Trust the Process: An Investigation into Astrophotography

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When it comes to astrophotography, there is a lot more going on 'under the hood' than meets the eye. The images we have come to know and love, are not what is truly captured by telescopes – the data they collect must be post-processed to facilitate human interpretation. Filtering out aberrations, adjusting for Doppler shifting, contrast stretching, dark signal subtraction, multiple-image compositions, and utilizing general color correction are all examples of the post-processing work that go into creating the final-product photos the general population sees. On the other hand, numerical methods are also applied to reduce error and optimize images using regression methods, among others, allowing for systematic development of image profiles. Telescopes capture non-visual data as well, such as x-ray and infrared wavelengths, which can be adapted to color profiles perceivable by the human eye; each wavelength category has a characteristic appearance, the source of which is often overlooked. These images are able to tell us more about the history of the universe, as the light captured can be up to 100 million years old. The James Webb Space Telescope is an excellent example of an upcoming investigation, which will portray exoplanets and their characteristics in a 'new light,' as well as delve into the early development of stars. The chronology and processes from the data captured to the final image is akin to those used in all forms of photography. Images from telescopes have become the standard for how we visualize the world past the bounds of Earth, extending deep into the cosmos. Astronomers do the heavy lifting in processing raw data collected by telescopes using color correction, aberration elimination, compositions, and more in order to generate an image which portrays the data collected in a manner that speaks to all of the people who see it. Astrophotography is able to demystify the reality outside the planet we call home, and answer questions about our past – even those we may not have thought to ask – through the viewing lense of a telescope.

I. Introduction

Photography – whether it be for hobby or career – has 3 main stages when it comes to imaging. First, is the collection of data itself, by the sensor, through the camera lense. Second, is the development of data to refine a message, by manipulating specific characteristics of the image through post-processing. Third, is the interpretation and appreciation of the photos captured; the act would be futile if not for an audience to appreciate the beauty and essence of the image. Not only are these images powerful means of conveying emotion, but they offer a truth that can impact perspectives and allow for new thoughts to develop. The development stage is the area often overlooked, although it can be argued that it bears the most influence on the final outcome. This paper will delve into the facets of astrophotography, following a chronological path comparable to the aforementioned stages of general photography, exploring and analyzing astrophotography in its full form.

II. Stage 1: Capture

Although trivial in the big picture, the process of capturing an image is at the core of understanding astrophotography and the modifications made down the line. Some general photography terms must be defined first:

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aperture (or ‘f-stop’, determined by the focal ratio) is the size of the opening through which light enters; shutter speed is how fast the shutter closes, determining how much light hits the sensor; ISO is the light sensitivity level of the camera; focus is what the camera is keeping sharp, by focusing the light coming from that area. These are all hard settings of the camera itself, which change the functionality. Some soft settings must be defined as well: exposure is the measure of how light/dark an image is, and white balance is the adjustment of white color, matching light outside the camera.

Images we see from NASA and other space exploration organizations, are captured using cameras which function in the same fashion as any other. By allowing a certain amount of light in, photons hit a sensor and are converted to electrons, and these voltage readings are recorded digitally in a linear manner, producing a digital image with incredible data [1]. Physical filters can be applied on the telescope itself to restrict certain wavelengths in order to ascertain a better understanding of visible colors and nonvisible wavelengths of light collected.

A. Telescope Structure

In theory, telescopes work similar to pinhole cameras, which allow a miniscule amount of light in through a hole (the aperture), and produces a larger or smaller image relative to where the optical focus of the image is. There are two telescope categories, refracting and reflecting; one uses lenses to gather and focus the light into an image, while the other uses mirrors to redirect the light into an image, respectively. Refractive telescopes were the first to be used, and often credited to Galileo, while the reflecting form credited to Newton – both utilized this technology to peer into the vastness of the cosmos, wanting to know more about the universe past the bounds of their home. Refracting telescopes are used to enlarge images, while reflecting telescopes are more common and allow for the observer to see distant objects.

