AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL075792

Key Points:
- Stationary gravity waves with large horizontal extent at the cloud top level of Venus have been repeatedly identified
- The locations of these waves show a clear connection to Venusian highlands, and wave amplitude depends on the local time at the highlands
- Monitoring of the stationary waves would bring information of the Venusian atmosphere along the wave propagation paths

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Citation:
Kouyama, T., Imamura, T., Taguchi, M., Fukuhara, T., Sato, T. M., Yamazaki, A., … Nakamura, M., (2017). Topographical and local time dependence of large stationary gravity waves observed at the cloud top of Venus. *Geophysical Research Letters*, *44*, 12,098–12,105. https://doi.org/10.1002/2017GL075792

Received 25 SEP 2017
Accepted 29 NOV 2017
Accepted article online 4 DEC 2017
Published online 23 DEC 2017

Topographical and Local Time Dependence of Large Stationary Gravity Waves Observed at the Cloud Top of Venus

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Abstract The existence of large stationary gravity waves was discovered during Akatsuki's first observation sequence in 2015. In this study, the further detection of large stationary gravity waves in brightness temperature images over a 1.5 year period is reported. The waves periodically appeared mostly above four specific highland regions in the low latitudes when these regions were in the local afternoon. The wave amplitudes attenuated after the wave locations passed beyond the evening terminator, and the locations of the waves tended to slowly drift eastward over their lifetimes. The appearances of stationary waves depend not only on surface topography but also on latitude and local time, suggesting that solar heating during the daytime and atmospheric structure affected by solar heating may control the excitation and propagation of stationary waves.

Plain Language Summary The Japanese Venus satellite "Akatsuki" has repeatedly found large atmospheric waves with north-south lengths, which sometimes reach more than 10,000 km at the cloud top level on Venus (altitude ~70 km). These waves have repeatedly appeared above the Venusian highlands in low latitudes, such as Aphrodite Terra. Interestingly, the waves appeared and became clearer each time the highlands passed from noon to evening; therefore, they can be regarded as "daily" Venusian phenomena. Despite westward wind speeds reaching 100 m s^{-1} at the cloud top level (known as atmospheric superrotation), the east-west propagation speeds of the large waves were nearly zero, and the waves stayed above their initial locations (stationary). This means that the origin of the waves could be the highland terrains below. Because waves can transport energy via propagation, stationary waves may transport atmospheric energy from the lower atmosphere to the cloud top level and may affect the speed of the superrotation. The existence and regular appearance of the large stationary waves indicate a continuous interaction between the lower and upper atmospheres on Venus via wave propagation, which provides a novel perspective of the Venusian atmosphere.

1. Introduction

Akatsuki is a Japanese satellite currently orbiting Venus that specializes in investigating the atmosphere of Venus. The satellite's unique set of instruments allows for the study of dynamics and cloud physics in the Venus atmosphere in an unprecedented manner. Fukuhara et al. (2017) discovered a large bow-shaped thermal feature extending from the equator to both the southern and northern high latitudes observed by Longwave Infrared Camera (LIR) (Fukuhara et al., 2011; Taguchi et al., 2007) after the Akatsuki Venus orbit insertion (VOI-R1) on 7 December 2015 (Nakamura et al., 2016). The feature was also found in cloud albedo variations observed by Ultraviolet Imager (UVI) (Nakamura et al., 2011). Based on 5 day successive observations after the VOI-R1, the large bow-shaped feature remained in essentially the same geographical position, above the western part of Aphrodite Terra, despite the existence of a fast background zonal wind (reaching 100 m s^{-1}) known as atmospheric superrotation at the cloud top level.

Various gravity waves have been found at the cloud top with the Venus Express observations: very small scale waves (typical wavelength 7–15 km) concentrated in regions above highlands seen in ultraviolet, visible and near-infrared images (Piccialli et al., 2014; Titov et al., 2012), small-scale waves (60–150 km) with small phase speeds that are apparently not linked to topography in ultraviolet images (Peralta et al., 2008), and small-scale stationary waves linked to topography in thermal infrared images (Peralta et al., 2017). Unlike these waves, the stationary wave feature observed by Akatsuki was much larger.

