factors necessary to white balance the whole image.

The method proposed by Lupton

In their work, Lupton et al. [7] present a method to scale the pixel values of bright stars to keep color information and to avoid to show them white. They introduce an intensity value (that can be defined as the average between the three bands r, g, b) which is mapped according to a function (they suggest to use the *arcsinh* as mapping function) and which can exceed the unity, but using r, g, b as factors to find the final pixel value, the color information is maintained. In this way, even the brighter stars are not white, but with a red, yellow or blue cast, etc. To avoid artifacts when a star shows long trails, they treat special cases, with very high counts (over 10.000 for each band) as saturated.

Rendering to produce "same sensation"

The second goal of rendering is to produce the same sensation as observing the sky with our vision system. In this case, due to the low levels of luminances, the color is often not involved. In any case, rendering the correct lightness appearance is the straightforward sub-goal. To this aim, a completely different method based on computational models of human vision system (HVS) is used. A family of HVS models called SCA (Spatial Color Algorithms) is often used as unsupervised image enhancer [8].

Modeling HVS is a delicate procedure that requires a careful procedure of calibration of both the input and the output data, in order to be quantitatively correct (otherwise a qualitatively approach would result in image enhancement). We do no present this procedure in detail here, it can be found in [9]. However we present the first psychophysical experiment that is at the base of the ancient knowledge of stellar magnitude estimation. From [9, p. 180]: "One of the first reported psychophysical experiments was the classification of stellar magnitude by Hipparchus of Nicea in the 2nd century B.C. Although his original manuscripts have been lost, Ptolemy documented them. After many centuries, stellar magnitude is still in common use today. It has been modified to be a photometric measurement starting with Pogson in 1856. The stellar magnitude changes by 100:1 when the measured luminance changes by 100 000:1. In other words, stellar magnitudes have a slope of 0.4 in a plot of log luminance vs. log stellar magnitude [10, 11]. With achromatic stimuli there is excellent correlation between stellar magnitude and the aperture mode of appearance." Hipparchus of Nicea was not just the founder of objective stellar observation, he set also the basis for the HVS modeling.

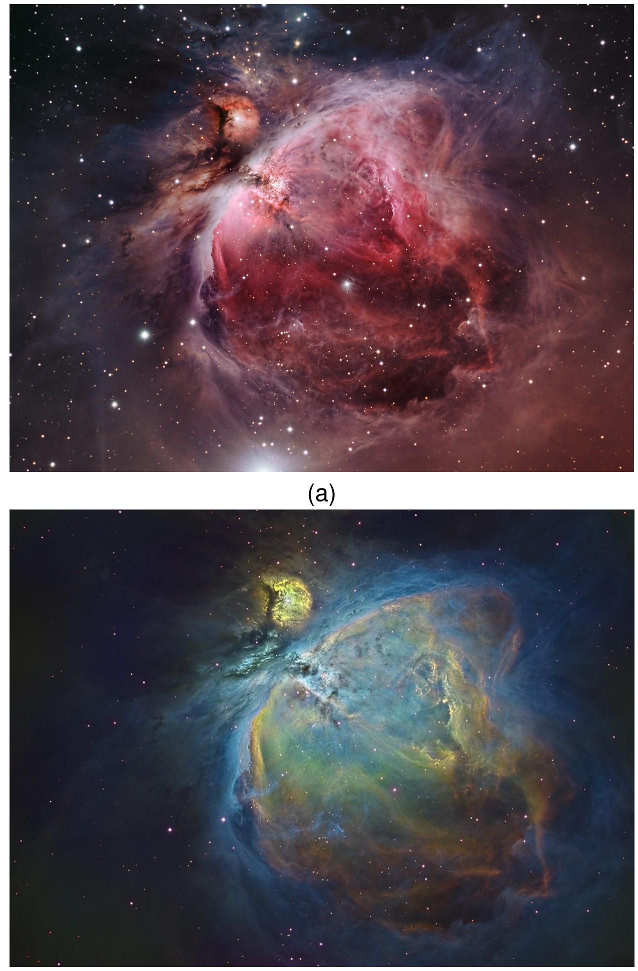
The interesting property of these algorithms is that they do not need any a-priori knowledge about the image to filter. Their principal action is to enhance the local contrast via a spatial comparison of each pixel value with the rest of the image values. Two main effects of the spatial comparison are: an automatic removal of possible chromatic dominants and a local dynamic range compression that is at the base of the local contrast enhancement. For detailed reviews of SCA family, refer to [9, 12, 13]. Differently from classic image enhancer, mimicking the visual adjustment of our vision system, produces in general a much-preferred output, in terms of color, contrast, readability and overall pleasantness in natural or synthetic images [14, 15]. The efficacy of this approach for astronomic images is reported in [16]. To the SCA family belongs ACE (Automatic Color Equalization) [17], whose rendering is shown in figure 4a).

