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ARTICLE

Diurnal Variations of Lee Wave Clouds on Mars Using Emirates eXploration Imager (EXI)

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Abstract: Understanding the diurnal behavior of lee wave clouds on Mars provides critical insight into the planet's mesoscale atmospheric dynamics and their interaction with surface topography. Lee wave clouds exhibit distinct spatial and temporal patterns that vary over the Martian day. In this study, we investigate the diurnal distribution and frequency of lee wave cloud activity during Martian Year (MY) 36 using observations from the EXI instrument aboard the Emirates Mars Mission (EMM) "Hope" spacecraft. A total of 50 lee wave events were identified, with a pronounced peak in activity during afternoon hours between solar longitudes (Ls) 270°–360°. Our analysis reveals a seasonal and local-time dependence for these clouds, providing a comparative framework with previous mission datasets. These findings not only improve our understanding of Martian weather processes but also support future efforts to model and predict terrain-induced cloud dynamics across key locations on Mars.

Keywords: Mars, Lee wave clouds, Planetary atmospheres, EMM, EXI, Cloud detection.

PACs #: 92.60.-e, 92.60.PW, 47.27.-i, 47.32.-y.

1. Introduction

Studying the diurnal behavior of lee wave clouds on Mars offers insights into aspects of the dynamics of the atmosphere. Lee wave clouds form as the air mass flows over elevated terrain and exhibit unique patterns that evolve during the Martian day. Studies of lee wave clouds link daily weather patterns to interactions between surface topography and atmospheric processes. As a result, studying these features is expected to advance knowledge and improve the impact of current and future missions.

1.1. Mars Atmosphere

Mars' atmospheric dynamics are a fascinating interplay of numerous factors that shape the behavior and evolution of its thin envelope. The low atmospheric pressure and low temperatures result in relatively weak winds compared with those on Earth, yet the planet experiences powerful dust storms that can engulf its entire surface. Seasonal variations also influence atmospheric dynamics, with carbon dioxide ice at the poles expanding and contracting, driving atmospheric circulation patterns. Furthermore, Mars' topography and surface features have a significant impact on its atmospheric behavior, affecting wind patterns and producing phenomena such as lee wave clouds [1].

1.2. Lee Wave Clouds

Martian lee wave clouds are formations that arise due to the interaction between the Martian atmosphere and the planet's surface topography. As a stable air mass flows over elevated features,

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such as mountains or crater rims, it generates atmospheric structures in the form of wave-like oscillations [2]. When the air rises over these terrains, it cools adiabatically, resulting in the condensation of water vapor and the formation of these clouds. This phenomenon is generated by topographic features, such as crater rims or mountains, which have been observed to vary in height from as low as 10 km [3] to as high as 35 km [4].

1.3. Properties

Lee wave clouds on Mars exhibit distinct properties that vary by season, and potentially by time of day. A recent study has demonstrated a strong correlation between topographic altitude and the vertical distribution of zonal wind [3]. Strong static stability near the ground and increasing wind speed with height through the troposphere support the trapping of internal gravity waves in the lower atmosphere, forming lee wave clouds [5]. Lee wave clouds on Mars are mainly observed downwind of elevated topographical features, such as mountains and crater rims, where the interaction of the prevailing winds with the terrain generates the atmospheric waves necessary for their formation.