A numerical simulation shows that the large bow-shaped feature can be explained by a stationary gravity wave generated by a near-surface (10 km), localized forcing in the equatorial region (Fukuhara et al., 2017). The wave's latitudinal scale increases with height and reaches planetary scale at the cloud top. Since gravity waves deposit momentum to the background flow where the waves dissipate and stationary gravity waves possess momentum in the opposite direction of the background flow, the superrotation could be decelerated by the attenuation of stationary waves in the upper atmosphere (cf. Bertaux et al., 2016; Lindzen, 1981) where strong radiative damping is expected (Crisp, 1986).

Notably, when the same region was observed by Akatsuki 1 month later, the stationary wave was absent (Fukuhara et al., 2017), suggesting a temporal variation in the atmosphere's dynamic conditions below the cloud top level. Because both zonal wind speed and static stability are expected to be low in the lower atmosphere (Seiff et al., 1980), the conditions of wave generation and propagation should be sensitive to their small changes. Therefore, investigation of the frequency, location, local time, and duration of the appearance of stationary waves at the cloud top should provide information about the physical conditions of the lower atmosphere where the waves are generated.

Since the VOI-R1, LIR has continued its observations for almost 3 Venus years (or 5 Venus solar days). Herein, we report large stationary wave events, which repeatedly occurred not only above Aphrodite Terra but also over other highland regions in the low latitudes and showed a local time dependence.

2. Observations and Data

LIR covers the wavelength range of 8–12 μm and captures the thermal radiation emitted from the cloud top level of Venus. The contribution function representing the sensed altitude is centered at ~65 km with a full width of 10 km at low and middle latitudes (Taguchi et al., 2007). The noise equivalent temperature difference, or temperature resolution of LIR, is 0.3 K at a target temperature of 230 K, and the absolute temperature accuracy is 3 K (Fukuhara et al., 2011).

The LIR observations were conducted from 7 to 11 December 2015 resumed on 15 January 2016 after a 1 month interruption, and LIR began regular observations in April 2016. The time interval of the image acquisition is usually 1 or 2 h, and image acquisition is typically repeated for more than 12 h each day. The spatial resolution of the Venus images changes according to the distance between Venus and Akatsuki, from 0.87 km/pixel at the periapsis altitude of 1,000 km to 7.0 and more than 300 km/pixel at 8,000 km and at the apoapsis altitude of ~360,000 km, respectively.

Data obtained between 7 December 2015 and 28 February 2017 were used in this study, which is about four Venus solar days, and images with a spatial resolution higher than 150 km/pixel were used, in which ~1,000 km scale structures are sufficiently resolved. During this period, LIR repeatedly detected large stationary waves in the brightness temperature images. These wavefronts were roughly aligned in a north-south direction, and the meridional spans exceeded several thousand kilometers. To clarify the basic tendencies of the large stationary waves, we have focused on stationary waves with spatial scales of at least 1,000 km and with more than a 1 K deviation of peak temperature in their center latitudes. A threshold was set to extract indubitable stationary waves, which can be recognized even in nonfiltered Venus disk images. High-pass filtering of the temperature data was performed to enhance wave features; this was completed by subtracting an image smoothed by a Gaussian function with a spatial scale of 15° from the original image.

