Discovering Martian Auroras: Applying Entropy Techniques to Data from the Emirates Mars Mission

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Abstract

The detection and analysis of Martian auroras provide critical insights into the planet's atmosphere and magnetosphere. This study presents the first application of an entropy-based method for detecting and analysing nightside martian aurorae, using data from the Emirates Mars Mission's Hope Probe. This novel approach quantifies the complexity of pixel intensity distributions to identify and characterise auroral structures on the martian atmosphere. Compared to traditional techniques, the entropy-based method showed superior sensitivity, effectively detecting subtle aurorae and distinguishing between discrete and diffuse aurorae. This research marks a significant advancement in Martian aurora studies, offering new insights into Mars' atmospheric and magnetospheric dynamics, establishing a methodological framework for future planetary research and highlighting the potential of computational methods in advancing our understanding of planetary phenomena.

1. Introduction

Auroral phenomena result from interactions between charged particles from solar winds, a planet's atmosphere and its magnetic field. On Earth, these interactions produce the infamous Northern and Southern Lights. However, auroras are not unique to Earth, as many planets possess magnetic fields and atmospheres, capable of interacting with solar wind particles to produce similar emissions. Mars, although having lost its global magnetic field, still experiences auroral activity due to its crustal magnetic field (Atri et al., 2022). Mars's crustal magnetic field, which is locked in specific regions of the crust, interacts with solar wind particles, leading to emissions associated with auroral sightings (Atri et al., 2022). These auroras are spotted in over 75% of Mars' nightside images and are known to change shape every 15 to 20 minutes (Lillis et al., 2022).

Martian auroras can be categorised into three main types: discrete, diffuse and proton auroras. Discrete auroras are caused by the precipitation of high-energy electrons into Mars' nightside atmosphere along closed magnetic field lines (Atri et al., 2022). The electron impact causes the electronic excitation of atoms and molecules, resulting in the emission of excited oxygen atoms, which are often associated with auroral sightings (Lillis et al., 2022). Similarly, diffuse auroras are caused by the global precipitation of solar energetic electrons and along open magnetic field lines. Unlike closed magnetic field lines, open magnetic field lines are connected to the planet at one end while the other end is extended into space, allowing energetic particles to enter the planets' atmosphere (Atri et al., 2022), (Gérard et al., 2017). Proton aurora occur on the dayside of Mars and are caused by the precipitation of solar wind protons into the atmosphere (Deighan et al., 2018).

This study focuses on detecting and analysing the auroras that are prominent on the Martian nightside. The brightest emission in these auroral patterns is the atomic oxygen 130.4 nm emission. Other emissions, such as the 297.2 nm oxygen emission, the 135.6 nm oxygen emission and the 289 nm CO2+ UV doublet, may also be present though they are generally weaker (Lillis et al., 2022).

The detection and analysis of auroras on Mars offer significant insights into the planet's atmospheric composition, magnetospheric processes and the variability of solar wind interactions. Previous studies have primarily relied on traditional radiance-based methods for detecting and studying auroras, spotting measurements of discrete auroras in the extreme ultraviolet (<110nm) and far ultraviolet (110-180nm) (Lillis et al., 2022). This research presents a novel approach utilising entropy to enhance the detection and characterization of nightside auroras on Mars.

2. Background

2.1 EMUS Instrument and Data Acquisition

In February 2021, the Emirates Mars Mission Hope Probe successfully entered orbit around Mars. Among the remote sensing instruments aboard the hope probe is the Emirates Mars Ultraviolet Spectrometer (EMUS), which captures ultraviolet images of Mars across a wavelength range of 100-170 nm. This instrument achieves high sensitivity in the far and extreme ultraviolet bands, providing a detailed and comprehensive view of the Martian atmosphere, spanning from the planet's surface to the edge of space (Holsclaw et al., 2021).

The EMUS instrument specifically targets emissions in the Martian upper atmosphere, focusing on key spectral lines such as the hydrogen Lyman-alpha (102.6 nm and 121.6 nm), oxygen (130.4 nm and 135.6 nm) and carbon monoxide (140-170 nm) emissions (Holsclaw et al., 2021). These emissions are vital for understanding the dynamics and composition of Mars' thermosphere and exosphere. Auroral phenomena on Mars, particularly on the nightside, are often characterised by 130.4 nm and 135.6 nm oxygen emissions. The EMUS instrument has revealed these auroral activities offering new insights into the behaviour and occurrence of martian auroras.