2. Previous Missions

Studying Martian lee wave clouds has progressed our understanding of the planet's atmospheric dynamics through various planetary missions. Starting in 1971, Mariner 9 successfully became the first spacecraft to enter orbit around Mars, providing groundbreaking imagery of the planet's surface and atmosphere. It captured early evidence of orographic cloud formations near the Tharsis Montes, including wave-like patterns consistent with lee wave activity [6]. Following this, the Viking missions launched in 1975 significantly advanced atmospheric studies on Mars, with their instruments capturing layered cloud formations and wave-like structures in the vicinity of major volcanic terrains [7]. In 1997, the Mars Global Surveyor (MGS) began operations with its Mars Orbiter Camera (MOC), significantly improving spatial and temporal resolution. MGS captured seasonal cloud formations over elevated terrain and helped establish mesoscale modeling efforts for wave-cloud generation [8]. The European Space Agency's (ESA) Mars Express, launched in 2003, contributed high-resolution stereo imaging via the HRSC and atmospheric profiling through the Planetary Fourier Spectrometer (PFS). These instruments detected cloud trains and lee wave structures near Arsia Mons and other volcanic complexes [9]. Most recently, the Emirates Mars Mission (EMM), launched in 2020 and operational since 2021, has provided a new level of atmospheric coverage through its payload of instruments, including the Emirates eXploration Imager (EXI), the Emirates Mars Infrared Spectrometer (EMIRS), and the Emirates Mars Ultraviolet Spectrometer (EMUS). EMM has provided unprecedented diurnal and seasonal monitoring of atmospheric phenomena, enabling detailed observation of lee wave clouds across varying latitudes and times of day [10]. Together, these missions showcase significant advances in observing Mars and highlight how EMM is setting a new standard in tracking and understanding lee wave clouds.

3. Occurrences and Locations

Cloud observations on Mars provide important information on local meteorology, atmospheric circulation, and seasonal climatic variations. The earliest cloud observations of clouds were detected by Mariner 9 and Viking orbiter missions back in 1979 in which cloud occurrences with seasons were recorded and obtained on specific locations on Mars since then[5]. It has been observed that lee wave clouds usually occur in mid-to-high latitudes on Mars and are rarely observed at the equator [1]. Seasonally, these occurrences usually occur during the spring and fall-winter time [1]. A full assessment on occurrences per season has been conducted based on the Mariner 9 and Viking orbiter images for Mars Year (MY) 13 and 14 has been performed. Observations show that during L_S = 0°–90°, lee wave clouds were seen to be abundant at mid-to-high southern latitudes and during L_S = 90°–180° in the southern mid-latitude and northern hemisphere [5]. Similar behavior was observed in Mars Color Camera (MCC) images during years MY 33 and 34, in which the amount of lee wave clouds could be seen near L_S = 90°–110°, reaching its peak near L_S = 100° with activity decreasing to a minimum near L_S = 140° [2]. In contrast, the Mars Global Surveyor (MGS), using MOC images, documents that there is little occurrence of lee wave clouds before Ls = 170°, captured during MY 26 [11]. For L_S = 180°–270°, there were only a few observations of lee wave clouds during this season observed by Viking and

Mariner 9. While a notable lee wave cloud occurrence was captured by MGS caused by Milankovic crater near the Northern polar region at L_S = 234° [11]. As the season progresses towards Northern winter L_S = 270°–360°, Mariner 9 observations show an abundance of lee wave clouds in the north, which might also be related to a global dust storm event that occurred during that time [5]. During this season, Mars has significant fall and winter lee wave activity in the mid-latitudes due to strong wind shear, with wind speeds increasing sharply with altitude due to the winter mid-latitude jet stream. This strong vertical wind shear is only present during these seasons [11]. Table 1 summarizes these findings.

TABLE 1. The table is a summary of reported lee wave cloud detections from Mariner 9, Viking, MGS, MOM, EMM captured observations for MY 13, 14, 26, 33, 34, and 36, categorized by solar longitude These findings were reported by French, 1981 [5], Kalita et al., 2022 [4] and Wood et al. 2003 [11].

Mars Year (MY)	Ls (Solar Longtitude)	Ls = 0°-90°	Ls = 90°-180°	Ls = 180°-270°	Ls = 270°-360°	Mission
	MY 13	mid-to-high Southern Latitudes	Southern mid-latidues and Northern hemisphere	Not reported	mid-latitudes	Mariner 9 and Viking
	MY 14	Not reported	Not reported	Not reported	mid-latitudes	Mariner 9 and Viking
	MY 26	Not reported	Not reported	Milankovic crater near Northern Polar region	Not reported	Mars Global Surveyor (MGS)
	MY 33	mid-to-high Southern Latitudes	Southern mid-latidues and Northern hemisphere	Not reported	Not reported	Mars Orbiter Mission (MOM)
	MY 34	mid-to-high Southern Latitudes	Southern mid-latidues and Northern hemisphere	Not reported	Not reported	Mars Orbiter Mission (MOM)
	MY 36	Southern mid-latidues and Northern hemisphere	Not reported	Mid-latitudes Northern Part	Mid-latitudes Northern Part	Emirates Mars Mission (EMM)