B. Image Distortion

The size of the telescope determines how sensitive it will be (similar to ISO), allowing more light in; similarly, the smaller the telescope and its aperture, the less light will be let in – this can result in hazy, faint images. The angular resolution, which defines the smallest visible angle in an image, is based on the aperture found as an inverse relation, and is dependent on the wavelength of light being observed.

A common issue of refractive telescopes is that of chromatic aberration, where certain wavelengths of light become blurred/unfocused due to the differing focal lengths [2]. Doppler shifting is also a common issue, a result of the motion of observed bodies either towards or away from an observer; light captured can appear ‘redshifted’ if the object is moving away from the observer, while an object moving towards the observer appears ‘blueshifted’. This distortion is produced by the shortening or lengthening of wavelengths transmitted, due to the initial velocity of the object compounding with that of the traveling waves. These are a few examples of distortions which can occur in telescopes, however there are a multitude of different issues which can arise when capturing light from such a distance and of varying wavelengths as well as intensity.

C. Data Types

Although humans see a colorful world here on Earth, full of vibrance and stimulation, we are actually missing out on a lot of the wavelengths of light in the electromagnetic spectrum, which exist at any moment all around us. The most amazing images we find are often adaptations of these ‘invisible’ wavelengths, filtered and processed to help us understand what the cosmic formation truly looks like as an entity. Wavelengths must be taken into consideration, as those which do not make it past the atmosphere without heavy distortion must be captured in space, rather than on land. These different wavelengths along the EM spectrum hold crucial information which characterizes the observed objects.

1. Optical Data

Optical data, or visual data, is the oldest and most common means by which the cosmos is observed – this data features wavelengths from the visible light portion of the EM Spectrum. It is often convoluted by the immense number of distortions, however, as light must pass through the atmosphere where it is disturbed heavily [3]. Optical Data is the most straightforward, where you get what you can see; data does not provide any more information past what can be visually interpreted from the image, but allows us to understand what we as humans would see if approaching the observed body.

2. Radio & Microwave Data

Radio data is able to capture images in extreme detail, having a high angular resolution due to the large nature of the wavelength [3]. This data creates an outline/contour of the observed body, and can also be used to determine composition, structure, and relative motion of the bodies similar to optical data.

Microwave data is also inhibited by the atmosphere; however, once above the atmosphere the entirety of space radiates cosmic microwaves, producing a cosmic microwave background, or CMB – this CMB is stipulated to be remnants of the Big Bang, dating back to the early formation of the universe [3].

3. Infrared & Ultraviolet Data

Infrared data is somewhat blocked by the atmosphere; however, the more pertinent issue arises from the fact that all objects above absolute zero emit infrared waves. These infrared waves, although difficult to refine, hold secrets to the formation of early galaxies and planetary systems [3]. Infrared waves are able to travel from deep within the cosmos, relaying information from objects immensely far away, often hidden behind gaseous clouds and dense regions of matter [4]. The vast nature of space comes through by means of infrared data – the James Webb Telescope (discussed later) is a prime example of such a telescope, uncovering truths about the universe we live in and how it and others like it came to be.

Ultraviolet data must be captured above the atmosphere, however otherwise it is similar in structure to that of visible light [3]. Ultraviolet data allows for observers to determine chemical compositions of the observed entities, understanding the inner workings of bodies [4].

4. X-Ray & Gamma-Ray Data

X-Ray data poses a difficult challenge, featuring an extremely long focal length [3]. This data is extremely useful to identify regions of excessively high temperatures, which indicate large magnetic radiation and extreme forces (gravitational or even explosive) [5]. This data, similar to infrared, allows us to better understand the formation and development of the cosmos.

Gamma-Ray data is even more difficult to capture due to further challenges in focusing the waves; rather, telescopes use filters to cast shadows where gamma-rays would have been present, to produce a 'negative' of the image in theory [3]. Gamma-Rays go even further than X-Rays, emanating from black holes and dying stars, affecting the space around it and the future timeline for many years to come.