This study uses the data collected by the EMUS instrument to analyse auroral activity on Mars. Specifically, data acquired from the OS2 and OSR collection modes were employed. The OS2 mode depicts the 3D structure of atomic hydrogen and oxygen within the inner corona, while the OSR mode captures high-resolution spectral data of hydrogen and oxygen emissions in Mars' thermosphere and exosphere (Holsclaw et al., 2021).

2.2 Significance of Studying Martian Auroras

Understanding and characterising Martian auroras is vital for multiple reasons. Firstly, the geographical and observational occurrence of auroras can provide valuable information about the Martian atmosphere, as interaction between energetic particles and the atmosphere can indicate the presence of specific molecules and atoms, revealing the composition of the atmosphere. Additionally, the location and strength of auroras can indicate areas with intense magnetic fields and offer insights into the planets' magnetosphere.

Auroras also serve as indicators of solar wind variability, as their occurrence is directly influenced by solar wind conditions. By studying the patterns of auroras on Mars, scientists can gain a better understanding of the planets' past climate and potentially predict future atmospheric changes. Moreover, comparative planetology allows researchers to compare between auroral phenomena on Mars and other planets, thereby enhancing our comprehension of planetary magnetic fields and atmospheres.

2.3 Employing Entropy to Study Auroras

Entropy is defined as a measure of disorder, randomness or uncertainty within a system. This fundamental concept in thermodynamics has broad applications across various scientific disciplines for analysing complex data. In planetary science, entropy provides a powerful and novel approach to detecting and characterising phenomena such as auroras. By quantifying the variability and unpredictability in the data, entropy enables the identification of subtle patterns and anomalies.

This study represents the first known application of entropy in the detection and analysis of Martian auroras, marking a significant advancement in the field. This study also marks the first time entropy has been employed as part of the Emirates Mars Mission. The application of entropy enables the segregation of auroral pixels from the background even in instances where traditional methods may struggle. By evaluating the complexity of pixel intensity distributions, entropy enhances our ability to identify and analyse auroras with greater precision. The successful implementation of entropy in this context not only contributes significantly to the study of Martian auroras, but also establishes a new methodological framework for planetary science. By leveraging advanced computational techniques, we can better understand other complex planetary phenomena that may similarly benefit from an entropy-based analysis.

3. Methodology

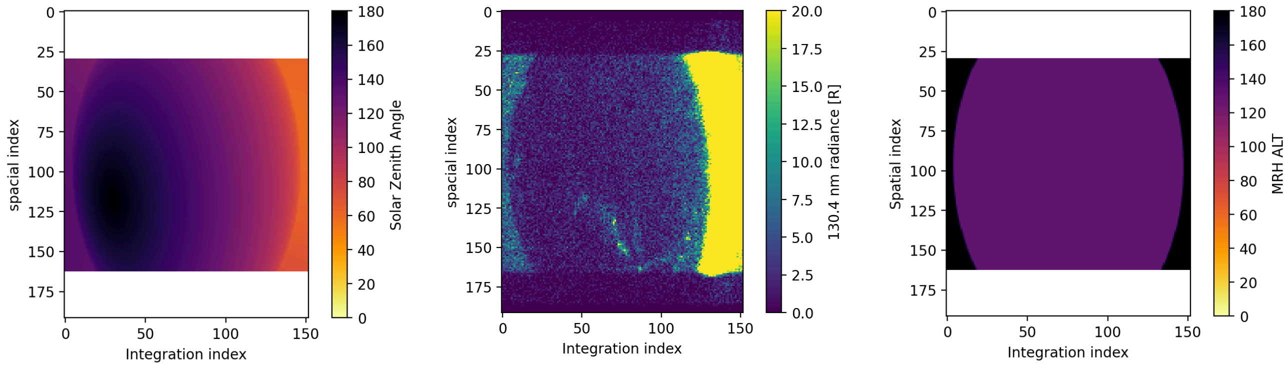
3.1 Automating Aurora Detection

The initial phase of the research focused on developing an algorithm using python designed to automate the search and detection of auroras on the nightside of Mars. As aforementioned, nightside aurorae are typically characterised by strong 130.4 nm emissions and weaker 135.6 nm emissions. These wavelengths are critical indicators used in the detection process. The algorithm was developed to process Level 2B (L2B) FITS files from the EMUS instrument which were accessed through the Emirates Mars Mission science data centre, specifically utilising data from the OSR and OS2 collection modes.