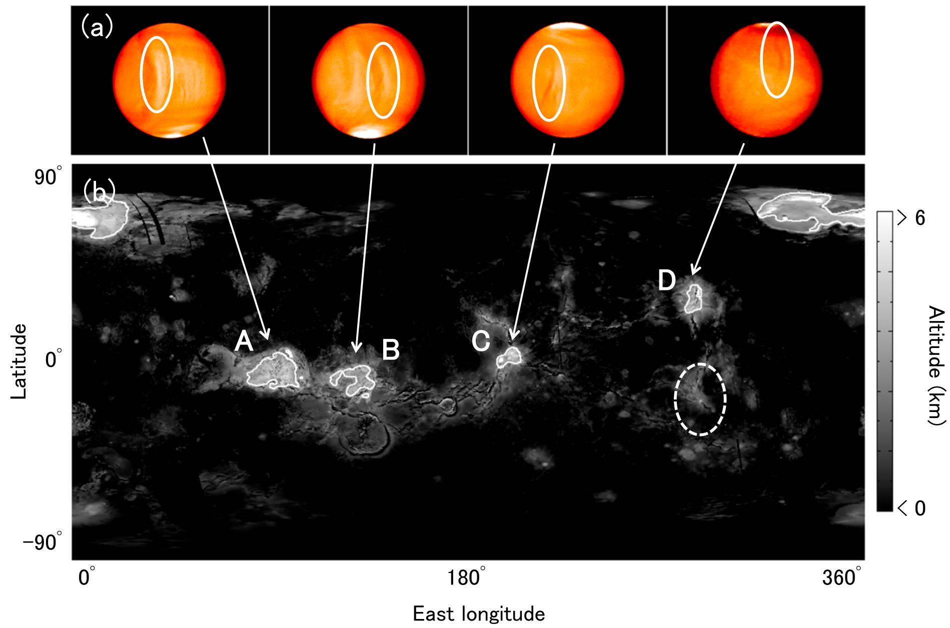

Figure 1. (a) Examples of large stationary gravity waves seen in brightness temperature images of the Venus disk taken by LIR and (b) the four highland locations surrounded by 3 km altitude lines (after 3° smoothing) on a Venus altitude map. Phoebe Regio is indicated by a dashed ellipse. The altitude range from 0 to 6 km is enhanced.

3. Characteristics of Large Stationary Waves

3.1. Locations of Stationary Waves

The large stationary waves appeared at specific longitudes with center positions above four specific highlands (Figure 1): Ovda Regio, in the western part of Aphrodite Terra (denoted as Region A in this study), where the first bow-shaped feature was discovered; Thetis Regio (Region B); Atla Regio (Region C); and Beta Regio (Region D). The latitudes, longitudes, and peak altitudes of these regions are summarized in Table 1. The topography data are taken from the Magellan global topography data records (4.6 km grid interval) of the Planetary Data System of NASA.

Examples of stationary waves above the four regions are shown as sequential brightness temperature images (Figure 2), which were mapped as longitude-latitude coordinates and then high-pass filtered. A limb-fitting technique was applied to improve the accuracy of the map projection (Ogohara et al., 2012). A zonal flow with a speed of 100 m s^{-1} at the equator can circulate over a zonal displacement of ~40° longitude in 12 h; however, the wavy features seen in Figure 2 remained in their initial locations and maintained their bow-like shapes over this timescale. In addition, the stationary waves in each region appeared repeatedly, and their locations and shapes were nearly unchanged. The peak-to-peak amplitude of the brightness temperature associated with the waves reached 3 K; assuming this variation resulted from only the cloud altitude variation, the altitude variation can be ~1 km based on the Venus International Reference Atmosphere temperature profile (Seiff et al., 1985). The contribution of the variation of atmospheric temperature to brightness temperature variation is under study.

Table 1
Highland Region Names, Longitude and Latitude Ranges (> 3 km Altitude), and Peak Altitude of the Four Regions Where Large Stationary Waves Were Identified

Region	A	B	C	D
Name of highland	Ovda Regio (Aphrodite Terra)	Thetis Regio (Aphrodite Terra)	Atla Regio	Beta Regio
Longitude	80°-105°	117°-138°	193°-204°	278°-286°
Latitude	−12°-6°	−16°-−2°	−3°-7°	22°-35°
Peak altitude (km)	5.7	7.4	8.9	6.5
Identified periods	Dec. 2015, Jul. - Aug. 2016	Aug. 2016	May 2016, Sep. 2016, Dec. 2016	May 2016, Jan. 2017

Note. Periods when the large stationary waves were observed are also listed.

