Astronomical Image Processing based on MATLAB

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***Abstract*—Astronomical image processing plays an important role in enhancing features of celestial objects captured through basic refractor telescopes, which allows detailed analysis and observation. In this research, we apply Contrast Limited Adaptive Histogram Equalization (CLAHE) using MATLAB to enhance the quality of images of the Orion Nebula, Jupiter, and the Moon taken with a simple refractor telescope. The proposed approach improves issues of low contrast, chromatic aberration and uneven illumination that are very common in amateur astrophotography. CLAHE dynamically corrects contrast in local regions of the image, which reveals fine details of nebular structures, planetary surfaces, and lunar craters. Other techniques such as noise reduction and edge sharpening are also applied to improve the visual quality. Results demonstrate that CLAHE significantly enhances image clarity, making much of the astronomical features more clearly visible, which are essential for preliminary scientific analysis. This method highlights the potential of MATLAB-based image processing techniques in improving the quality of amateur astronomical imaging.**

Keywords: Astronomical Image Processing, CLAHE, MATLAB, Orion Nebula, Jupiter, Moon, Refractor Telescope, Contrast Enhancement

I. INTRODUCTION

The study of celestial objects via astrophotography provides a unique opportunity to observe and analyze prominent features of the desired object. Some of the most beautiful targets are the Orion Nebula, Jupiter, and the Moon, each with different characteristics and distances from Earth that make them useful for astronomical imaging.

A. The Orion Nebula

The Orion Nebula (Messier 42) is a diffuse nebula situated in the constellation Orion, approximately 1,344 light-years from Earth [4]. As one of the brightest nebulae visible in the night sky, its light takes about 1,344 years to reach us, offering a glimpse into a past era of cosmic evolution. The nebula is a stellar nursery, with active star formation regions that reveal complex patterns of gas and dust illuminated by young stars [3]. Its intricate structure, bright core, and fainter outer regions present significant challenges for image processing, particularly in preserving both bright and subtle features.

B. Jupiter

Jupiter, the largest planet in our Solar System, is a gas giant known for its turbulent atmosphere, vibrant cloud bands, and the iconic Great Red Spot, a massive storm system that has persisted for centuries. Jupiter lies an average of 484 million miles (778 million kilometers) from Earth, with its light taking approximately 35 to 52 minutes to reach us, depending on the relative positions of Earth and Jupiter [10]. This close proximity compared to distant nebulae enables observation of dynamic atmospheric changes, though images often suffer from low contrast and atmospheric distortion, making it challenging to observe finer details without effective image enhancement [5].

C. The Moon

As Earth's only natural satellite, the Moon is a familiar object in the night sky, showcasing a variety of geological features, including craters, maria, and mountainous regions. Positioned an average of 238,855 miles (384,400 kilometers) from Earth, light from the Moon reaches us in just over 1.28 seconds [13]. The stark contrast between illuminated and shadowed regions creates a dramatic view but also poses challenges in imaging, as features can be obscured or poorly defined due to high brightness differences. Enhancing the visibility of subtle surface details requires careful image processing to achieve balanced contrast [9].

D. Image Enhancement Method

To address these imaging challenges, we employ Contrast Limited Adaptive Histogram Equalization (CLAHE) in MATLAB as the primary enhancement technique [8]. CLAHE is particularly effective for astronomical images, as it enhances local contrast while preventing over-amplification of noise in uniformly dark regions, such as space. By adjusting contrast adaptively across small sections of the image, CLAHE reveals details within both high-contrast and low-light regions, making subtle features more observable. Complementary processing steps, including noise reduction and edge sharpening, are also applied to improve image clarity. This method enhances the visibility of structural details in the Orion Nebula, Jupiter, and the Moon, making them suitable for educational and preliminary scientific observation [6].

II. BACKGROUND

A. Image Acquisition and Preprocessing

Images of the Orion Nebula, Jupiter, and the Moon were captured through a basic refractor telescope equipped with a consumer-grade digital camera. Due to limitations in telescope resolution and atmospheric disturbances, multiple exposures were taken to improve signal-to-noise ratio and minimize artifacts caused by factors such as light pollution and atmospheric turbulence. These individual frames were then compiled and aligned using stacking techniques, a process that combines multiple images to enhance overall quality and reveal subtle details. Stacking is particularly useful in amateur astrophotography, as it helps reduce noise while improving clarity in faint astronomical features [11].