Rendering to enhance contrast and astrophisical features

The third rendering goal is to enhance contrast and visual features of interest in the images. According to the chosen features of interest, the methods can vary widely affecting their measure of success. In general, changes of the local contrast are at the base of these techniques and in many cases they are used as pre-filtering for further computer vision analysis. Here it follows a description in more details of these three goals.

Photometric based color calibration with Pixinsight

Vincent Peris and Juan Conejero have implemented in the Pixinsight software system a physics based method [18]. The basic idea of this approach is to assume the nucleus of some galaxies as the reference white. We recall that galaxies have been classified first by Hubble considering their morphology in 1961. The classes considered by Paris and Conejero are Sb - spiral galaxies with a central bar and large bulge, Sc and Sd - spiral galaxies with smaller bulge. The authors declare "The average of these galaxies provides a source of the entire range of stellar spectral types and populations, so it can be considered as the best unbiased white reference, truly representative of the observed deep sky". As with methods proposed by Tomsik and Lupton, also this method needs an astrometry tool to identify the region of sky observed and to identify most relevant stars with their class characterization. It is not necessary that the white reference is present in the observed field, since star catalogues have an associated set of filters whose white reference is known. Moreover a color calibration can be performed by comparing the stars color index of the observed field to the color index in the star catalog and by deriving RGB weights to be applied for color correction. A rendering with Pixinsight is shown in figure 4c.


(a)

(b)

Figure 5. Two different rendering of the Orion nebula M42. a) RGB rendering. Image taken from [19], b) Hubble palette. Image taken from [20].

The Hubble color palette and the false colors

There is a third issue related to rendering photographs taken in infrared or ultraviolet bands with special filters devised to get information about presence in nebulae of the elements hydrogen, sulfur and oxygen. These photographs are mainly taken by orbiting telescopes, with filters H-alpha, for hydrogen, SII for sulfur and OIII for oxygen. Since these bands are beyond the visual interval, to get colorful picture it is customary to use a false color method, using in particular the so called Hubble Palette, where SII is mapped to the red channel, H-alpha to the green and OIII to the blue channels. The difference between RGB and SII,Ha,OIII flash colors can be observed in figure 5 (Orion nebula M42, a) RGB [19], b) Hubble palette [20]).

Rendering enhanced features

To improve contrast it is usual to apply a histogram transformation that maps with a logarithmic scale the luminance data of an image. The transformation of inverse hyperbolic sine, arcSinh, has the interesting property of behaving as linear close to zero, and becomes logarithmic while approaching 1. This transformation has the effect of stretching input luminance values keeping high contrast for low levels and compressing high levels thus avoiding saturation of high luminance areas. An implementation has been proposed by Lupton et al. [7] who also introduce a factor to control the position where the mapping moves from linear to logarithmic.

Conclusions

The human visual system evolved to perceive in color the world around us as illuminated by the Sun. During the day the light levels give raise to the photopic vision, stimulating our three types of cones and making the sunlight appear white. A sky observer during the night would not have the same sensation has the low light levels stimulate only rods. From this simple fact originates the problem on how to render the colors of celestial objects. In this paper we presented some methods to color balance astronomical pictures. Some of them aim at creating natural appearance, where natural means how do celestial objects would appear if their brightness was enough to stimulated our photopic vision. However, this is not the only possible solution. Sometimes, we are more interested in inspecting the deep sky to find information, i.e. for scientific porpoise. In this case, a color rendition that increases the local contrast, could help in revealing details that would otherwise be lost. Finally, there are information that our eyes could not see even if the star light was higher, but that can be register by a camera using special filters, in infrared or ultraviolet bands. In this way, it is possible to know about the emission gas or the elements composing for example nebulae. As these wavelengths are not perceivable by our visual systems, it is permissible, if even not mandatory, to use false colors to represent information.

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Author Biography

Daniele L. R. Marini graduated in physics at the Universita degli Studi di Milano in 1972. Since 1978, his research has encompassed several areas of graphics and image processing. He is an associate professor, now retired at the University of Milano, teaching computer graphics and image processing for the undergraduate programs in informatics and in digital communications. He is a member of ACM, SIGGRAPH, IEEE, and he is a fellow of IS&T.

Cristian Bonanomi received his PhD in computer science from the University of Milan in 2011. He is a research fellow at the Department of Computer Science of the University of Milan. He has his research interest in computer graphics, vision human perception, color appearance models, and digital photography.

Alessandro Rizzi is full professor at the Department of Computer Science at the University of Milan. From 1990 his research has been in the field of color, digital imaging and vision perception. He has been one of the founders of the Italian Color Group, Secretary of CIE Division 8, IS&T fellow and vice president. In 2015 he received his Davies medal from the Royal Photographic Society.