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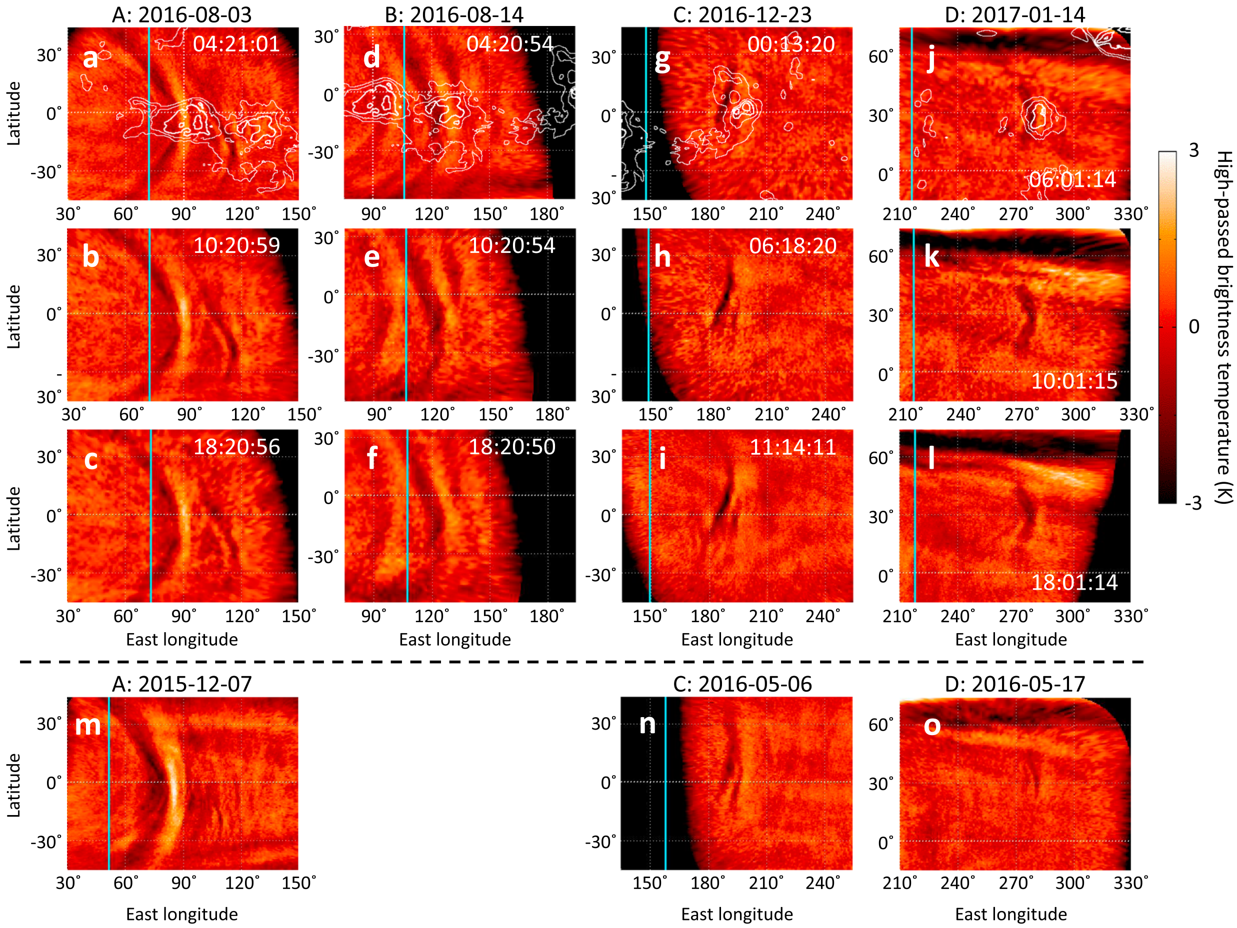

Figure 2. Time series of stationary wave events at (a–c) Region A, (d–f) Region B, (g–i) Region C, and (j–l) Region D derived from three successive shots (high passed) by LIR within half a day, and (m–o) wave events in different periods in Regions A, C, and D. The direction of the background zonal wind is from right to left. The surface topography after a smoothing with a spatial scale of 3° is overlain with contour lines (1 km) in the upper panels, and lines higher than 3 km are enhanced. Blue lines denote evening terminator longitudes.

All four highland regions have peaks higher than 5 km and are widely higher than 3 km. Other regions did not show clear stationary wave signatures that exceeded the threshold, although ambiguous wavy features were sometimes observed in these regions.

The central locations of the stationary waves were slightly west (presumably downstream) of their nearest highland peaks. This tendency was the same as the bow-shaped feature first reported by Fukuhara et al. (2017). The horizontal wavelengths of the features around their center latitudes were no wider than 30° in all cases. However, the latitudinal extent and shapes were variable depending on the regions in which they appeared. The length of the stationary feature in Region A reached ~10,000 km in the north-south direction; such long features have not been confirmed in Regions C and D. While the stationary features in Regions A and D showed symmetrical, bow-like shapes, the stationary feature showed a nonsymmetrical shape in Region C, which has a narrower and more complex topography (i.e., two local peaks) compared to the other three regions. These differences could indicate that the appearance of stationary features may reflect differences in surface topography, and therefore, it is suggested that the local topography may contribute to the generation of stationary waves.