4. Methodology

Initially, the EXI L2A RGB band dataset for MY 36 was filtered to identify images containing lee wave cloud patterns. Filtering the data was attempted through various approaches for automation, ranging from simple classification techniques for cloud detection to machine learning with specific cloud patterns that lee wave clouds exhibit. However, these methods didn't achieve the reliability required for accurate lee wave identification. Out of 3706 EXI L2A RGB band images processed, 591 images were identified to contain potential lee wave clouds. Through manual verification, it was concluded that the developed code is more suitable for general cloud detection rather than specifically for lee wave clouds, as it did not successfully capture the unique cloud pattern and required adjustments. The General Pre-trained Transformer (GPT)-4 was briefly tested as well. GPT-4 is an OpenAI model that can be used for image detection by integrating advanced language understanding with computer vision. It can be used to analyze the images. Using this model could potentially resolve these issues; however, due to time constraints, a manual approach was adopted in which a total of 50 images were detected with lee wave clouds in EXI observations. Utilizing AI capabilities for image classifications using deep learning methods is an extended topic for future work. Recent advances in deep learning have demonstrated strong potential in the automated identification of orographic cloud phenomena. Coney et al. [12] developed a convolutional neural network model trained on hand-labeled vertical velocity fields to detect and characterize

trapped lee waves with high precision. Their method effectively segments lee wave structures and enhances the spatial understanding of their formation over complex terrain. While their approach focuses on Earth-based Numerical Weather Prediction (NWP) data, such methodologies offer strong potential for adaptation to Martian cloud detection studies. In future work, we can consider the application of similar deep learning frameworks, particularly for the automated recognition of lee wave cloud trains in imagery from missions such as EMM.

5. Results

Along the full MY 36, lee wave clouds were found in a total of 50 EXI image observations. The observations captured at multiple local times provided valuable insight which is crucial in the overall understanding of how lee wave clouds behave during the day and the different timing they can develop. The images were screened initially using machine learning-based detection methods. However, due to challenges in optimizing algorithm to detection of lee wave clouds (as highlighted in the Methodology section of this paper), the images were then filtered manually. Based on these observations, we found that during L_S = 0°–90°, lee wave clouds were observed in in the mid-latitude region between 22° North latitude and ~ –20° South. At the beginning of the season, the lee wave clouds were observed in the Northern part initially. As the season moved towards L_S = 0°–90°, the occurrences shifted towards the southern part of the hemisphere. with respect to local time, lee wave clouds occurred in the afternoon time (between >12:00 – 19:00) and a few observations that identify lee wave clouds during the evening time (>19:00 – 00:00). During L_S = 90°–180°, there were no detections of lee wave clouds, which is consistent to previous mission results that lee wave cloud occurrences decreases during this season. For L_S = 180°–270°, only one observation was identified in mid-latitude Northern part around the Arabia Terra during the evening time (>19:00 – 00:00). Viking and Mariner 9 observations are similar with low activity level being observed during MY 26. As the season progresses to L_S = 270°–360°, numerous lee wave clouds appear during the morning time (>00:00 – 12:00) and afternoon time (between >12:00 – 19:00) in the mid-latitude Northern hemisphere. These results are very consistent with other missions that observed lee wave clouds dating from MY 13 to MY34 as summarized in Table 1.

