Remarkable waves observed in the atmosphere of Venus, 2015–2020

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Observations at long infrared wavelengths by the *Akatsuki* spacecraft during 2015 December revealed the presence of a remarkable bow-shaped high-albedo atmospheric wave, elongated north–south and stretching over both hemispheres across a wide range of latitudes, up to 10,000km in length. Its velocity was nearly zero with respect to the surface, and its initial longitude placed it at the western side of one of the three highest regions of the planet. Amateur data at shorter infrared wavelengths recovered long, narrow N–S elongated waves or discontinuities in late 2016 and again during 2019–'20, but they showed typical velocities for that waveband, corresponding to synodic rotation periods of around five days. This short note reviews the *Akatsuki* data and more recent ground-based observations. Furthermore, it speculates whether waves could also have been generated by the possible surface volcanic activity first reported in BAA observations during 2017.

Akatsuki's atmospheric wave, 2015 December – 2016 January

A remarkable Venusian atmospheric wave was identified in the long-wave infrared (IR) images from the *Akatsuki* space probe of the Japanese Aerospace Exploration Agency (JAXA) during 2015 December, as announced briefly in this *Journal* and illustrated in popular magazines.[1,2] The feature (shown in Figure 1) was a large bow-shaped wave centred upon the equator and extending north–south over some 10,000km across a wide range of latitude. (10,000km equates to a latitude range of 95°.) It was located near the dayside evening terminator (marked by a dashed line in Figure 1), and it remained nearly stationary with respect to the slowly rotating surface. It was slightly warmer than the surrounding atmosphere. Animations of the *Akatsuki* wave reveal at most an extremely slight movement in longitude, but the data were of short time span.[3]

Akatsuki observed the feature only during 2015 Dec 7–12, just before orbital insertion, and subsequently a change in its orbit terminated the observations. When it was able to observe the region again on 2016 Jan 16, the feature had disappeared.

The wave's altitude of 65km corresponds to the boundary between the Venusian upper troposphere and lower stratosphere; at this layer the wind speed of normal clouds is of the order of 100ms^{-1} with respect to the ground. For atmospheric features recorded in the infrared, a near-stationary drift is unique. Synodic atmospheric rotation periods in the infrared region of 5–6 days, somewhat dependent upon latitude but more strongly upon wavelength (and hence upon altitude), are typical. The wave feature was extremely conspicuous at the very long infrared wavelength (λ) of 10 microns (1 micron (µm) = 1,000nm), but a trace of it could also be detected in the ultraviolet (UV): see Figure 1. (*Akatsuki* carried two IR cameras, for imaging in different spectral ranges.) A useful review of the type of information to be gleaned from observations in different wavebands is available.[4]

From the location of the wave near surface longitude 90°, the *Akatsuki* investigators considered it had been created by uprising airflow over the *Aphrodite Terra* mountain range, which reaches 5km in altitude. The feature was therefore regarded as a gravity wave (not to be confused with gravitational waves). Computer models run by the *Akatsuki* team suggest that air flowing over the elevated terrain could generate a gravity wave which propagates upward to the cloud tops, where it appears as a large bow-shaped wave.[3,6] Gravity waves have been positively observed in the atmospheres of other planets, from the Earth (leeward of the Andes mountains, for instance) out to Pluto.

In the nocturnal hemisphere, a high IR albedo corresponds to a locally warmer area, because temperature sharply decreases with height above the strongly heated surface.[5] However, upon the sunlit hemisphere, brightness in the near-IR implies greater reflectivity. On the side of the wave towards the terminator there was always an equally long, dark and irregular bow-shaped marking.

The *Akatsuki* investigators formally announced their findings in 2017 February.[6] During the 2017 European Planetary Science Conference, J. Peralta (JAXA) suggested that near-IR imaging by amateurs might record such sharp cloud discontinuities having planetary-scale dimensions, and Kardasis subsequently made an attempt.