It should be noted that there was no clear confirmation in LIR observations of any stationary feature above Maxwell Mons, which is the highest mountain on Venus, although small wavy patterns were identified in close-up cloud images (Piccialli et al., 2014). Maxwell Mons is located at 60°N, while the four regions exhibiting stationary features are in the lower latitudes ($< 35°$). In addition, a stationary wave pattern was observed on 25 January 2017 above Phoebe Regio, which is also a highland almost symmetrically located in Region D on the other side of the equator; the wave shape was rather obscure compared to the waves observed in

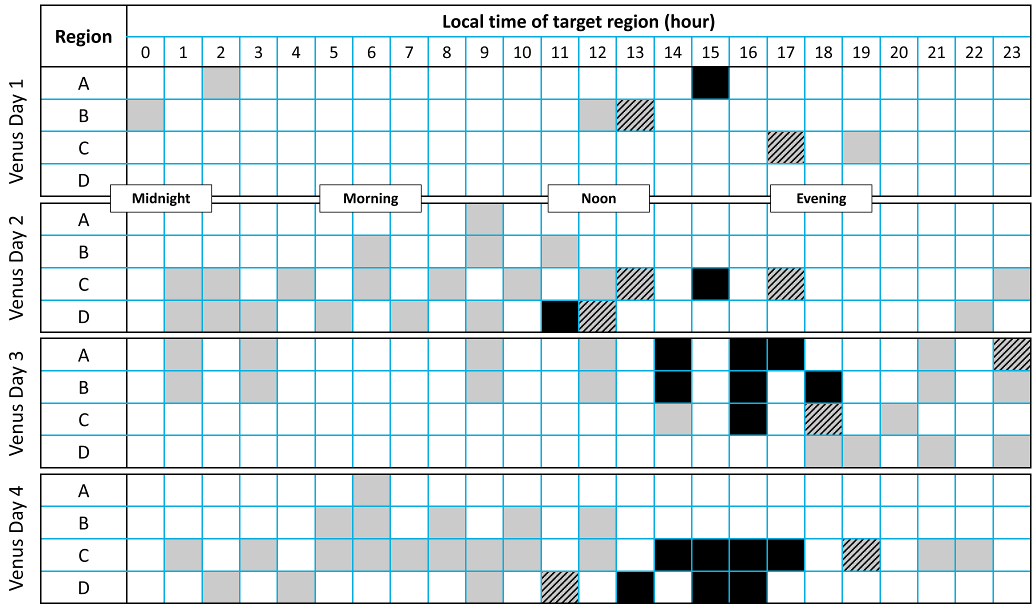

Figure 3. Distribution of stationary waves identified in LIR images at the four target regions over local time during four Venus days. Each cell covers 1 h (e.g., 12 h = 12.0–13.0 h). Black, hatched, and gray cells indicate that the waves were clearly identified (peak amplitude >1 K), marginally identified (0.5–1 K), or not identified (<0.5 K), respectively. White cells indicate no observation with a resolution higher than 150 km/pixel. The first Venus day covered 22 October 2015 to 15 February 2016; the second day covered 15 February to 12 June 2016, the third day covered 12 June 2016 to 6 October 2016, and the fourth day covered 6 October to 31 January 2017.

Region D. Phoebe Regio has a high (~5 km) but narrower peak, which rises by 1 km within a 10 km horizontal distance and has a lower base altitude compared to Region D.

3.2. Local Time Dependence

A common feature of every stationary wave appearance was that it became significant when it approached the evening terminator. To clarify the local time dependence, the occurrence of stationary waves with respect to the local solar time for Regions A through D was summarized for a period of four Venus solar days (1 Venus solar day = 117 Earth days) (Figure 3). For this study, to avoid dividing the data in any event into different Venus days, every Venus solar day was set to begin when 0°E longitude passed local noon.

The stationary waves were significant mostly in the afternoon and early evening, while they were seldom detected during the midnight or morning. Focusing on the local time of 15–16 h, stationary waves were identified at every observation opportunity. The clear dependence on local time suggests that the lower atmosphere experiences similar conditions every Venus solar day, at least in the four studied regions.