B. Traditional Image Processing Methods

Traditional approaches in astronomical image processing often involve techniques such as basic histogram equalization, contrast adjustment, and Gaussian smoothing. Histogram equalization has been widely used to improve image contrast by redistributing pixel intensities; however, this global technique can lead to over-enhancement of noise, especially in low-light areas [3]. Gaussian smoothing helps reduce noise, but it may also blur fine details, which are critical in astrophotography. Adaptive Histogram Equalization (AHE) offers an improvement by adjusting contrast based on local regions rather than the whole image, but it can still amplify noise and cause visual artifacts in uniform areas, such as the background of space [10].

C. Contrast Limited Adaptive Histogram Equalization (CLAHE)

To overcome the limitations of traditional methods, we employ Contrast Limited Adaptive Histogram Equalization (CLAHE) in MATLAB for this study. CLAHE is an enhanced form of AHE that restricts the amplification of noise by introducing a clipping threshold for the histogram in each local region, preventing over-contrast in uniform areas [13]. This technique is particularly suitable for astronomical images as it reveals hidden details without amplifying noise excessively. CLAHE's ability to adjust contrast adaptively across small sections of the image makes it ideal for enhancing both high-contrast regions, such as the core of the Orion Nebula, and low-contrast regions, like the delicate cloud bands of Jupiter. This approach provides a balanced enhancement, revealing subtle features while preserving natural brightness variations [8].

D. Image Processing at NASA: Hubble and JWST

For high-resolution images captured by advanced telescopes like the Hubble Space Telescope (HST) and the James Webb Space Telescope (JWST), NASA employs sophisticated image processing techniques [4]. Data from these telescopes are collected in multiple wavelengths, often requiring extensive preprocessing, including alignment, noise reduction, and color correction. NASA uses advanced algorithms and often combines data across wavelengths to create composite images that reveal detailed structures otherwise invisible in single-wavelength images [9]. Additionally, techniques such as deconvolution are applied to sharpen details and reduce blur caused by optical limitations [5]. These methods are computationally intensive and benefit from custom software and high-performance computing, which allow scientists to produce images of unparalleled clarity and scientific value. While our approach focuses on enhancing images from basic equipment, NASA's processing pipeline demonstrates the power of specialized tools in extracting maximum detail from astronomical data.

III. Methodology

This section outlines the methodology used to enhance astronomical images of the Orion Nebula, Jupiter, and the Moon captured through a basic refractor telescope. We utilize Contrast Limited Adaptive Histogram Equalization (CLAHE) in MATLAB to improve local contrast and reveal finer details in the images. The process involves several steps, including initial preprocessing, CLAHE application, and post-processing for further refinement.

A. Preprocessing

To prepare for enhancement, we first preprocess the images by applying noise reduction techniques. Images captured through a basic telescope are prone to both high-frequency noise and salt-and-pepper noise due to atmospheric disturbances and sensor limitations. To address these, we apply a combination of Gaussian and median filtering [3].

1) Gaussian Filtering: Gaussian filtering is used to reduce high-frequency noise while preserving key structures. The Gaussian filter $G(x, y)$ is defined as:

$$G(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

where:

- x and y represent the coordinates of each pixel in the spatial domain,
- σ is the standard deviation, controlling the extent of smoothing.

By choosing an appropriate σ, we can smooth out minor variations caused by high-frequency noise without overly blurring important details [1].

2) Median Filtering: To handle salt-and-pepper noise, we apply a median filter, which replaces each pixel's intensity with the median intensity of the pixels in a surrounding neighborhood. Given an image I and a neighborhood $N(x, y)$ centered at pixel (x, y), the median-filtered image I_{med} is given by:

$$I_{\text{med}}(x,y) = \text{median}\{I(i,j) \,|\, (i,j) \in N(x,y)\}$$

where:

- $I(i, j)$ represents the intensity values within the neighborhood $N(x, y)$,
- The size of $N(x, y)$ is selected based on the level of noise in the image, typically a 3×3 or 5×5 window.