Infrared wavebands & the ground-based observer

The upper wavelength limit for red light is 780nm. Infrared wavebands may be conveniently grouped into the following categories,[7] of which only the short wave region is accessible to amateurs:

Short wave	780–1,400nm (1.4µm)
Medium wave:	1.4–3.0µm
Long wave	> 3.0µm

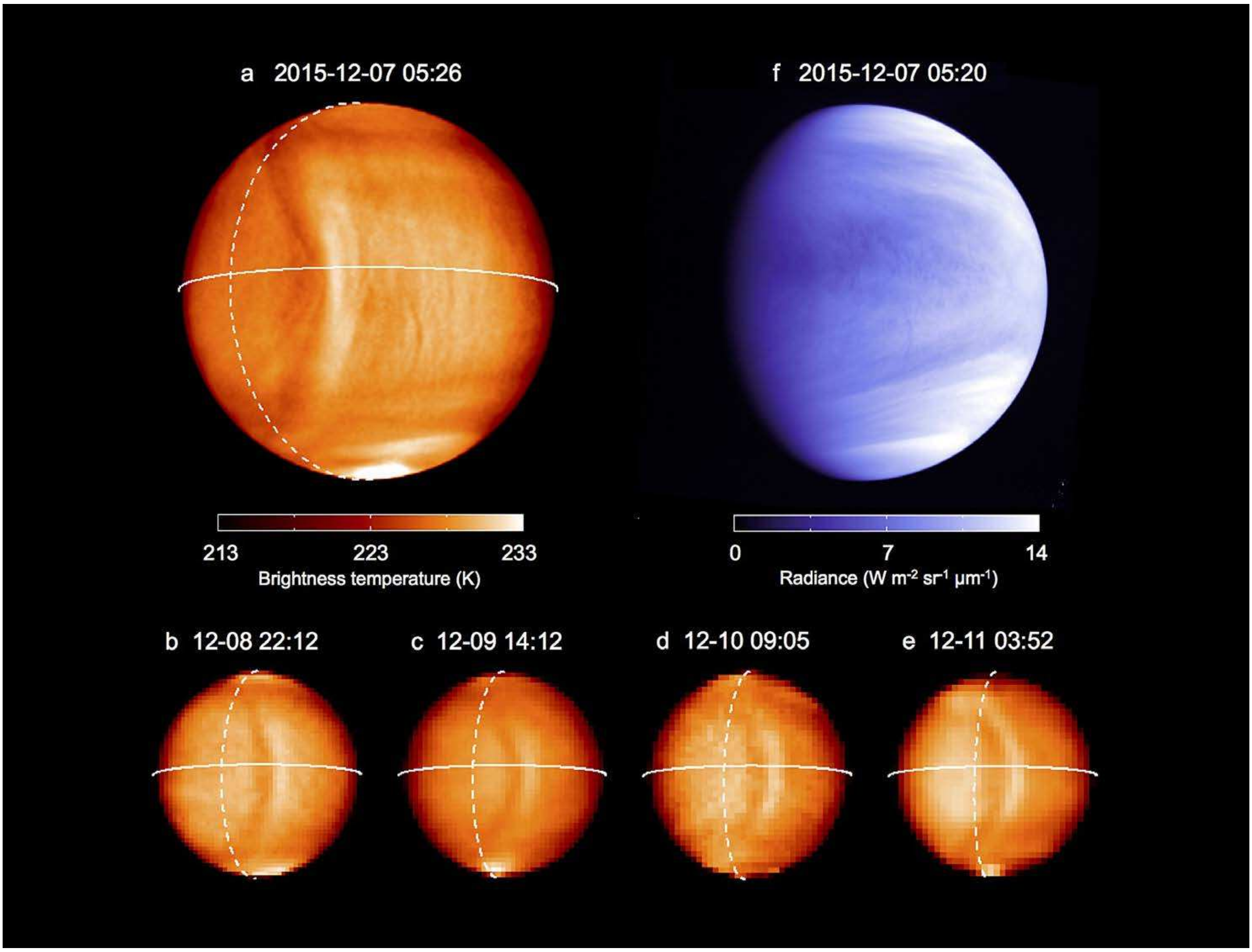

Figure 1. The atmospheric gravity wave discovered by *Akatsuki*, in false colours. The orange-coloured images (a–e) covering 2015 Dec 7–12 were taken by the Long-wave Infrared Camera (LIR), while the blue-coloured image (f) was taken by the Ultraviolet Imager (UVI). The solid line shows the planet's equator. The sunlit portion of the planet lays to the right of the dashed line marking the terminator. North is up. *JAXA*

Near-infrared images are nearly always bland in comparison with high-contrast ultraviolet ones. In the UV, the characteristic chevrons of the equatorial Y and psi markings always dominate the visible albedo patterns. Moreover, the atmospheric wave had been recorded by the spacecraft at a wavelength of 10μm in a waveband inaccessible to amateurs, so it was not originally considered to be a possible observational target for the BAA.