3.3. Time Evolution

The time evolution of a stationary wave from emergence to disappearance above Region A was investigated for a period of over a month, from 12 July to 24 August 2016 (Period 3). Figure 4 shows the time evolution of the wave amplitudes, the peak locations at the center latitude of the bow shape (5°S), and their appearances from high-resolution images of Region A. Due to the orbital period, the time interval was ~10.5 Earth days. The temperature was averaged within a latitudinal range of ±15° for every longitudinal bin to extract latitudinally expanding components. The local time of the peak temperature moved from 13 h to 20 h from 12 July to 24 August and was accompanied by a variation in the peak amplitude, which increased from 13 h to 15 h and decreased after a wave peak passed beyond the evening terminator.

Notably, the peak longitude of the wave moved eastward by at least 20° (upstream direction) during its appearance. In addition, another stationary wave, which was standing on 14 and 24 August in Region B, also showed an eastward movement of the temperature peak by a few degrees over 10 days (Figure 4). These observations suggest that stationary waves are not exactly stationary. The speed of the movement is much

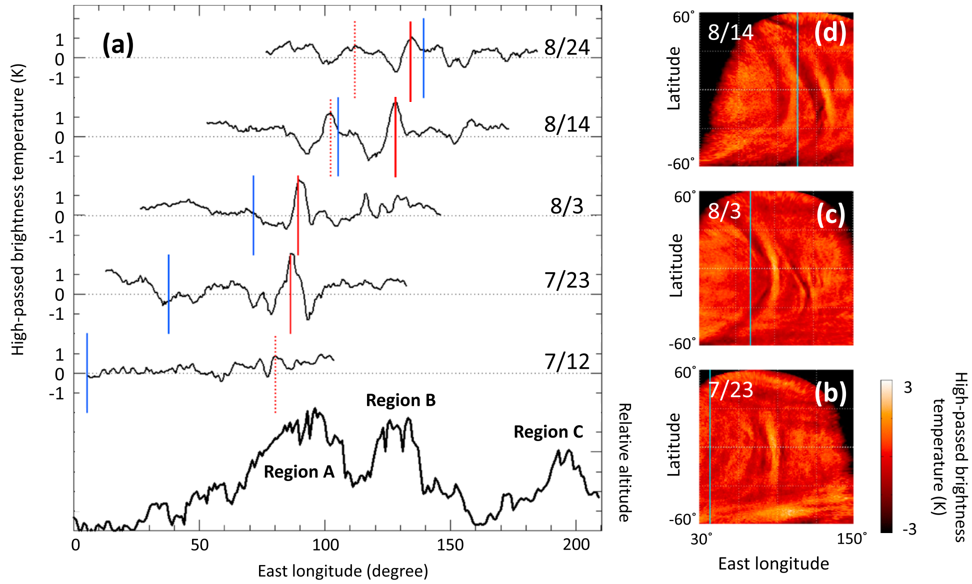

Figure 4. (a) Time evolution of the wave signature in Regions A and B in high-passed LIR images. Brightness temperature is an average over the latitudinal range of 20°S–10°N for each longitudinal bin. Red lines denote the longitudes where local maxima in the brightness temperature occurred (solid = more than 1 K; dotted = less than 1 K). Blue lines are the longitudes of the evening terminator for each date. Surface topography is also shown at the bottom. (b–d) Time evolution of the wave shapes between 23 July and 14 August.

slower than the movement of the subsolar point; hence, the movement does not simply relate to the movement of the subsolar point. Although this is the only case in which the time evolution of a stationary feature could be monitored for more than 1 month, the eastward movement of the peak position was also seen during a different observation period for Region A (Fukuhara et al., 2017).

4. Discussion

The characteristics of topographically generated gravity waves at high altitudes are expected to be sensitive to background wind and thermal structures in the lower atmosphere. The observed characteristics of the stationary waves in this study may provide data about the atmospheric conditions below the upper clouds, which are not well constrained due to the scarcity of observations.

The stationary nature of the waves and their correspondence with the highland locations suggests that stationary waves are generated as mountain waves, which are enhanced by winds hitting mountain slopes and passing over mountain summits. Because zonal wind speed increases with height in the lower atmosphere of Venus, higher mountain altitudes are advantageous for wave generation. The lack of clear wave detection above Phoebe Regio, an isolated high mountain in the low latitudes, might be attributed to the mountain's narrow width, which easily leads to an evanescent condition for a mountain wave (Durran, 1986). Young et al. (1987, 1994) studied the theoretical characteristics of the vertical propagation of stationary gravity waves in the Venus atmosphere, and they showed that waves with horizontal wavelengths of $<$50 km are evanescent and strongly attenuated in the lower atmosphere. Because horizontal wavelength of a mountain wave is influenced by the longitudinal scale of a mountain, a narrow highland will be disadvantageous to the generation of vertically propagating waves.