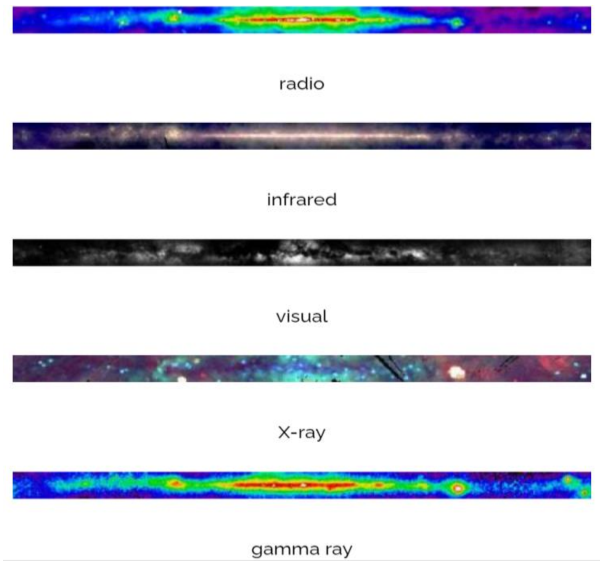

Fig. 1 Multi-wave representation of data types collected from Milky Way Galaxy [6].

III. Stage 2: Development

After collection of imaging data, the results out-of-camera are typically not ideal, and can be riddled with distortions for numerous reasons – some of which were discussed previously – as well as a general lack of vigor and emphasis. However, in the modern age we are able to modify images with high dexterity and precision, facilitating corrections and modifications which can bring an image to life. This can be done using traditional image post-processing akin to that of general photography, as well as using numerical methods to generate regression models, for example, to minimize error. Common forms of both are detailed as follows.

Post-Processing or 'editing' is a process that all photographers are familiar with, and has become a staple in the photographic process. Although editing photographs has a negative connotation in the modern age, it plays a crucial role in the end-product of astrophotography, which is distributed to the general population. Post-processing allows for the narrative which photographers wish to convey to shine through, past any distortions or lack of relatability.

A. General Post-Processing Methods

General photography editing methods include color correction, applying color profiles or 'filters,' adjusting settings such as exposure and white balance, and so on. These change the appearance of the image, in terms of light modification. There are further editing methods such as spot correction and compositions which work to alter the image itself, correcting for distortions and eliminating unwanted data from an image.

1. Aberration Elimination

Aberrations originate from lens imperfections, found in refractive telescopes which utilize lenses to focus light into an image. The generally appear around the edges of a photograph, where the light is distorted most extremely, as the lense does not maintain the size of the image from the center throughout the rest of the frame. This distortion in an image can be attributed to excess data, so the simplest way to handle it is either cropping or retouching in post-production. Using a brush or stamp tool to cover up the outer bounds of the star(s) in question, or simply cropping them out.

2. Multiple Image Composition (Stacking)

When shooting in the moment, it can become difficult to adjust for exposures and avoid 'noise' (grainy textures often found in low light/dark photographs) from having too high of an ISO. Multiple Compositions allows for shots to be taken at multiple exposures or ISO levels, and combined in post-production to generate an image of the optimal scenario, combining the best features of each image, and excluding the unwanted data – this can be visualized as stacking images on top of one another, and taking the average of all the data to compose the most accurate result. This method can also eliminate distortions such as aberrations or unwanted objects which may unexpectedly appear in certain shots.

This method can also be applied from an artistic perspective, smoothing out movement and stacking it on images taken in intervals to form one cohesive image – the most common form of this can be seen in star trails, where stars can be seen circumpolar to the celestial pole. This stacking also allows for sharper images, and long exposure images which let in light for long periods of time to capture distant or faint objects.

3. Dark Signal Subtraction

Dark Signal Subtraction in practice works to minimize the noise-to-signal ratio, in a more prominent manner than normal multiple image compositions can achieve. Astrophotography inherently consists of dark frames, with luminous light sources as the focal point of an image. The methodology involves taking a 'light frame' image, where the image is overexposed to a certain degree, highlighting all the light that has entered the camera to the extent where it may appear hazy and indistinguishable, along with an extremely dark frame where little to no light is visible. Once in post-production, rather than stacking images as with multiple image compositions, the dark frame is subtracted from the light frame, leaving minimal to no noise in the image and the focal point much clearer and prominent in the image than before.