We have checked through the BAA image archive for the period covered by the *Akatsuki* observations, and found no records of linear N–S streaks, bright or dark, in either IR or UV images. Examination was made without further processing of the observations. Since IR features present very low contrast, they require special image treatment to reveal the subtle details.

Infrared observations by amateurs, 2016 October–December

The *Akatsuki* wave was not discussed in the recent long-term report for 2007–'17,[8] but during the past year an equally remarkable phenomenon was recorded by several amateurs in the near-infrared as an extremely long and narrow discontinuity oriented N–S. Unlike the *Akatsuki* wave it did not display any noticeable bow-shape, but it did consist of a long bright streak followed by a dark line. Kardasis was the first to draw attention to it, and he recently gave advance details in the Section bulletin, *Messenger*,[9] where he noted that P. Miles and A. Wesley (both based in Australia) had observed a similar feature in late 2016, during the 2017 E. elongation. A search was therefore made for more sightings, through the Section records as well as the ALPO Japan and PVOL websites.[10,11] As a result, we now have several periods over five years during which apparently similar waves or discontinuities have been sighted.

Looking back through the records with the benefit of hindsight, a handful of sightings of a similar phenomenon could be identified from the late 2016 near-infrared images, although the feature appeared less prominent than in the *Akatsuki* images, did not exhibit a bow shape, and often looked fragmentary. Because amateur infrared images are usually heavily processed, they can sometimes exhibit one or more 'step' artefacts towards the terminator, so a linear vertical feature often represents this. For that reason, the very few sightings of a real wave in 2016 had not originally been noticed. Simultaneous visual and ultraviolet images were

Table 1. Near-infrared wave phenomena, 2016 October–December

Date & time (UT)	*Observer*	*Wavelength*	*CM1 (°)**	*Angular distance from wave centre to CM (°)*	*Longitude of wave, System I (°)*	*Comments*
2016 Oct 15, 15:00	R. Sedrani	850nm	337.7	29	–	The image is low resolution, but shows a bright spot just S. of the equator followed by a dark marking, slightly elongated N–S.
2016 Oct 20, 07:49	P. Miles	1000nm	350.4	29	–	The measured feature was the centre of the bright area, which was followed by a partial N–S dark streak probably arising from the conjunction of two dark spots at different latitudes but similar longitudes. It was not an atmospheric wave, but is included for completeness.
2016 Oct 20, 07:52	A. Wesley	1.0–1.05µm	350.4	30	–	
2016 Oct 24, 07:27	A. Wesley	1.0–1.05µm	1.1	32	34	This was measured to the (partial) bright wave crest; it was also imaged on the same date by Miles at 06:33 UT.
2016 Oct 29, 08:00	P. Miles	1000nm	14.6	38	–	The feature seen on Oct 29 was shorter, located south of the equator only.
2016 Oct 29, 08:01	A. Wesley	1.0–1.05µm	14.6	38	–	
2016 Dec 19, 07:56	P. Miles	1000nm	150.3	30	181	A patchy and irregular bright N–S streak appears to cross the equator.
2016 Dec 24, 15:57	L. Morrone**	685nm	164.2	26	–	Again a definite but patchy bright streak, orientated N–S, in both hemispheres. Range in D_e, 2016 Oct–Dec: +1.5 to +2.5°.

* CM1 indicates the central meridian of the surface in System I according to *WinJUPOS*. The longitude of the wave in System I was only calculated for the initial sighting. The angular separation from the CM was measured at the equator and is probably correct to ±1–2°.