3.1.1 Algorithm Design of Conventional Methods

The algorithm begins by extracting and processing data from the fits file and plotting three critical factors essential for identifying the locations of auroras on Mars. The factors include the Solar Zenith

Angle (SZA), the oxygen 130.4 nm radiance and the altitude from the martian surface. The algorithm computes and plots the SZA for each pixel in the dataset, a crucial parameter that determines the nightside of mars (figure 1a). The algorithm then processes the radiance data, focusing on the 130.4 nm emissions, which is strongly associated with auroral activity (figure 1b). Finally, the algorithm examines the altitude data to ensure that the detected auroras are a part of the martian atmosphere (figure 1c).



(a) (b) (c)

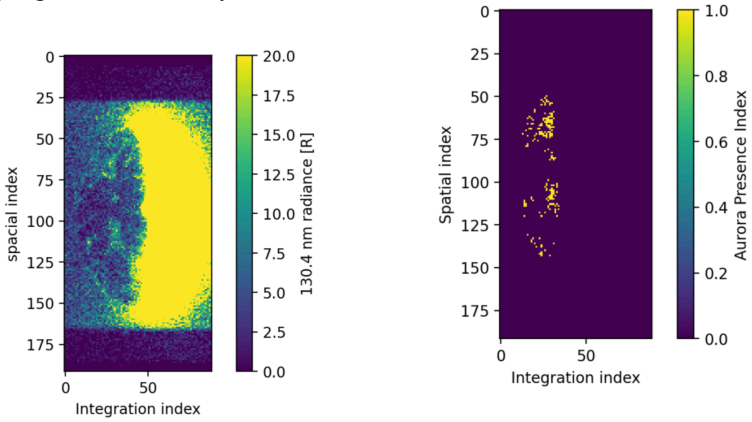
Figure 1. Images plotting the three critical factors essential for identifying the locations of auroral activity on Mars from data file “emm_emu_l2b_20220707t170546_0237_osr_30337_f_v03-00.fits” (a) Plots of solar zenith angle on spatial vs. spectral indices. (b) Plots of 130.4nm radiance on spatial vs. spectral indices. (c) Plots of MRH altitude on spatial vs. spectral indices.

The algorithm systematically iterates through each pixel plotted in Figure 1, applying a series of logical conditions to identify the pixels that meet all the conditions for auroral sightings. The first criteria is that the solar zenith angle must exceed 120°, indicating nighttime conditions on Mars. The second step involves filtering pixels based on their radiance at the 130.4 nm wavelength, noting only those pixels with radiance values above 10 Rayleighs, a reliable threshold for auroral emissions. Finally, to further refine the detection process, the algorithm applies geographical constraints, focusing on pixels corresponding to altitudes of 130 km or lower. This step minimises false positives by ensuring that only emissions seen on the planets’ surface are considered, rather than those from the surrounding atmosphere.

3.1.2 Implementation and Verification of Conventional Methods

By integrating these three criteria, the algorithm generates detailed plots that highlight the regions where all three conditions are met simultaneously, with the auroral pixels being distinctly highlighted against the Martian background. The identified auroral pixels are stored in an array, which records their spatial and integration indices, effectively mapping the longitudinal and latitudinal locations of auroras on Mars.

To verify the accuracy of these detections, the algorithm’s results are compared against the original 130.4nm radiance image. The verification process includes both visual inspection and computational overlay techniques to ensure that detected auroral pixels align with the corresponding radiance data. The algorithm's effectiveness is clearly demonstrated by comparing images before and after processing as shown in figure 2. The enhanced detection capabilities reveal detailed auroral structures that were previously less discernible in the raw data, thereby confirming the algorithm's precision and reliability in identifying auroral activity.