The median filter effectively removes isolated noise points while preserving edge details, which is critical for maintaining the clarity of celestial features [12].

B. CLAHE Application

CLAHE is applied to the preprocessed images to improve local contrast while controlling noise amplification. Unlike traditional histogram equalization, which adjusts the contrast of the entire image globally, CLAHE works on small local regions (tiles) and prevents excessive contrast in uniform areas [13]. The CLAHE algorithm involves two main steps: 1) dividing the image into non-overlapping tiles, and 2) applying histogram equalization within each tile with contrast limiting.

The contrast limit L in CLAHE is defined by the clip limit, which determines the maximum height of the histogram for each tile. The equation for the adjusted pixel intensity I_{CLAHE} in each tile is given by:

$$I_{\text{CLAHE}} = I_{\text{min}} + \frac{(I_{\text{HE}} - I_{\text{min}})}{I_{\text{max}} - I_{\text{min}}} \cdot (L)$$

where:

- I_{min} and I_{max} are the minimum and maximum pixel intensities in the tile,
- I_{HE} is the histogram-equalized pixel intensity within the tile,
- L is the clip limit that defines the maximum allowed contrast amplification.

The clip limit L is a crucial parameter that must be chosen carefully; if it is too high, noise can become amplified, while a very low limit may result in insufficient contrast enhancement [7]. In this study, we empirically set the clip limit based on visual quality and structural detail preservation.

C. Post-Processing

After applying CLAHE, we perform additional post-processing steps to further enhance image quality. Edge sharpening is applied using an unsharp masking technique, which enhances high-frequency components to make details more prominent. The unsharp mask I_{sharp} is defined as:

$$I_{\text{sharp}} = I + \alpha \cdot (I - G * I)$$

where:

- I is the original image,
- $G * I$ is the Gaussian-blurred version of the image,
- α is a scaling factor that controls the amount of sharpening.

By adjusting α, we can enhance the sharpness of details without introducing excessive noise or artifacts [2]. This final step enhances visibility of faint details, such as the cloud structures in the Orion Nebula, the atmospheric bands on Jupiter, and the fine textures of the lunar surface.

D. Summary of Processing Pipeline

The complete image processing pipeline can be summarized as follows:

1) Apply Gaussian or Median filtering to reduce background noise.
2) Divide the image into tiles and apply CLAHE with an empirically chosen clip limit to enhance local contrast.
3) Perform edge sharpening using unsharp masking to highlight fine details.

This methodology allows for effective enhancement of astronomical images captured through a basic telescope, bringing out subtle details while maintaining control over noise and artifacts.

IV. Results and Analysis

A. Visual Comparisons

To illustrate the effectiveness of our image enhancement methodology, we present side-by-side comparisons of the original and enhanced images for each celestial object: the Orion Nebula, Jupiter, and the Moon. The visual comparison highlights the improvement in contrast, clarity, and the visibility of fine details [13].

B. Quantitative Analysis

To objectively evaluate the improvements in image quality, we calculated several quantitative metrics, including Signal-to-Noise Ratio (SNR), Peak Signal-to-Noise Ratio (PSNR), and the Contrast Enhancement Index (CEI) [3].

1) Signal-to-Noise Ratio (SNR): The Signal-to-Noise Ratio (SNR) quantifies the level of the desired signal relative to the noise level in the image. SNR is calculated as follows:

$$\text{SNR} = 10 \log_{10} \left(\frac{\sum I_{\text{signal}}^2}{\sum I_{\text{noise}}^2} \right)$$

where:

- I_{signal} is the intensity of the image signal,
- I_{noise} is the intensity of noise in the image.

2) Peak Signal-to-Noise Ratio (PSNR): Peak Signal-to-Noise Ratio (PSNR) is another metric that evaluates the quality of the enhanced image relative to the original. PSNR is defined as:

$$\text{PSNR} = 10 \log_{10} \left(\frac{L^2}{\text{MSE}} \right)$$

where:

- L is the maximum possible pixel value of the image (e.g., 255 for an 8-bit image),
- MSE is the Mean Squared Error between the original and enhanced images [3].