** Image found at ALPO Japan website.

Table 2. Near-infrared wave phenomena, 2019 December – 2020 April

Date & time (UT)	*Observer*	*Wavelength*	*CM1 (°)**	*Angular distance from wave centre to CM (°)*	*Longitude of wave, System I (°)*	*Comments*
2019 December						
2019 Dec 3, 15:20	E. Kardasis	884–900nm	275.1	6	281	A well-defined bright wave.
2019 Dec 8, 13:49	E. Kardasis	884–900nm	288.5	14	–	A bright spot south of the equator remains. Range in D_e, 2019 Dec: +2.0 to +2.0°.
2020 March–April						
2020 Mar 11, 16:30	J. Camarena**	850nm	179.4	32	211	A definite N–S streak crossing the equator. Also recorded on Mar 11 by L. Morrone**
2020 Mar 11, 16:45	E. Kardasis	884–900nm	179.5	30	210	
2020 Mar 16, 15:00	Y. Naryzhniy**	950nm	192.0	38	–	As Mar 11. Also recorded on Mar 16 by L. Morrone.** The wavelength used by Calapai is in the red rather than the IR.
2020 Mar 16, 16:01	G. Calapai**	685nm	192.1	36	–	
2020 Mar 21, 17:35	E. Kardasis	884–900nm	204.8	32	–	As Mar 11, 16. Also recorded Mar 21 by D. Kananovich.**
2020 Mar 26, 15:20	Y. Naryzhniy**	950nm	216.9	41	–	As Mar 11, 16, 21, but becoming less obvious.
2020 Mar 31, 16:15	Y. Naryzhniy**	950nm	229.2	41	–	The wave was still long, but became very faint and hard to measure.
2020 Mar 31, 17:04	E. Kardasis	884–900nm	229.3	37	–	
2020 Apr 5, 16:40	Y. Naryzhniy**	950nm	241.2	–	–	The wave was faintly present, but too faint to measure.
2020 Apr 10, 16:12	E. Kardasis	884–900nm	252.8	38	–	The wave was again faint and discontinuous. After Apr 10, the narrowness of the crescent made the detection of wave phenomena challenging.
2020 Apr 25, 17:27	E. Kardasis	884–900nm	285.7	41	–	Definite but faint N–S light streak: the final positive record for the 2020 E. elongation. Range in D_e, 2020 March–April: –3.2 to –5.6°.

* CM1 indicates the central meridian of the surface in System I according to *WinJUPOS*. The longitude of the wave in System I was only calculated for the initial sighting. The angular separation from the CM was measured at the equator and is probably correct to ±1–2°.