(a) (b)

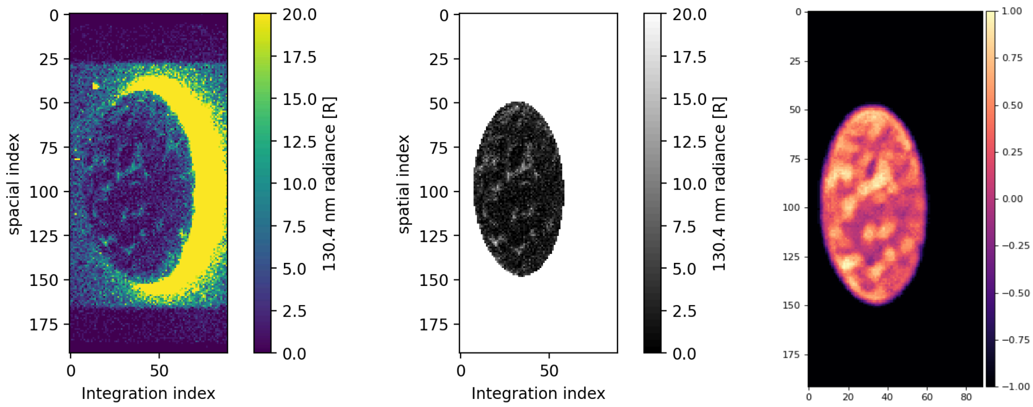
Figure 2. Aurora Location from data file "emm_emu_l2b_20230211t155830_0334_osr_42637_r_v03-00.fits.gz' (a) Plots of 130.4nm radiance on spatial vs. spectral indices. (b) Aurora pixels satisfying all three conditions.

3.2 Exploring Entropy-Based Aurora Detection

Entropy-based methods have been sparsely applied in auroral studies and have not yet been utilised in the context of studying mars nor part of the Emirates Mars Mission, making this approach both novel and promising.

3.2.1 Algorithm Design of Entropy Method

Entropy is calculated based on the variability and complexity of pixel values in an image. Areas with high entropy are likely to contain complex structures, such as auroras, while regions with low entropy tend to be uniform and lack auroral activity. The algorithm processes the 130.4 nm radiance images, extracting the nightside data and applying a binary colour filter, before applying an entropy function to highlight areas with significant auroral activity. This is depicted in figure 3.



(a) (b) (c)

Figure 3. Process of applying entropy function to 130.4nm radiance images as part of the entropy-based aurora detection process. Data accessed through file "emm_emu_l2b_20230225t043632_0340_osr_43523_r_v03-00.fits' (a) Plot of 130.4nm radiance on spatial vs. spectral indices. (b) Plot of 130.4nm radiance undergoing a binary colour filter. (c) Plot of 130.4nm radiance after an entropy function was applied.

The image is then normalised and a threshold entropy value of 0.75 is set. The algorithm then segregates auroral pixels from the background, providing a clear distinction between regions with and without auroral activity. This segregation is depicted in figure 4.

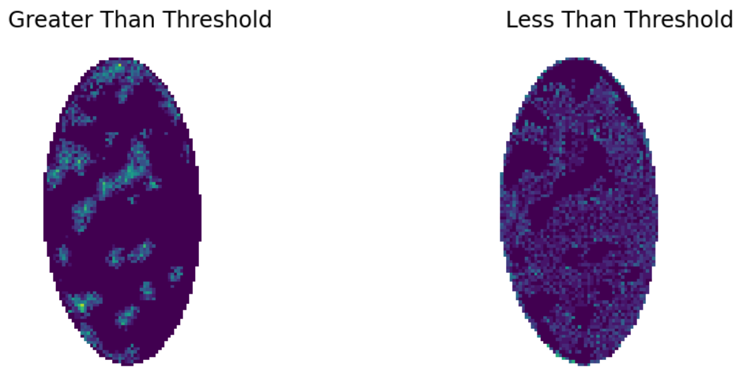


Figure 4. Process of segregating auroral pixels above a threshold of 0.75 from the martian background. Data accessed through file "emm_emu_l2b_20230225t043632_0340_osr_43523_r_v03-00.fits'.