4. *Contrast Stretching*

Contrast Stretching brings out hidden details unbeknownst to the photographer during the original composition, by changing the linearity of photon capture to a more logarithmic curve, which is the way we humans experience the world with our own eyes [1]. This stretching is done by manipulating the dynamic range, increasing contrast in areas which were much darker to bring out data that was present, but suppressed by the linear representation of the photon capture by the camera sensor.

5. *Doppler Shifting*

Doppler Shifting, resulting in 'redshifted' or 'blueshifted' objects in an image, is a difficult issue to mitigate – especially so when it comes to photographing new areas of the cosmos, with objects that have not been categorically analyzed yet. Prior data is required to calculate the speed and direction of the shifting, in order to get an idea for the actual color. This analysis of what the object should be emitting in terms of light can also be determined spectroscopically if the composition of the object is understood well. For example, fitting a star to a blackbody curve, and tracking its emission and absorption lines, will allow for an astronomer to determine the deviation from normal for such an object in the sky. From there, it is only a matter of applying a color shift, changing all the colors a certain amount respective to the amount of doppler shifting present in the given direction of motion [1].

6. *General Color Correction*

Color Correction is the most widely used method of post-processing, and has the most influence on the way we perceive the distributed images of the cosmos. Telescopes rarely capture colored images – rather they obtain extremely precise data in black and white, to ensure preservation of light levels and detail/accuracy. Color is added through post-processing to facilitate a tangible understanding of the observed object. These colors can be assigned by a multitude of parameters, such as observed composition, energy levels/temperatures, luminosity, etc.

We understand colors by means of the visible portion of the EM Spectrum; many wavelengths do not fall in this region, such as x-ray and infrared waves for example, and these must be colorized for human interpretation as well. Similar to parameters for observable wavelengths, parameters such as energy levels are utilized to create a representation of what we would see if the wavelengths captured were visible light waves corresponding to colors [7]. This process is a form of artistic rendering, as seen in the lower image of Figure 3, and is not scientific analysis.

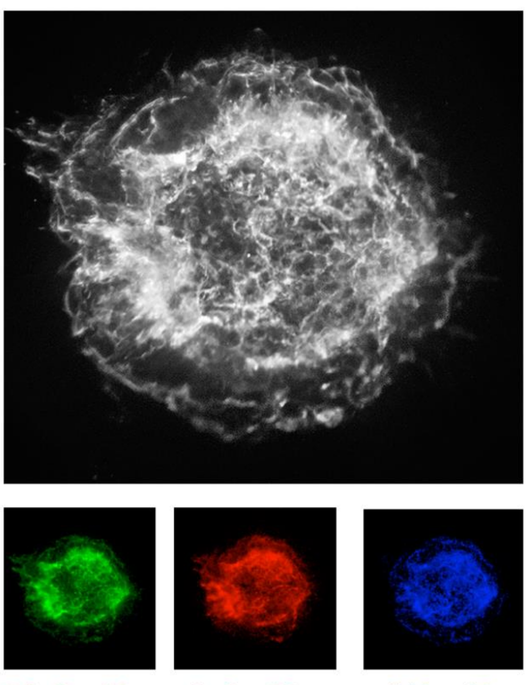

Fig. 2 RGB data classification of supernova 'Cas A' using x-ray energy parameters [7]

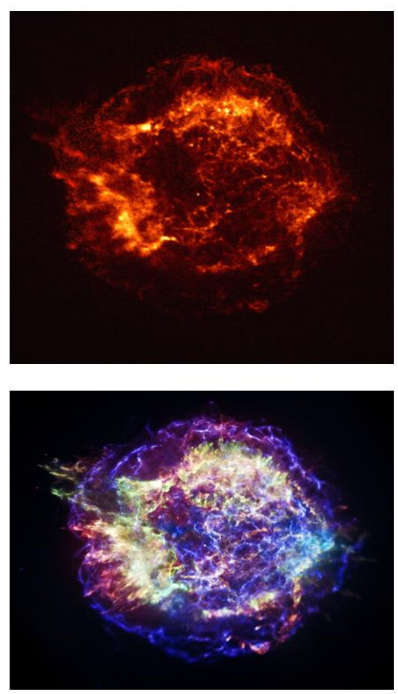

Fig. 3 Color corrected supernova 'Cas A' using different color profiles [7]