For a stationary gravity wave to reach cloud height, the direction of the background zonal wind needs to be westward down to the excitation level so that the wave can avoid breakdown at a critical level, where the horizontal phase velocity of the wave equals the background wind velocity. This consideration imposes a strong constraint on the zonal momentum balance near the surface and the mechanism of superrotation. The wind field at the altitudes where the waves were excited is highly uncertain because the measured zonal wind speed was near zero below ~5 km altitude (Schubert et al., 1980). A possible mechanism for the superrotation, in which a combination of Hadley circulation and axisymmetric eddies plays a role (Gierasch, 1975;

Rossow & Williams, 1979), postulates a near-surface eastward flow at the surface so that westward momentum is transferred from the solid planet to the atmosphere. Generation of superrotation by thermal tides excited at the cloud level (Fels & Lindzen, 1974), which is another proposed mechanism, should also produce an eastward flow at the equatorial-surface level induced by the momentum deposition from thermal tides (Takagi & Matsuda, 2007). These requirements are compatible with the propagation of stationary gravity waves up to cloud heights if the eastward flow is confined to the near-surface layer.

The preferential occurrence of stationary waves during the afternoon might be attributed to the local time dependence of wave generation or propagation. It might be possible that thermal tides reach the surface (Takagi & Matsuda, 2005, 2006) and cause a diurnal variation in the zonal flow at the surface level in such a way that westward winds are enhanced in the afternoon. Another possible explanation is that solar heating of the surface produces locally warmer regions at high altitudes in the late afternoon; this warm air produces local high pressure above the highlands similar to the Tibetan high pressure in the Earth's troposphere, leading to upward wave propagation from the high pressure in the ambient westward flow. This topographically driven, indirect wave excitation can work even if westward flow does not exist at the top of the mountain, although quantitative evaluation based on boundary layer modeling is required. The local time and latitudinal dependence of wave transmission through the cloud level convective layer could also potentially contribute to the observed tendency; Imamura et al. (2014) argued, based on numerical experiments, that convection is less active around the local time of 10–20 h (and shifted toward the evening side), and less active at lower latitudes than at higher latitudes because of the stabilizing effect of the solar heating in the upper cloud. Since strong convection might induce large eddy viscosity leading to the dissipation of stationary waves, this could explain the exclusive appearance of the waves in the low-latitude regions.

The stationary features detected in the VIRTIS images were more widely distributed than those in the LIR images; the cause of this difference is unclear, although the wide spectral band of LIR (8–12 μm) may lead to a deep averaging kernel that fails to detect short vertical wavelength waves. More extensive statistical studies using images taken by different sensors would better constrain the characteristics of stationary waves and the physical conditions of the lower atmosphere.

5. Conclusions

Since the successful Akatsuki Venus orbital insertion on 7 December 2015, LIR has continued its observations and has repeatedly detected large stationary gravity waves above four highland regions located at low latitudes. The large stationary gravity waves frequently appear in the afternoon and less frequently and ambiguously in the midnight and morning.

The existence and regular appearance of large stationary gravity waves in the atmosphere of Venus presents a new perspective of vertical coupling of the lower and upper atmospheres. Because of a lack of observations of the lower atmosphere and surface, it is unclear what atmospheric phenomena contribute to the excitation of stationary gravity waves. However, the occurrence of stationary gravity waves and their topographical and local time dependence must reflect conditions of both the lower atmosphere where the waves are excited and the atmosphere through which the waves pass. Modeling studies that consider the surface topography will be important for understanding the contribution of stationary gravity waves in the Venusian atmosphere to the current superrotation state.

Acknowledgments
This study is supported by the following grants: JSPS KAKENHI 15K17767, 16H02225, 16H02231, and 16K17816, and MEXT-Supported Program for the Strategic Research Foundation at Private Universities (S1411024). The version of the data used in this study is v20170901, and the data will be available at AKATSUKI Science Data Archives (https://www.darts.isas.jaxa.jp/planet/project/akatsuki/) by June 2018 and at the PDS of NASA (https://pds.nasa.gov).

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