3.2.2 Verification of Entropy Method

The effectiveness of the entropy-based method is validated through a detailed comparison with the original radiance images. This section presents a series of images alongside their corresponding files, illustrating visual comparisons between the 130.4 nm radiance plots and the entropy-filtered images greater than the threshold of 0.75. These comparisons highlight the method's capability to accurately detect and enhance the visibility of auroral structures.

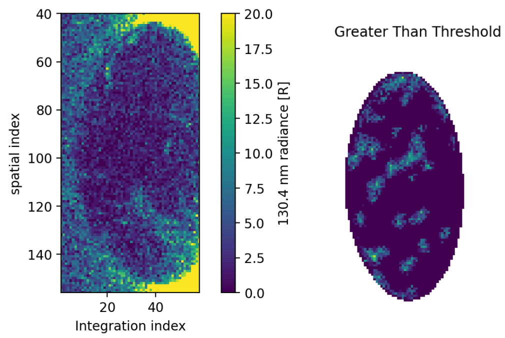


Figure 5. File "emm_emu_l2b_20230225t0
43632_0340_osr_43523_r_v03-00.fits"

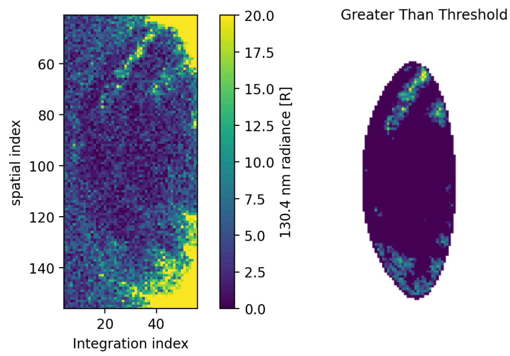


Figure 6. File "emm_emu_l2b_20230225t0
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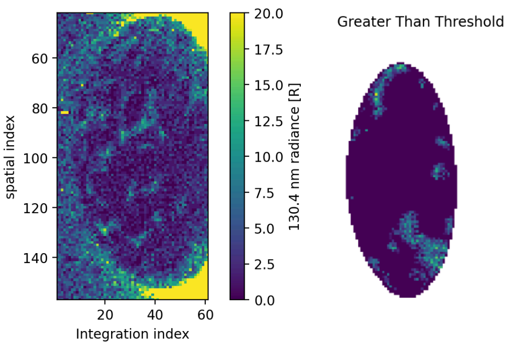


Figure 7. File "emm_emu_l2b_20230213t1
54731_0335_osr_42757_r_v03-00.fits"

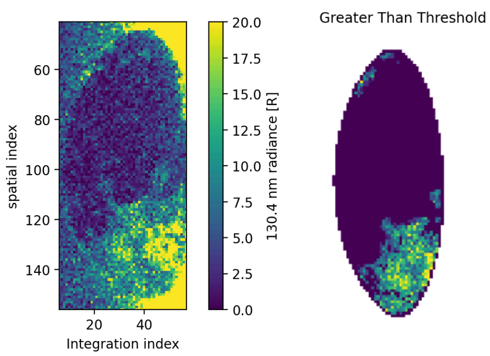
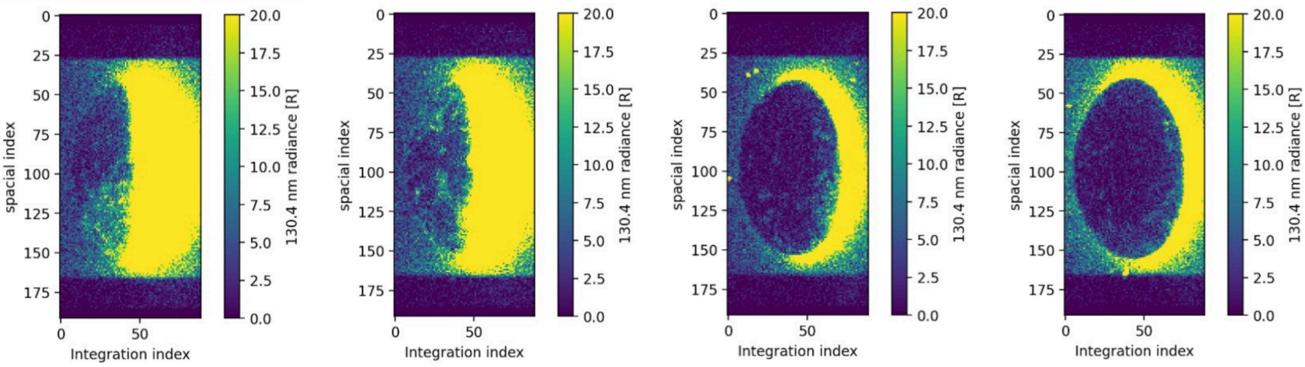