B. Numerical Post-Processing Methods

Numerical Methods are the implementation of mathematical techniques to solve logical/arithmetic problems, to determine necessary parameters or optimize scenarios; this can be applied to astrophotography, to reduce distortions, create image profiles, etc. [8]. Optimization methods such as Steepest Descent and Golden Ratio can be extrapolated to find extrema in the data and refine an image to the content which is desired, cutting out extra distortions such as noise and chromatic aberrations. Parameter Estimation methods can also be applied, such as the Least Squares method, to determine values for proper representation of an image from black and white to color, based on energy levels or blackbody curves. For example, parameter estimation can be implemented to determine linear gradients for light inputs on a sensor, to reduce noise and light pollution distorting the image.

Linear Regressions can also be found, presenting a mathematical form of an image which best fits the given data. Using regressions can prove useful to systematically develop image profiles, which develop an image from its core data to a final product in full color. An image profile consists of a certain filtering that is applied across an image, or the change required in data values to approach the true image from the data captured. The regression method can be applied in large batches, to speed up image post-processing tremendously, resulting in an almost-autonomous process which is often more accurate than traditional methods.

IV. Stage 3: Interpretation

Interpretation is a subjective practice, and has a different influence on every observer. Through post-processing, data collected is refined into an image which is interpretable to the human eyes, allowing for a visual story to be conveyed. We can learn incredible details about the objects in question, simply by observing their behaviors and structures over time. As a fact of life, interpretation is one of the key elements of existence; all things exist, but interpretation lends meaning and purpose to mere existence.

Artistic renderings also serve a purpose, to further educate the planet's inhabitants about the universe which surrounds us. Life does not boil down to simple collections of data, as that would be a futile endeavor – rather, both logic/reasoning and emotion make us humans who we are. Images of the cosmos convey understandings of the reality that is beyond earth's bounds, reminding us that life and existence is not confined to this planet alone. All entities have energy, the core of life itself, and observing photographs of these entities provides an immense expansion of one's perspective, altering the means by which one lives and the understanding of life itself.

Deep sky photographs are also able to depict the history of the universe; light captured by telescopes peering far into the abyss of space, collecting data from infrared, x-ray, and gamma-rays can be up to 100 million years old. The James Webb Space Telescope is a project slated to launch in 2021, which will portray exoplanets and their characteristics in a manner we have never been able to observe before, and gather info about the early development of stars as well. The JWST is a reflective telescope that will collect data from mid-infrared wavelengths from beyond the dust clouds, and see formations of stars and planetary systems alike [9]. This discovery mission will surely impact our perception of life, and provide basis for further exploration.

V. Conclusion

Being able to peer into the universe generates emotions like no other experience; there is a vast reality past the planet Earth, and learning more about it through images brings a child-like excitement which can be attributed to discovery and exploration. Astrophotography lifts the veil and allows humans, both astronomers and the general public alike, to see the world for what it truly is, and answer questions about our past – even those we may not have thought to ask – through the lense of a telescope.

Although there is a large amount of work that goes into the generation of such images, the payoff is beyond rewarding, and impacts every inch of society. By capturing images using numerous forms of technology and data types, and putting the data through general and numerical processing methods, the end product is incomparable to any other. As we come to realize the 'collective ignorance' and lack of knowledge mankind holds in the big picture, facing the unknown head-on, astrophotography provides pieces to the puzzle; it allows us to learn more about existence, how we came to be, and what the future holds for us – the final composition of the puzzle, unbeknownst to us. Exploration of the cosmos feels equally as magical as it does scientifically demanding - therefore, one must learn to trust in the process, and prepare for an expansion of perspective.

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