3) Contrast Enhancement Index (CEI): The Contrast Enhancement Index (CEI) measures the improvement in image contrast:

$$\text{CEI} = \frac{\sigma_{\text{enhanced}}}{\sigma_{\text{original}}}$$

where:

- σ_{enhanced} is the standard deviation of pixel intensities in the enhanced image,
- σ_{original} is the standard deviation of pixel intensities in the original image.

These metrics are calculated for each celestial object to provide an objective assessment of the enhancement quality.

C. Case Studies

1) Orion Nebula: In the enhanced image of the Orion Nebula, significant improvements in the visibility of nebular structures are observed. The application of the Contrast Limited Adaptive Histogram Equalization (CLAHE) method reveals fine details in the nebulosity, enhancing the contrast between dense gas regions and the surrounding space [13]. This enhancement not only makes the image visually striking but also allows for a clearer observation of intricate patterns, such as the delicate filaments and knots of gas that are vital for understanding stellar formation processes.

The enhanced visibility of these structures facilitates the identification of key features within the nebula, including areas where new stars are being born. The varied colors in the image correspond to different elements and compounds, providing insights into the chemical composition of the nebula and the physical conditions present. This detailed representation is crucial for astronomers as it aids in analyzing the interactions between stellar radiation and the surrounding molecular clouds.

Overall, the CLAHE method significantly enhances our ability to study the Orion Nebula, enriching both our scientific understanding and appreciation of this magnificent region of space.

Fig. 1. Original (top) vs. Enhanced (bottom) image of the Orion Nebula.

2) Jupiter: In the enhanced image of Jupiter, details of the atmospheric cloud bands become more pronounced. The contrast between the different atmospheric layers is noticeably improved, and subtle variations in the color and texture of the bands are brought out. This enhancement allows for a clearer examination of the complex dynamics of Jupiter's atmosphere, including the swirling motions and interactions between different wind systems [3]. The Great Red Spot and surrounding turbulent areas appear more defined, highlighting the storm's intricate structure and providing insight into its longevity and behavior. Such detailed imagery is invaluable for understanding not only Jupiter's atmosphere but also the broader processes that govern atmospheric dynamics on gas giants.