** Image found at ALPO Japan website.

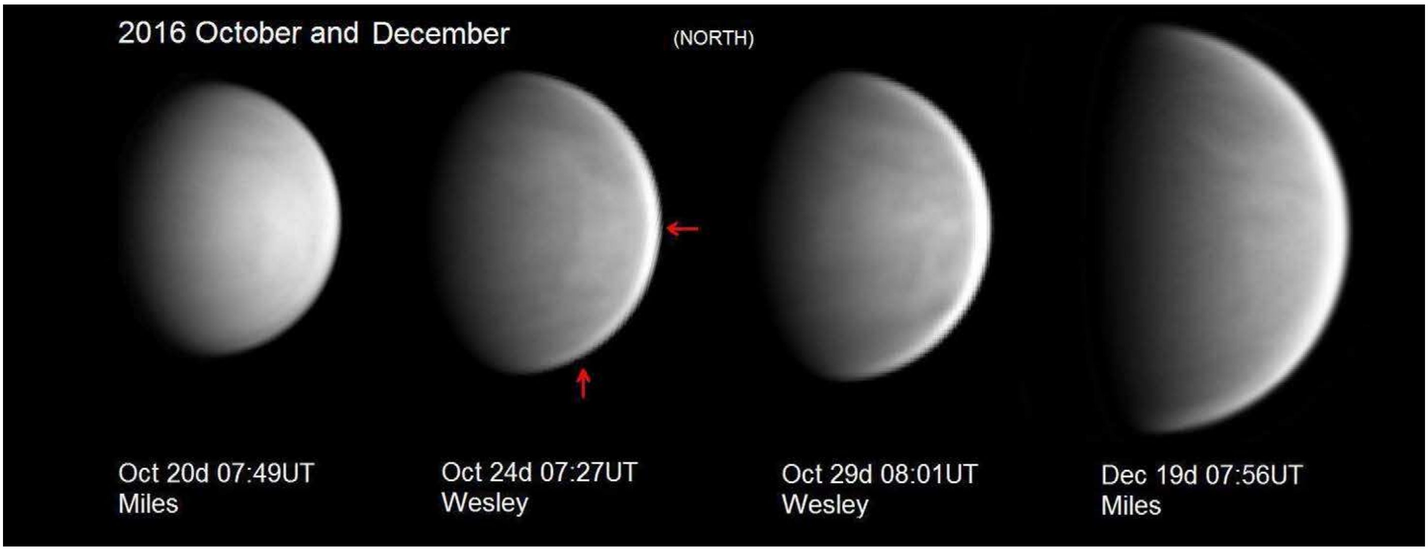

Figure 2. Ground-based infrared images of probable and actual waves in 2016 October and December. The location of the 2016 Oct 24 wave is indicated. North is uppermost to facilitate comparisons with *Akatsuki*. The images are not to scale. (Miles: 508mm refl. & GS3-U3-32S4M camera; Wesley: 406mm refl. & BFLY-PGE-31S4M.) See text for further details.

searched, but no obvious sign of the wave was seen. The wave recorded by *Akatsuki* had been only weakly visible in the spacecraft's extremely high-resolution UV images: if one had not first seen the IR results, it would probably have been overlooked.

Table 1 and Figure 2 summarise our findings from the BAA image archive. The latitude of the sub-Earth point (D_e) was small, and is stated at the foot of the table. A short-lived wave feature was recorded on 2016 Oct 24 & 29. It contained part of a bright arc oriented N–S, with a dark N–S feature adjacent to it on the terminator side. At this elongation there were many excellent daily images during October–December, but only those five days apart recorded the wave-like phenomena. Another recurrent bright feature had also been recorded on Oct 15 & 20: it does not appear to have been a wave or discontinuity, but is included in Table 1.

The 2016 October phenomenon differed further from the *Akatsuki* wave in exhibiting an atmospheric drift typical of near-infrared features, and therefore must have been a different type of object. An observation on Dec 19 by Miles appears to record another, fragmentary, linear feature (also shown in Figure 2). This was re-observed by Morrone on Dec 24 (image from the ALPO Japan website),[10] but images on Dec 29 failed to show it.

The rotation period of the 2016 Oct 24–29 and Dec 19–24 features were found to be 5.10 ± 0.04 and 5.39 ± 0.04 days, respectively. BAA data show similar mean periods of 4.72 days for a selection of dark features over a wide range of latitude at the 2010 E. elongation,[8] and 4.99 days for equatorial bright spots during the 2004 W. elongation.[12]

None of the 2016 October UV images showed any trace of a wave: a long sequence of UV/IR image pairs by Wesley may be studied in Figure 4 of our 2007–'17 report.[8]

Recent infrared observations by amateurs, 2019–'20

In his observations during the 2020 E. elongation just completed, Kardasis was able to identify and draw attention to another apparent reincarnation of the wave phenomenon. On 2019 Dec 3.[9] Kardasis (observing from Athens, Greece) imaged a possible wave, but it quickly dissipated, reappearing once only at the next rotation on Dec 8 in diminished form (Figure 3). A few months later on 2020 Mar 11 he recorded a long, vertical bright streak with a dark band on the terminator side; nothing had been visible on Mar 6. This resembled the 2016 Oct 24–29 and Dec 24–29 features. Kardasis found that it again recurred every five days, and alerted other observers: some of the results are shown in Figure 3. Confirmatory sightings were posted at the ALPO Japan website,[10] by Calapai (Italy), Camarena (Spain), Kananovich (Estonia), Morrone (Italy) and Naryzhniy (Ukraine). It continued to be visible until Apr 25. We have measured many of these for longitude (Table 2) and other characteristics (Table 3).

The rotation periods for the 2019 December and 2020 March–April waves were found to be 5.04 ± 0.04 days (approximately), and 5.01 ± 0.01 days (more precisely), respectively. Again, these are perfectly normal periods for this waveband. There is a possibility that the discontinuity existed between December and March, but was not prominent as a vertical feature. It will be interesting to see if it will be re-observed during the 2020 W. elongation.