6. Discussion

The seasonal and spatial pattern of lee wave clouds on Mars is consistent with those reported in previous missions. The lee wave clouds appeared mostly at mid-latitudes from 22°N to ~20°S during the early Martian season (L_S = 0°–90°) with cloud activity beginning in the northern hemisphere and progressively migrating southward with season. in terms of local timey, the clouds were observed more frequently in the afternoon, although additional detection was also observed in the evening. No lee wave clouds were identified during L_S = 90°–180°, consistent with previous observations that report reduced activity in this Interval For L_S =180°–270°, only a single case of lee wave cloud formation was detected in the northern mid-latitudes around local noon. As the season progressed to L_S = 270°–360°, lee wave cloud activity increased, concentrated in the northern mid-latitudes during both the morning and afternoon hours. Fig. 1 presents the number of detections as a function of local time and season for MY 36 captured by the EMM mission. Based on the results, lee wave clouds exhibited the highest activity during L_S = 270°–360° in the afternoon time between the hours of 12:00-19:00. This is a correct representation of cloud formation and radiative transfer mechanism. During the afternoon, the heat from the sun warms the surface which creates a weak convection. This supports the lifting mechanism and allows the water vapor to rise. The higher in altitude it goes, the cooler it gets. Therefore, forming condensation into water ice clouds. Compared to the evening, the surface cools very quickly since Mars radiates heat fast. As a result, this supports less cloud formation during the evening time.

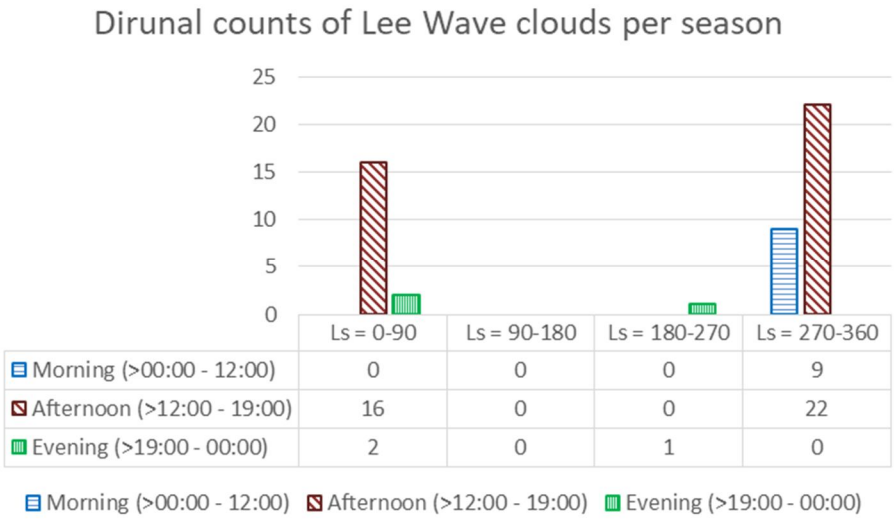

FIG. 1. Diurnal counts of lee wave clouds per season as a function of local time based on data from the EXI instrument on the EMM.

7. Conclusion

Assessing lee wave cloud identification during MY 36 using the EMM dataset provided valuable context for understanding the spatial and seasonal distribution of these phenomena. By analyzing red band imagery from EXI, we confirmed 50 distinct lee wave cloud occurrences, with peak activity observed during the afternoon hours in the late southern spring to early summer (L_S = 270°–360°). Comparisons with previous mission data validated our detection approach and underscored the significance of diurnal evolution in lee wave behavior. While this study focused on capturing the global characteristics of lee-wave cloud activity across the whole study period, a logical next step is to refine our analysis to focus on specific regions and events. In particular, the work by Gebhardt et al. [13], which presents sub-hourly EXI observations of a rapidly evolving dust storm and associated lee wave clouds near Lyot Crater, demonstrating the power of high-frequency, location-focused monitoring. Their findings reveal how morning gravity-wave patterns evolve into afternoon convective dust activity, which emphasizes the dynamic coupling between topography and atmospheric processes. Our future efforts will focus on prioritizing site-specific case studies aimed at predicting lee-wave formation and diurnal transformation, thereby deepening our understanding of Martian mesoscale meteorology.

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