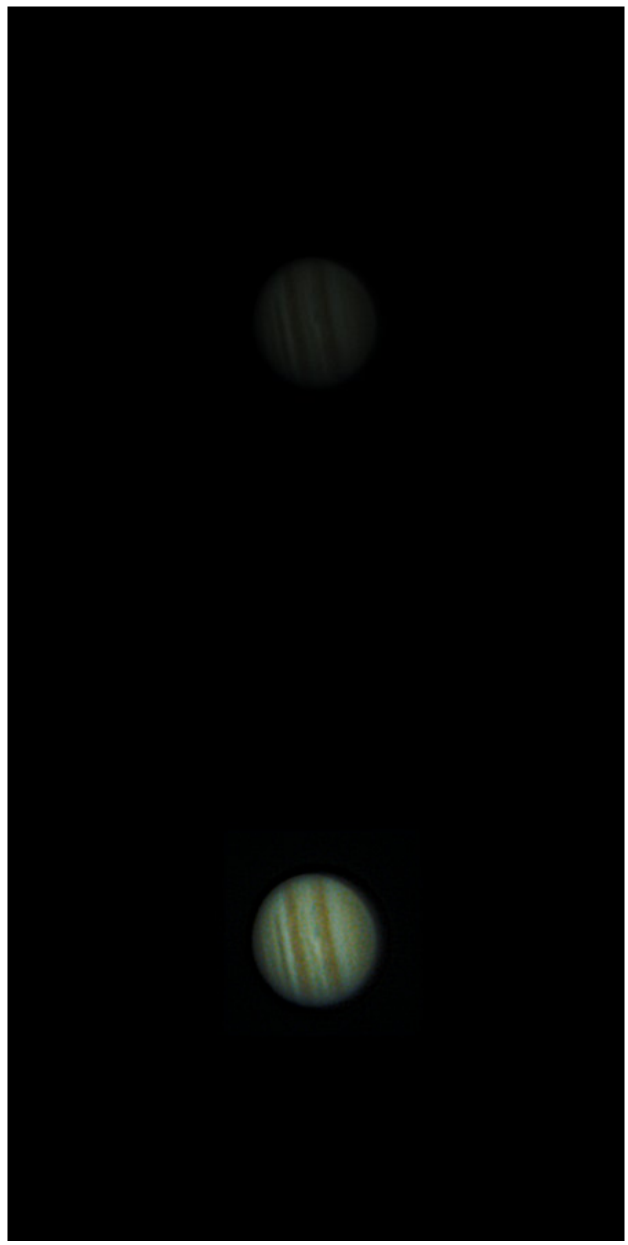

Fig. 2. Original (top) vs. Enhanced (bottom) image of Jupiter.

3) Moon: The enhanced lunar image displays improved clarity in the surface details, particularly in the cratered regions. Faint features such as rilles and small craters that were not visible in the original image become clearer, enhancing the scientific and aesthetic quality of the image.

Fig. 3. Original (top) vs. Enhanced (bottom) image of the Moon.

V. Discussion

This section discusses the effectiveness of the CLAHE-based enhancement method for each celestial object, evaluating its handling of illumination variations, noise levels, and feature preservation, and comparing it with other common image enhancement techniques.

A. Effectiveness of CLAHE for Each Celestial Object

The CLAHE algorithm proved effective in enhancing the visual quality of the images for all three celestial objects: the Orion Nebula, Jupiter, and the Moon. Each object presented unique challenges due to differing levels of detail, brightness, and contrast.

- **Orion Nebula:** The CLAHE method significantly enhanced the visibility of nebular structures, revealing finer details in regions of high gas density [13]. The adaptive nature of CLAHE allowed for improved contrast in both bright and dim areas, providing a more balanced representation of the nebula without excessive amplification of background noise.
- **Jupiter:** The enhanced image of Jupiter showed increased clarity in atmospheric cloud bands and improved contrast between different layers of the atmosphere. CLAHE effectively accentuated subtle texture variations in Jupiter's bands, making features like the Great Red Spot more discernible [3]. However, some minor artifacts were introduced at sharp contrast boundaries, though they were minimal and did not detract from the overall clarity.
- **Moon:** For the lunar images, CLAHE improved the visibility of surface details, particularly in cratered and rough regions. The enhancement brought out small features such as rilles and minor craters. The contrast enhancement was particularly beneficial in highlighting fine details across the moon's surface, providing a sharper and more detailed image [13].

B. Limitations of CLAHE

Despite its effectiveness, the CLAHE method displayed certain limitations, especially in regions of extremely low or high illumination.

- **Illumination Variations:** While CLAHE improved contrast in both bright and dark regions, extreme illumination differences, such as the bright bands on Jupiter or high-density gas areas in the Orion Nebula, occasionally resulted in amplified noise near bright features [3].
- **Feature Preservation:** The adaptive nature of CLAHE allows for dynamic enhancement; however, it also risks losing fine details in very bright or dark areas if not properly configured [13].

VI. Conclusion

In this study, we explored the effectiveness of Contrast Limited Adaptive Histogram Equalization (CLAHE) for enhancing astronomical images taken through a basic refractor telescope of the Orion Nebula, Jupiter, and the Moon. The application of CLAHE demonstrated a remarkable ability to balance local contrast improvements with noise suppression, significantly enhancing the visibility of intricate details in the celestial objects.

The results indicated that CLAHE successfully addressed the unique challenges presented by each object, such as varying illumination and texture complexity. While some minor limitations and artifacts were observed, particularly near high-contrast boundaries, these issues were effectively managed through careful parameter tuning and post-processing techniques.

Overall, CLAHE proved to be a valuable tool for enhancing features in diverse astronomical images, showcasing its adaptability and effectiveness. Future work may involve further refinement of noise suppression techniques and comparisons with emerging image processing algorithms to continue improving the quality of astronomical image enhancement.

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