Length, width & height

The original wave and the features observed in the ground-based data were long, bright streaks, each of which was followed by a dark band, and which covered an exceptional range of latitude.[1–3,6,9] The spacecraft images revealed a markedly bowed and irregular shape, but the more recent images generally portrayed a narrower and more uniform wave lacking a bow shape. Ground-based data were of shorter IR wavelength than *Akatsuki*, corresponding to a slightly higher altitude in the planet's atmosphere.

It is worth considering whether the narrow dark line observed upon the recent amateur images towards the terminator side could have been a shadow. This would only have been detectable if the bright wave had been at a great elevation above its surroundings.

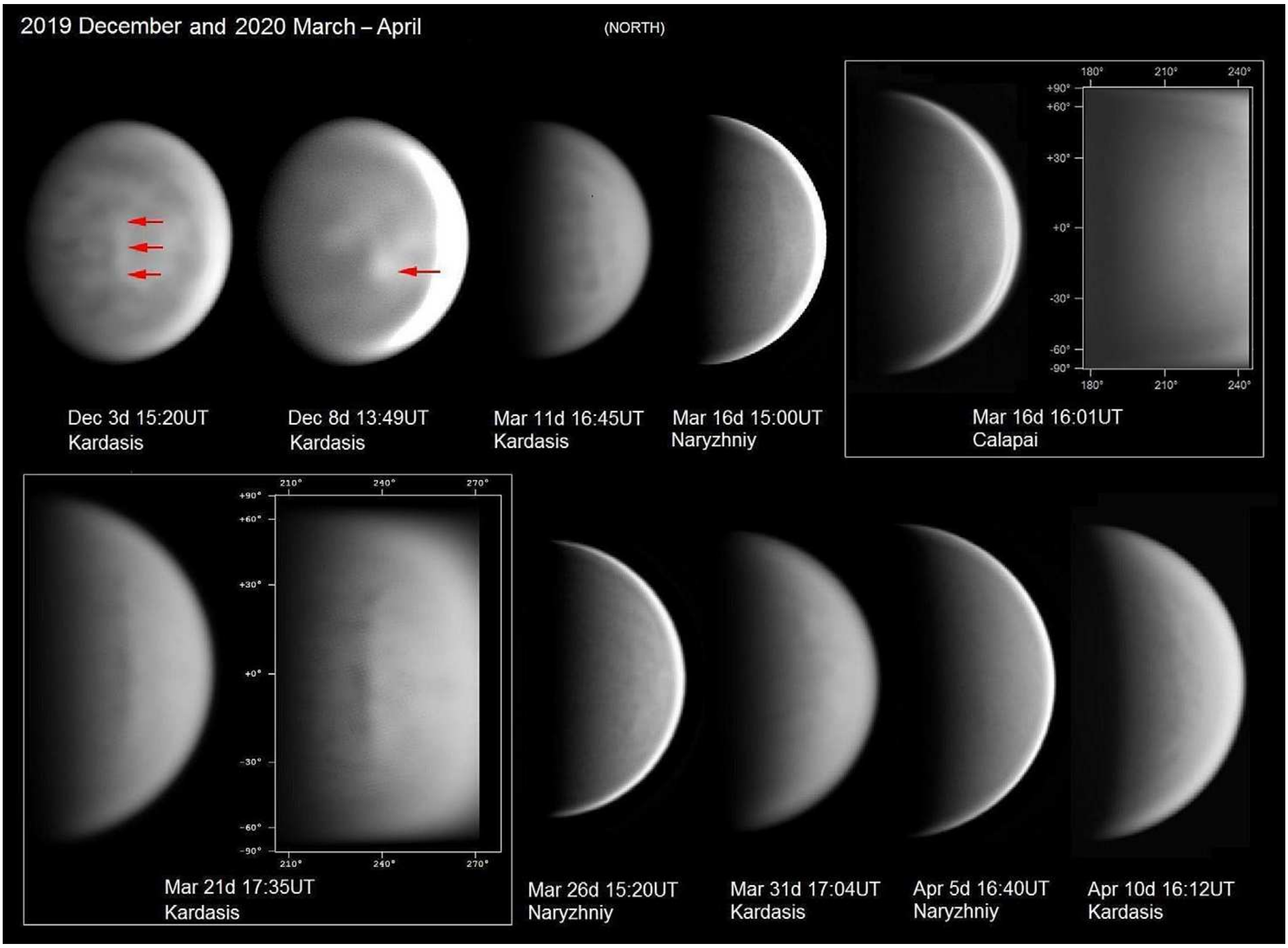

Figure 3. Ground-based infrared images of atmospheric waves in 2019 December and 2020 March–April. The locations of the 2019 December waves are marked. North is uppermost to facilitate comparisons with *Akatsuki*. The images are not to scale; the two maps are Lambert cylindrical projections with planetocentric latitudes and System I longitudes. (Calapai: 279mm SCT and ASI120MM camera; Kardasis: 356mm SCT & ASI290MM; Naryzhniy: 400mm DK Cass.) See text for further details.

That the dark line existed on one side only of the bright wave crest rules out the possibility of it being a mere artefact.

If the dark line really was a shadow, it is a simple matter to calculate its height at the latitude of the sub-Earth point, knowing its angular separation from the geometric terminator and the phase angle.[13] As an example, we measured the image of 2020 Mar 16 taken by Naryzhniy (from the ALPO Japan website), which is particularly sharp, and calculated an altitude of 112 ± 30km. This result is clearly impossible, so the dark line simply was an albedo feature. Other images yielded similar values.

Table 3 gives the length and width measurements of the dark band adjacent to the bright wave, this being the easier of the two to measure. The maximum length of some 7,000km is rather shorter than the *Akatsuki* wave (which extended to some 10,000km), yet nevertheless covered some 66° in latitude.

Origin of the waves

The final question to be considered here is whether the more recent waves or discontinuities (although moving at typical atmospheric velocities) had originated near surface longitude 90° at the western edge of the *Aphrodite Terra* mountain range, like the original *Akatsuki* wave, or above other highland regions. A topographic relief map for reference is given in Figure 4, upon which the foregoing features are identified.