Figure 8. File "emm_emu_l2b_20230211t1
02730_0334_osr_42631_r_v03-00.fits"

3.3 Entropy Analysis for Aurora Classification

In addition to detecting auroras, this research explores the use of entropy to differentiate between the strengths of different types of auroras on the martian nightside. Discrete auroras are typically well-defined and occur in localised regions, while diffuse auroras are more widespread and less intense. The complexity and randomness of these auroral structures can be quantified using entropy, providing a means to classify them based on their entropy values. To characterise the auroras, the nightside radiance images were first converted to grayscale, isolating the regions where auroras were detected. The entropy for each region was then calculated using a standard entropy function that measures the randomness of pixel intensity values.

The resulting entropy values were analysed to determine a threshold that distinguishes between diffuse and discrete auroras. Discrete auroras, with their higher intensity and localised nature, exhibited higher entropy values, indicating greater complexity as shown in figure 9a and 9b. In contrast, diffuse auroras, characterised by broader and more uniform emissions, showed lower entropy values as shown in figure 9c and 9d. By applying this threshold, the algorithm was able to classify the detected auroras into discrete and diffuse categories, providing additional insights into the nature of the auroral events captured by the EMUS instrument.



(a) (b) (c) (d)

Figure 9. Images of both high and low entropy images. (a & b) Images with high entropy values. (c & d) Images with low entropy values.

This method however, still has limitations as the current approach to differentiating aurora types based on entropy values needs further refinement. The threshold used to classify discrete and diffuse auroras may not fully capture the nuances of auroral variations and the method's sensitivity to noise requires improvement. Further research is needed to enhance the accuracy of this classification and to better understand the underlying physical processes that contribute to these entropy variations.

4. Results & Discussion

4.1 Aurora Detection: Radiance-Based vs. Entropy-Based Methods

The primary objective of this research was to assess the effectiveness of a novel entropy-based method in detecting and characterising Martian auroras, with a specific focus on the martian nightside.

The radiance-based detection algorithm served as a benchmark for comparison with the novel entropy-based method..

4.1.1 Performance of the Radiance-Based Detection Method

The radiance-based algorithm successfully identified auroral pixels in the majority of the analysed FITS files. By focusing on the 130.4 nm oxygen emission, the algorithm was able to detect regions with increased auroral activity. The performance of this method was validated through a direct comparison with visual inspections of the raw radiance images, where the algorithm's outputs consistently matched areas with high emission intensity. This method is reliable in identifying well defined auroral regions, demonstrating its continued relevance in planetary auroral studies.

4.1.2 Introducing the Entropy-Based Detection Method

The entropy-based approach, being the first of its kind in the context of Martian aurora detection, offered a novel way to identify and analyse auroras. Unlike the radiance-based method, which relies only on emission intensity, the entropy-based method quantifies the complexity and randomness within pixel values to highlight auroral structures. This method proved particularly effective in segregating auroral pixels from the background, even in instances where the radiance was less noticeable. The entropy-based method's strength lies in its ability to detect subtle and complex auroral features that might be overlooked by conventional radiance analysis.

4.1.3 Comparative Analysis and Accuracy

A direct comparison between the radiance-based and entropy-based methods was conducted across several datasets. The analysis revealed that the two methods had an average pixel match accuracy of 80% for auroral regions. Notably, the entropy-based method identified some additional auroral features that were faint, which the radiance-based method did not detect. For non-auroral regions, both methods exhibited a match accuracy of 95%, confirming the validity and accuracy of the entropy-based method as a complementary tool for aurora detection.