The waves recorded in ground-based imaging must have traversed some 70° of the surface every day. Although we are confident that we noticed them upon their first rotation, the earliest records of their surface longitude (System I in *WinJUPOS*) may be of very little value, unless the waves had always formed upon the dayside. For the record, they are included in Table 4.

Most longitudes upon Venus include portions of elevated terrain at *some* latitudes, but no correlation with the highest surface point, *Maxwell Montes*, was noticed.

During 2017 May, P. Miles and A. Wesley detected bright areas in the IR thermal emission from the Venusian night side, as reported in this *Journal*.[5] The location of the brightest (and therefore warmest) of these was near latitude –2°, longitude 43°, in *Eistla Regiones* (a region centred at +16°, 40°). Interestingly, this is close to the initial longitude of the 2016 October wave.

As this paper was being completed, a further study was published by Peralta *et al.* (2020) which discusses further records (both spacecraft and ground-based) of the wave discontinuity phenomenon, with the rotation periods being in close accord with ours.[14] Our investigation of the ground-based data was made independently.

Interpretation & conclusion

The very slow drift with respect to the surface measured for the *Akatsuki* 2015–’16 wave imaged at 10μm is exceptional for an atmospheric feature. Subsequent waves or discontinuities seen by ground-based observers in 2016 October–December, 2019 December and 2020 March–April at 0.685–1.00μm were not stationary and rotated with the atmosphere; they did not exhibit any bow shape, but did cover a similarly large north–south extent. Like the initial wave, they were not long-lived as distinct features.

The observations of bright spots at the surface on the night side of the planet, by Miles and Wesley in 2017,[5] lead one to speculate whether ongoing volcanic activity – if that is what such features really represent – could have been a source of energy for generating atmospheric waves. That the atmospheric features and the bright spots appeared only comparatively recently may be highly significant.

Whatever their interpretation, the Venusian atmospheric waves or discontinuities are remarkable features, which observers should continue to look for, report, and study in the future.

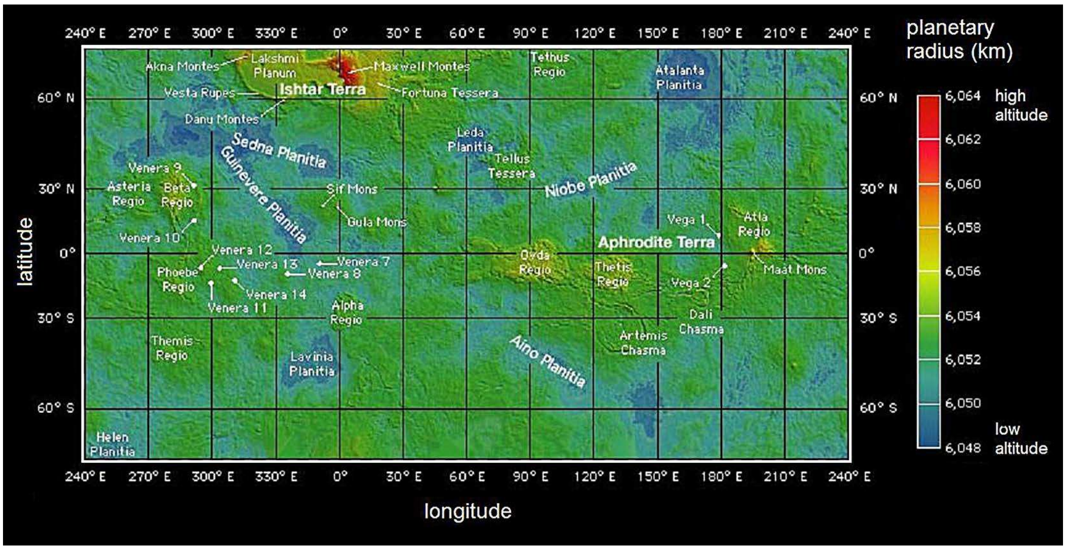

Figure 4. False colour map of Venus derived from laser altimetry measurements by the *Magellan* spacecraft. North is uppermost. *NASA/JPL/MIT*

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Notes & references

1 McKim R. J., *J. Brit. Astron. Assoc.*, **127**, 286 (2017)
2 See for example Dickinson D., *Sky & Telesc.*, **133**(5), 8 (2017). See also the corresponding website article: **skyandtelescope.org/astronomy-news/japans-akatsuki-spies-massive-wave-on-venus/**
3 The JAXA website includes a movie of the IR gravity wave during 2015 December: **http://www.isas.jaxa.jp/en/topics/000883.html**
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9 Kardasis E. (M.), ‘A planet-scale cloud discontinuity event is observed in Venus’, *Messenger* (BAA Mercury & Venus Section Newsletter), no.3, 21 (2020 April)
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13 A formula for calculating the height of a cloud throwing a shadow onto the gibbous disc of Venus is easily derived. Let θ be the angular separation between the wave and the central meridian, and w the width of the shadow at the latitude of the sub-Earth point. If i is the phase angle in degrees, then the true height of the cloud feature will be equal to $w \sin(90–i+\theta)$.
14 Peralta J. *et al.*, *Geophy. Res. Lett.*, **47**, e2020GL087221 (2020): **doi.org/10/1029/2020GL087221** (Accepted 2020 May 1)

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Table 3. Selected length & width measurements

Date	*Observer*	*Length (km) of the dark band to nearest 100km*	*Width (km) of the dark band to nearest 10km*	*Comments*
2016 Oct 20	Wesley	3900	380	Only visible in the south
2016 Oct 24	Wesley	4800	440	
2016 Oct 29	Wesley	2900	440	Only visible in the south
2016 Oct 29	Miles	5900	420	
2020 Mar 11	Kardasis	5700	200	Less sharp image
2020 Mar 16	Narayzhiny	5500	340	
2020 Mar 16	Calapai	5800	380	
2020 Mar 16	Morrone	5200	380	Hard to measure
2020 Mar 21	Kananovich	5500	510	Hard to measure
2020 Mar 21	Kardasis	7000	610	Less sharp image

Table 4. Initial longitudes of atmospheric waves

Date when first observed	*Surface longitude (°) when first observed*	*Significant topographical feature(s) at same longitude*
2016 Oct 24	34	Over E. *Ishtar Terra* (and see below)
2016 Dec 19	181	Towards E. end of *Aphrodite Terra*
2019 Dec 3	281	Over *Beta Regio – Phoebe Regio*
2020 Mar 11	211	At the E. end of *Aphrodite Terra*