4.2 Key Parameters of Auroral Occurrences

The entropy-based algorithm simultaneously records and saves the key parameters associated with these aurora pixels, such as the geographic coordinates and the strengths of 130.4 nm and 135.6 nm emissions. These data points are crucial for understanding auroral activity on mars. By mapping the detected auroras pixels to their latitude and longitude, the algorithm provides a detailed spatial distribution of auroral occurrences on Mars. The recorded geographic coordinates offer a valuable dataset for analysing how auroras are distributed across the Martian surface, particularly in relation to known crustal magnetic fields.

The correlation between auroral locations and these magnetic anomalies can deepen our understanding of the interactions between Mars' localised magnetic fields and incoming solar wind particles. The geographical data recorded in this study lay the groundwork for future research. Researchers can utilise this dataset to conduct more in-depth studies on the relationship between auroral occurrences and Mars' magnetic field. The methodology and data from this study also have the potential to be adapted for auroral studies on other planets with similar atmospheric and magnetic characteristics.

4.3 Characterization and Classification of Auroras

One of the significant contributions of this study is the classification of auroral types based on entropy values. The algorithm differentiated between discrete and diffuse auroras, with discrete auroras showing higher entropy values due to their well-defined and localised structures. These auroras appeared as bright concentrated spots, corresponding to regions of intense emissions. In contrast, diffuse auroras, characterised by a broader and more uniform distribution of light, exhibited lower entropy values. This distinction provides a clear method for categorising auroras on Mars, enhancing our understanding of their formation and characteristics.

Several case studies were examined to illustrate the effectiveness of the entropy-based classification method. For instance, one dataset from February 2023 showcased a sinuous discrete aurora with a high entropy value, sharply contrasting with the surrounding diffuse aurora. This case not only exemplifies the method's ability to detect auroras but also its precision in classifying different types.

4.4 Quantitative Evaluation of Entropy-Based Classification

4.4.1 Accuracy and Reliability

The quantitative analysis involved comparing the entropy-based classifications against manual classifications performed by experts. The results showed that the entropy-based method achieved an average classification accuracy of 84% for discrete auroras and 93% for diffuse auroras. This high level of accuracy highlights the potential of entropy as a reliable tool for aurora classification, marking a significant advancement in the study of Martian auroras by quantifying complexity and differentiating between auroral types.

4.4.2 Limitations and Future Work

While the entropy-based method showed promising results, the study also identified areas for improvement. The current threshold for distinguishing between discrete and diffuse auroras may not fully capture the nuances of auroral variations, particularly in cases where auroras exhibit intermediate characteristics. Additionally, the method's sensitivity to noise and variations in pixel intensity suggests that further refinement is needed. Future research will focus on optimising the entropy threshold and enhancing the algorithm's efficiency, potentially by integrating additional parameters such as particle energy and noise reduction.

5. Implications and Future Direction

5.1 Implications and Future Research Directions

The use of entropy in detecting and characterising Martian auroras marks a significant step forward in our understanding of these phenomena. The ability to distinguish between discrete and diffuse auroras enhances our understanding of the underlying processes that drive these phenomena. This distinction improves our ability to interpret the diverse magnetic and atmospheric conditions on Mars, leading to a more comprehensive understanding of the planet's dynamic atmosphere.

Future research could focus on refining the entropy-based classification thresholds to further improve the accuracy of aurora characterization. Fine-tuning these thresholds could allow for a more precise differentiation between auroral types and their associated processes. Additionally, integrating entropy-based methods with machine learning could enhance the process of analysing auroras, enabling the identification of subtle variations within discrete or diffuse auroras that may correlate with specific atmospheric or magnetospheric conditions on Mars. Such advancements could also facilitate the development of predictive models for auroral activity, offering a more detailed understanding of Mars' response to solar wind fluctuations.

6. Conclusion

This research demonstrates the effectiveness of an entropy-based approach in detecting and analysing nightside auroras on Mars. By leveraging data from the Emirates Mars Mission and employing advanced computational techniques, this study contributes to our understanding of Martian atmospheric and magnetospheric dynamics. The findings highlight the importance of incorporating innovative methods in planetary science and reinforces the value of the data from the Emirates Mars Mission in expanding our knowledge of Mars.

7. References

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